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# Assessment and Governance of Sustainable Soil Management

Edited by
Katharina Helming, Thomas Koellner, Bernd Hansjürgens and Katrin Daedlow

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# Contents

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*Editorial*

# Assessment and Governance of Sustainable Soil Management

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**Abstract:** The globally increasing demand for food, fiber, and bio-based products interferes with the ability of arable soils to perform their multiple functions and support sustainable development. Sustainable soil management under high production conditions means that soil functions contribute to ecosystem services and biodiversity, natural and economic resources are utilized efficiently, farming remains profitable, and production conditions adhere to ethical and health standards. Research in support of sustainable soil management requires an interdisciplinary approach to three interconnected challenges: (i) understanding the impacts of soil management on soil processes and soil functions; (ii) assessing the sustainability impacts of soil management, taking into account the heterogeneity of geophysical and socioeconomic conditions; and (iii) having a systemic understanding of the driving forces and constraints of farmers' decision-making on soil management and how governance instruments may, interacting with other driving forces, steer sustainable soil management. The intention of this special issue is to take stock of an emerging interdisciplinary research field addressing the three challenges of sustainable soil management in various geographic settings. In this editorial, we summarize the contributions to the special issue and place them in the context of the state of the art. We conclude with an outline of future research needs.

**Keywords:** soil functions; agricultural practices; sustainability assessment; ecosystem services; resource use efficiency; soil policy; soil governance

## 1. Introduction

Soils are at the nexus of multiple United Nations Sustainable Development Goals (SDGs) [1]. While Keesstra et al. [2] identified direct or indirect contributions of soils to as many as 13 of the 17 SDGs, a fundamental role of soils exists for at least four of them: arable soils account for the largest part of global food provision (SDG 2); soils are the basis for bio-based renewable energy production to ensure energy security (SDG 7); the storage capacity of soils for organic carbon is paramount for climate change mitigation (SDG 13); and the capacity for water purification and retention, nutrient and matter cycling, and the habitat function of soils are essential for maintaining the terrestrial environment and biodiversity (SDG 15). The link between soil processes and SDGs is usually conceptualized via soil functions [2]. Arable soils provide five key functions: biomass production, water purification, carbon sequestration, habitat for biodiversity, and recycling of nutrients and (agro)chemicals [3].

While agricultural soil management does, by definition, favor the production function over other functions, it is the challenge for sustainable soil management to maintain multifunctionality [4].

From a natural science perspective, it is important to understand how soil functions emerge from interacting soil processes. While soil sciences have impressively advanced knowledge about chemical, physical, and biological processes in soils, their interrelations and links to soil functions are not yet well understood. Such an understanding requires a systems approach to the development of indicators of soil functions [5]. Ludwig et al. [6] conceptualize the analysis of soil functions from the perspective of the social–ecological–systems framework [7] and propose the resilience of the soil system as an integrated sustainability indicator. This approach may allow for the identification of tipping points toward an irreversible or permanent loss of soil functions. However, the authors admit that the quantification of such an indicator remains out of sight. Bünemann et al. [8] provide a critical review of the assessment and indication of soil quality and function. They argue that the process of developing an indicator for soil quality and function assessments requires the involvement of actors, stakeholders, and end users in order to be useful for supporting management and policy decisions in practice.

While it is the task of natural science disciplines to jointly develop a systemic understanding of interactions of soil process with soil functions, it requires socioeconomic and agronomic expertise to address sustainable soil management. We see three challenges in developing socioeconomic and agronomic research in this context (Figure 1): (i) to establish analytical linkages between soil management and soil functions; (ii) to assess the relevance of soil functions to fulfilling societal targets, including ecosystem services, resource use efficiency, and sustainable development; and (iii) to understand how governance instruments affect farmers' decision-making regarding sustainable soil management. The three challenges establish linkages between the five elements of the Drivers–Pressure–State–Impact–Response (DPSIR) framework [9], which is a well-established framework for the analysis of human/nature relationships (Figure 1).

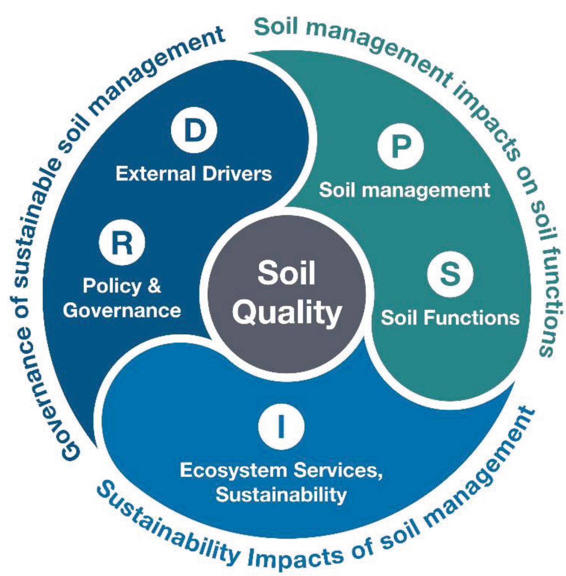


**Figure 1.** Three main analytical challenges for sustainable soil management. Letters indicate the relationship to the Drivers–Pressure–State–Impact–Response (DPSIR) framework for analyzing human/nature interrelations [9].

The first challenge is to understand soil management practices and how they impact soil processes and functions. Agricultural crop management includes tillage, crop choice and rotation, fertilization, weed management, pest management, irrigation and drainage, harvesting, and residue management. Each of these activities interferes with soil processes. Soil conservation practices such as conservation tillage aim at avoiding soil threats and maintaining soil multifunctionality, which often is at the cost of yield performance [10]. Policy instruments such as the agri-environmental payment schemes of the European Common Agricultural Policy (CAP) aim at compensating farmers for income loss associated with soil conservation management practices [11]. However, with the globally increasing demand for biomass-based food, feed, energy, and fiber, not least reinforced through renewable energy policies or bioeconomy strategies, the quest for sustainable intensification practices is expressed, which aims at integrating the highest productivity with the maintenance of a broad range of soil functions [12,13]. This integration requires the stimulation of ecological interactions at the soil–plant interface, thereby improving the efficiency of natural resource use [14]. Emerging management technologies associated with, for example, smart farming technologies [15] or improved use of biological pest antagonists [16] are expected to offer potential for the implementation of sustainable intensification [17]. However, institutional factors (e.g., regulations, prices, norms, habits) and policy conditions for their implementation (e.g., market factors, enforcement), along with possible interference with farm management constraints and their impacts on a wider set of sustainability goals, have yet to be assessed.

Sustainability assessment of soil management is the second challenge of providing an evidence base for sustainable soil management. This process involves assessing intended and unintended, direct and indirect impacts of human activities on societal targets such as the UN sustainable development goals [18]. Assessments are applied at the level of EU and national policy, regional landscape planning, and farmers' practices [19]. Helming et al. [4] developed a conceptual framework for the sustainability assessment of soil management that links the concepts of resource use efficiency and ecosystem services to account for the most prominent perspectives. This framework involves a dynamic *ex ante* approach that builds upon the DPSIR framework [9] and links external driving forces to soil management, soil process changes, and their implications for sustainability targets. While the concept is comprehensive, its implementation is challenged by the multitude of indicators that must be estimated, valued, and prioritized for specific geophysical and socioeconomic contexts. Targeted data collection, research synthesis methods, and user-oriented approaches are key to successfully conducting such dynamic assessments [20]. For example, a stakeholder-inclusive process of indicator selection for the assessment of soil management may improve its relevancy for sustainable development targets [21].

The outcomes of sustainability assessments can be seen as a prerequisite for the third challenge of providing an evidence base for sustainable soil management, which is related to governance mechanisms and policy-making. Although a number of publications have emerged in recent years about policy analysis regarding soil management, particularly in Europe [11,22,23], soil-related governance is far less well understood than the governance of other natural resources such as water, air, or biodiversity [24]. Research must reveal how governance mechanisms at multiple administrative levels interact, which instruments are most relevant for farmers' decision-making, what role property rights and tenure systems may play in the efficiency of governance instruments, and how governance interacts with other drivers of soil management, such as climate change, technological advances, consumer preferences, and education and advisory systems.

The objective of this special issue is to compile the latest interdisciplinary research on the three challenges outlined above. The idea is to shed light on the emergence of an interdisciplinary research community dealing with the sustainable management of soils. The motivation for this project stems from the German interdisciplinary research program "Soil as a Sustainable Resource for the Bioeconomy—BonaRes" (www.bonares.de), which was established to develop a scientific evidence base for agricultural soil management that maintains soil functions while increasing agricultural production in support of the implementation of the German bioeconomy strategy. The BonaRes program consists of 10 collaborative research projects on various aspects of sustainable soil management. It is complemented by the BonaRes Centre to develop a coherent approach to data management, soil modeling, sustainability assessment, and governance [25]. While the core of research in BonaRes focuses on the natural science aspects of soil management, processes, and functions, there is increasing awareness about the role of socioeconomic research to better understand the full complexity of, the opportunities for, and the obstacles to sustainable soil management. Taking the interdisciplinary setting of BonaRes as a stepping-stone, this special issue invited interdisciplinary and transdisciplinary research on the assessment and governance of sustainable soil management from various contexts across the globe. The outcome is 15 papers dealing with the management, assessment, and governance of agricultural soils and their relationship to soil functions, ecosystem services, and sustainable development. The papers address a wide range of agronomic practices and include reviews, conceptual papers, meta-analyses, and empirical studies of cases in Europe, Central America, the Middle East, and Asia. The papers are outlined and placed in the context of the three research challenges described in the following sections.

## 2. Soil Management Impacts on Soil and Soil Functions

Soil management of arable fields is performed to improve the growth conditions for agricultural crops. Soil management thereby favors the production function of soils over other functions, with the target of producing food, feed, and fiber. However, soil degradation processes are negative side effects that seem to be exacerbated by increasing agricultural intensity [26]. Agricultural production is therefore considered a major cause of soil degradation processes. These processes include erosion by wind and water, loss of biodiversity, compaction, salinization, loss of organic carbon, and diffuse water and soil pollution [22]. The cause–effect chains between agricultural management practices, on the one hand, and soil degradation processes, on the other, are not straightforward. These chains are subject to spatially varying geophysical and climatic site conditions as well as the temporal dynamics of weather and vegetation processes. For example, water erosion occurs on sloped land when precipitation exceeds the infiltration capacity of the soil, but that is highly dependent on the vegetation status and the coverage of the soil surface with plant material [27]. The same holds true for wind erosion, which soils are particularly susceptible to when the surface is bare and dry [28]. The design of crop rotations and tillage practices determines the length of time during which the soil is bare during the vegetation year. Conservation agriculture is defined as an approach to optimizing coverage of the soil surface with organic material and improving the soil's infiltration and water-retention capacity [29]. It combines no-till practices with residue management and differentiated crop rotations.

In this special issue, several papers analyze the impacts of conservation agriculture and other innovative soil management practices on soil functions (Table 1). Ghaley et al. [30] provide a meta-analysis of the effects of conservation agriculture on soil multifunctionality for the main environmental zones of Europe. Building upon a literature synthesis and employing an expert-based scoring system, the authors identify overall positive effects of conservation agriculture, while in the case of conventional agriculture, negative effects dominate across the five soil functions mentioned above (production, water purification, carbon sequestration, habitat for biodiversity, and recycling of nutrients and (agro)chemicals). Ghaley et al. [30], however, point to the need for field investigations to better understand systemic factors of soil management, climate, soil process interactions that lead to changes in soil functions, and associated ecosystem services.

Lalani et al. [31] employ a farm research approach to study the impacts of conservation agriculture on dryland farming systems in central Syria. Although the research was restricted by the outbreak of armed conflict in Syria, preliminary results indicate that conservation agriculture is of particular benefit for soil moisture and for grain and straw productivity. The authors conclude that in a semi-arid marginal area such as central Syria, conservation agriculture may be the only option with progressing climate change because of its moisture-saving characteristics [31].

Nuppenau [32] takes the complex system relationships between crops and soils as a starting point from which to design a dynamic optimization modeling approach for crop rotations that better considers ecological information and feedback loops. Such an approach is also meant to account for the long-term positive effects of deep-rooting and/or N-fixating crops such as alfalfa on soil structure, organic turnover, organic carbon sequestration, soil rootability, and water capacity. Such positive effects may, in the long run, outweigh the short-term negative effects on economic return compared to other crop rotations. Addressing long-term effects in complex modeling approaches is indeed important to reveal and assess possible benefits of conservation agriculture practices that, from the short-term view, still suffer from lower yields and economic returns compared to conventional practices [10].

**Table 1.** Overview of contributed papers addressing the impacts of soil management on soil functions.

| Authors | Soil Management Type | Soil Management Topic | Region | Spatial Scale | Paper Type; Knowledge Base |
|---|---|---|---|---|---|
| Ghaley et al. [30] | Tillage, crop rotation, residue management | Effects on soil functions | Europe | Field | Meta-analysis |
| Lalani et al. [31] | Tillage and soil moisture retention | Yield, cost-effectiveness, trade-offs | Syria | Farm | Empirical analysis |
| Nuppenau [32] | Crop rotations | Economic optimization and ecosystem services | Germany | Farm | Modelling framework |
| Frelih-Larsen et al. [33] | Subsoil management | Farmers' acceptance | Germany | Farm | Empirical analysis |
| Seydehmett et al. [34] | Water utilization and management | Future trends and soil salinization | China/northwest region | Landscape/region | Modelling analysis |
| Ledermüller et al. [35] | Tillage, field traffic | Risk assessment of soil compaction | Germany/Lower Saxony | Field | Spatial analysis and modelling |

The utilization of subsoil for root growth and water and nutrient utilization is another key factor of soil-improving agricultural practices [36]. Frelih-Larsen et al. [33] analyze determining factors for farmers' decision-making on the implementation of subsoil-improving management practices. These include biological measures such as integrating deep-rooting crops and mechanical practices. General acceptance of biological measures of subsoil utilization was found to be far higher than that of mechanical practices. However, economic barriers also hinder the integration of such crops into rotation [33].

In semi-arid and dryland regions, irrigation of crops is one major cause of soil degradation risk because of secondary salinization. Irrigated agriculture accounts for more than 40% of global food production, and it covers nearly one-fifth of the world's cropland [37]. The degree of soil salinization is a factor of natural soil properties, climate, water quality, and farmers' decisions regarding the technology and amount of irrigation, as well as desalinization measures such as leaching. In their contribution to this special issue, Seydehmet et al. [34] apply a Bayesian networks approach to integrate assumptions on farmers' decision-making into model simulations of future salinization for a Chinese watershed. Particularly because of the integration of stakeholder perceptions, the modeling approach proved to be a useful tool to support future decision-making on land reclamation and irrigation with regard to avoiding salinization.

The contribution by Ledermüller et al. [35] also reports on the development of a decision support tool for farmers to help avoid soil degradation. This tool addresses the problem of soil compaction caused by heavy machinery. Soil moisture determines the susceptibility of soils to compaction under mechanical pressure and is highly dynamic depending on temporal patterns of precipitation. Ledermüller et al. [35] integrated spatiotemporal factors into a risk map for soil compaction, which farmers can use to optimize the timing of traffic and tillage operations. Such decision-support systems are particularly important to assist farmers in better aligning soil management with soil function maintenance.

Despite the variety of topics covered by the papers in this special issue, two items for future research stand out. The first is the need to acknowledge the systemic interrelations between agricultural soil management practices and soil process reactions leading to responses in soil functions [5]. Linear processes and one cause–one effect relationships rarely exist in soils, which makes the identification of best management practices complex. In particular, long-term effects and feedback loops must be accounted for to best capture the impact of alternative soil management practices on soil functions. The second future research item is the need to develop methods of synthesizing scientific evidence into support for farmers and other decision-makers regarding soil management.

**3. Sustainability Assessment of Soil Management, Analysis of Trade-Offs and Synergies**

Sustainable soil management implies not only the proper maintenance of soil quality, but also the need to comply with farm management constraints and a wider set of environmental and socioeconomic targets, as set out in the SDGs [2]. The assessment of soil management impacts on multiple targets, as well as trade-offs and synergies between them, provides an important evidence base for decision-making at the farming system and policy-making levels. Such an assessment must be forward-looking (*ex ante*) so that it can anticipate possible impacts of alternative management options before decisions are made [38]. Scenario techniques are often used to capture technological, economic, and climatic driving forces and future frame conditions in which the soil management options are embedded [39]. The assessment also needs to capture a wide range of environmental and socioeconomic impact categories to allow for an analysis of intended and unintended, short-term and long-term impacts. Impact categories cover relevant societal aspects to which soils contribute. These emerge from soil functions and include, for example, food production, biodiversity conservation, climate action through carbon sequestration and mitigation of greenhouse gas emissions, flood control, disease control, and human health [2]. This list is not conclusive and depends on the specific conditions in which an assessment is placed, its geographic setting and purpose. Stakeholders involved in the assessment process may have their say in selecting and weighing impact categories, such as what is recommended in the *Sustainability Assessment of Food and Agriculture* (SAFA) guidelines [40]. The key point of the assessment is to identify synergies and trade-offs between the different impact categories as they are affected by soil management options.

Regarding the conceptualization of impact categories, the concept of ecosystem services (ES) is a prominent and well-elaborated approach to assess the services provided by ecosystems in support of human well-being [41]. The ES concept captures a wide range of regulating, cultural, and supporting services and builds on established scientific ground. Although the linkage between soil functions and ES is still subject to scientific debate [4], the potential for linking natural processes in the soil to societal aspects of human well-being is not contested [42].

In this special issue, four papers assess the impacts of soil management practices on economic aspects, ecosystem services, and sustainable development (Table 2). Schwilch et al. [43] provide an important step toward implementation of the ES concept related to soil management. They developed a factsheet-based scoring procedure for soil-related ES and applied it to 26 soil management measures on field trials across Europe. While direct measurements could be utilized to determine short-term impacts, expert-based estimations were used for long-term assessments. The results of both long-term and short-term assessments were meant to be a basis for stakeholder-based valuation of soil management practices. With this tested procedure, the authors close an important knowledge gap associated with the practical implementation of ecosystem service assessment. Nuppenau [32] uses the ES approach to conceptualize the assessment of crop rotation impacts with a dynamic optimization model. Similar to Schwilch et al. [43], he emphasizes the long-term effects of soil conservation management practices, which are not captured by many state-of-the-art assessments and modeling approaches.

**Table 2.** Overview of contributed papers on sustainability assessment of soil management practices.

| Authors | Soil Management Type | Soil Management Topic | Region | Spatial Scale | Paper Type; Knowledge Base |
|---|---|---|---|---|---|
| Schwilch et al. [43] | Specific management practices | Impact of management on ecosystem services | Europe | Plot/wider area | Meta-analysis |
| Nuppenau [32] | Crop rotations | Economic optimization and ecosystem services | Germany | Farm | Modeling framework |
| Correia and Pestana [44] | Carob tree management | Cost-effectiveness | Portugal | Field/farm | Empirical |
| Quynh and Kazuto [45] | Nitrate fertilizers | Nitrate use efficiency | Vietnam | Field | Empirical |

While the ES concept is best placed for landscape-level assessments [46], farm-level assessments may bring into focus other impact categories, including economic measures such as cost–benefit ratios and risk attributes and measures of resource use efficiency. An example of farm-level assessment is provided by Correira and Pestana [44]. For a case study in Portugal, they assess the benefits and costs of planting carob trees as an alternative to high-intensity farming. In addition to exerting positive effects on ES through increased carbon sequestration in the soils, carob tree plantations can provide additional revenues for farmers and prove to be a measure of risk sharing under conditions of climate change. The latter two factors are particularly important for farm-level decision-making.

A third level of assessment is provided by Quynh and Kazuto [45]. The authors assess the impact of specific organic fertilizers on nutrient use efficiency and water quality. In this case, the production of organic fertilizers from the byproducts of coffee production is a good example of resource-efficient production, which is another paradigm of sustainable management [4]. Such a process proves, however, to have negative side effects on water quality because of the high leaching potential of the nitrogen compounds in the organic fertilizers. The conclusions are that such fertilizers from recycled materials need specific quality control mechanisms and cannot, per se, be said to be more sustainable compared to mineral fertilizers.

Sustainability assessment of soil management is a powerful tool to reveal linkages between soil functions and societal targets and values. At the same time, it provides a scientific evidence base for soil management at different levels of decision-making. In this regard, it serves as an important information base for the development of governance mechanisms that steer soil management in the direction of sustainable development. However, sustainability assessment of soil management is only an emerging scientific field. While promising methodological frameworks for its implementation exist [3,4,47], empirical implementation is still in its infancy. The papers of this special issue add to this emerging scientific field with important examples.

## 4. Governance for Sustainable Soil Management

Soil governance aims to regulate soil use and management in a way that meets societal targets and expectations. Soil governance structures include, for example, actors and decision-makers, property rights, formal and informal institutions, and regulations such as command-and-control or incentive-based policy instruments [24]. Although the sustainable use of soils, the prevention of soil degradation, and the maintenance of all soil functions are well-respected policy goals, their implementation remains flawed. Policy regulations are an outcome of comprehensive negotiation and deliberation in the policy formulation process, which ideally should imply impact assessments of policy options in order to deter unintended impacts. Sustainable soil governance requires a thorough understanding of the linkages between ecosystem services emerging from soil functions and impact assessments of soil management [4]. Furthermore, soil governance is affected by complex interrelations with other policy fields, such as the Common Agricultural Policy of the European Union (EU) or climate action and bioeconomy strategies. In addition, governance often takes place across several decision-making levels, from the farm level, over regional and national governance levels, to European and supranational scales, and incorporates manifold actors with different perceptions, values, and interests regarding soil management. These governance challenges are subject to comprehensive research, and the following contributions (Table 3) to this special issue help to close the knowledge gaps on sustainable soil governance.

**Table 3.** Overview of contributed papers on governance for sustainable soil management.

| Authors | Soil Management Type | Soil Management Topic | Region | Spatial Scale | Paper Type; Knowledge Base |
|---|---|---|---|---|---|
| Stankovics et al. [48] | Soil degradation, contamination, and sealing | Soil legislation and implementation standards | European Union/five Member States | Country | Empirical |
| Stubenrauch et al. [49] | Phosphorous fertilizers | Legislation of phosphorous fertilizers | Germany, Costa Rica, Nicaragua | Country | Empirical |
| Hansjürgens et al. [50] | General | Ethical considerations in soil legislation | Not specified | Not specified | Conceptual |
| Bartkowski et al. [42] | General | Definition of property rights | European Union and Germany | Country | Conceptual/empirical |
| Daedlow et al. [51] | General | Contracting of property rights | Germany | County/field | Conceptual/empirical |
| Bartkowski and Bartke [52] | General | Determinants of farmers' behavior | Europe | Farm | Review |

Two papers provide insights about emerging challenges in the formulation and implementation of soil regulations at the national and supranational levels that do not fully address the requirements of sustainable soil management. Stankovics et al. [48] investigate the obstacles, differences, and gaps in soil legislation and administration in five European countries (the United Kingdom, Germany, France, Austria, and The Netherlands) that could not agree on the proposal for a Soil Framework Directive in the EU in 2014. This lack of agreement ultimately resulted in the directive being refused. In these countries, issues of soil degradation and contaminated sites are generally well defined but are mostly embedded in environmental legislation, which makes soil issues a byproduct in environmental protection and results in a lack of reinforcement and liability. Due to divergent liability, levels of restriction, and some gaps in the content of soil protection, a harmonization of existing policies in EU member states toward a possible new Soil Framework Directive appears difficult.

Stubenrauch et al. [49] examine fertilizer legislation with regard to soil protection in Germany, Costa Rica, and Nicaragua and assess similarities and differences in the standardization and regulation of efficient fertilizer use in these countries. The authors found that in all three countries, the legislation does not comprehensively protect soils. In addition, control mechanisms of existing legislation are largely missing, and phenomena such as rebound and shifting effects of regulations and soil management are not addressed. Thus, from the authors' perspective, legislation in these countries does not fulfill its role as a driving force for sustainable soil management.

In their contribution on the ethical, legal, and economic considerations of soil protection, Hansjürgens et al. [50] focus on justifications for soil conservation legislation, with a particular emphasis on the creation–ethical arguments reinforced by Pope Francis in his encyclical *Laudato Si'* [53]. The authors show that the Pope's encyclical reveals a new relationship of the Catholic Church with nature (and soils). At the same time, such a relationship is reflected in legal prescriptions as provided by the German Constitutional Law and in economic arguments focusing on the definition of property rights regimes. These creation–ethical, legal, and economic considerations may serve as important reference points for soil conservation and sustainable soil management. They jointly emphasize that the long-term interests of the general public should be given priority over short-term private interests of farmers and landowners.

Two further papers address the issue of property rights and its linkage to soil characteristics and management. Bartkowski et al. [52] discuss how the concept of ecosystem services can be used to reassess the definition of current land property rights. The multifunctionality of soils implies that land property has special obligations regarding public welfare and suggests that current definitions of land property with a strong focus on private decision-making are imperfect from the perspective of the sustainable use of soils. The authors analyze two cases, the Common Agricultural Policy of the EU and German planning instruments, to demonstrate the inadequate consideration of soil multifunctionality in common private land property rights, which results in deficient internalization of externalities in agricultural markets. Policy instruments addressing such discrepancies could include, for example, taxation or incentives. The link between private property rights and soil quality is investigated by Daedlow et al. [51]. The authors contest theoretical assumptions about landowner and tenant relationships by studying empirical relations between soil quality, land rent prices, and land rent proportions at the county level in Germany. Given the manifold forms of ownership, the study challenges the general assumption that landowners take better care of their soils than tenants do. For example, it is shown that there is no direct correlation between rented arable land and low soil quality in Germany. The authors discuss the detected inconsistencies between theory and data that might emerge due to, for example, regulations of land markets, path dependencies in agricultural structures, and internalization of soil protection costs. The authors also stress the importance of examining the influence of the design of tenancy agreements with respect to soil conservation measures in future research.

Governance structures such as property rights are directly linked to farmers' decision-making about soil management. The importance of understanding this connection is shown by Bartkowski and Bartke [52], who review 78 European scientific studies about determinants of farmers' behavior and decision-making and link them to the assessment and development of soil governance instruments. Based on a conceptual framework, they investigate not only the social–institutional environment of farmers' decision-making, but also behavioral determinants, such as pro-environment attitudes, goodness of fit, and past experience. Research gaps in farmers' behavior include issues such as adoption of technologies, advisory services, bureaucratic load, risk aversion and social capital, social norms, and peer orientation. The authors stress the importance of a complex understanding of behavioral perspectives to improve the efficiency, effectiveness, and legitimacy of soil governance in general.

Despite an increasing number of studies published in recent years, soil governance research still needs to tackle many scientific gaps. For example, research about barriers and supporting factors that help to harmonize soil governance among the Member States of the EU and upscaling on the European level would help to establish efficient soil governance. Furthermore, the ecosystem services concept can be further applied to inform the design of soil management institutions, which would help to advance the understanding of the extent to which actual implementation of soil governance fails to address societal goals and cope with trade-offs. Likewise, living labs could be established where transdisciplinary research groups investigate to what extent impact assessments of soil management practices are considered in concrete policy formulation and implementation processes. Finally, studies identified the problem of unspecified soil policy instruments that often operate to a limited degree toward sustainability. Thus, soil governance research should address the development of tailor-made soil conservation instruments that specifically affect particular soil and land use types, as well as the design of corresponding soil property rights and land tenancy agreements.

## 5. Conclusions and Recommendations

Sustainable soil management of arable land means that biomass production for food, feed, and fiber can be integrated with soil functions to provide ecosystem services and contribute to sustainable development goals. Research can support sustainable soil management by providing an evidence base for the interrelationships between soil management practices and soil functions and between soil functions and sustainability targets. While there is agricultural management to produce biomass and maintain the economic basis of the farming enterprise, society and economy profit not only from agricultural goods, but also from other ecosystem services supported by soil functions. Nevertheless, trade-offs between provisioning services and habitat and between regulating and cultural services are evident. Such compromises stress the importance of developing new management approaches and assessing the impact of alternative management regimes on multiple outcomes in a comprehensive framework. To further this goal, close collaboration is needed between natural scientists trying to understand soil functions and social scientists and economists investigating how they can be transformed into services with social and economic value.

The contributions of this special issue provide examples of promising interdisciplinary research that places the use of soil within a wider societal context. These studies address challenges related to the management, assessment, and governance of soils. While each contribution emphasizes particular research questions, some common analytical challenges emerge. The first challenge is the understanding that one-size-fits-all management solutions do not exist. Rather, soil management must be adapted to site-specific geophysical and socioeconomic conditions. The second key challenge is the notion of time in the assessment and governance of soil management. Often, soil-improving management options turn out to be advantageous only after a long time period, while they are practically not suitable in the short term and without incorporating long-term effects. Efforts must be made to better understand such long-term management effects and to better address them in impact assessments. Furthermore, novel governance mechanisms are required that help farmers overcome short-term economic constraints and better gain the advantages derived from long-term soil quality. Such governance instruments can be justified, because sustainable soil management contributes to public goods in the long term, for which society should be ready to pay. This perspective leads to the third challenge, which is the interplay between private and public interests. While farmers have a private (business) interest to produce food, the other services provided by soil functions have the character of public goods. This private–public interrelationship is not yet well reflected in the property rights related to soils and must be better regulated by innovative governance mechanisms. With this special issue, an effort was made to shed light on the potential of an emerging interdisciplinary soil research community to advance the systemic understanding of sustainable soil management.

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# Institutional Economics of Agricultural Soil Ecosystem Services

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**Abstract:** Who owns the soils? What seems to be a straightforward legal issue actually opens up a debate about the ecosystem services that can be derived from soils and the distribution of benefits and responsibilities for sustaining functioning and healthy soils. In particular, agricultural land use may be constrained by a lack of properly defined property rights. Using the new institutional economics perspective, we show that multifunctionality of soils and an attribute-based property rights perspective substantiate the intuition that land property implies special obligations towards the common good. The concept of ecosystem services can illustrate the variety of beneficiaries of multifaceted soil ecosystem services. This allows identification of reasons for unsustainable soil management that result from imperfections in the definition of property rights. We suggest implications for improved governance of agricultural soils using two case studies in the EU context: the EU Common Agricultural Policy and the use of planning instruments to steer agricultural soil use in Germany. Thus, we contribute to achieving the societal goals of more sustainable land use by detecting causes of shortcomings in current land regulation and by suggesting governance approaches to support a more sustainable management of agricultural soils.

**Keywords:** ecosystem services; governance; institutions; land; property rights; soils; sustainability

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## 1. Introduction

Soil, or, more generally, the pedosphere, is an essential element of most ecosystems. Without it, terrestrial life is virtually impossible. Anthropogenic land use change has progressively challenged the availability of healthy soils that provide the ecosystem services necessary to sustain human life. Accordingly, recent research, policy documents, and initiatives have emphasised the importance of well-functioning soils: the International Year of Soils 2015, the EU Soil Thematic Strategy (STS), and the Global Soil Partnership (GSP) are just a few examples. At the same time, soil degradation remains a global challenge [1–3]; effective governance structures for sustainable soil management are lacking [4]; and in the EU, the plans to adopt a Soil Framework Directive have failed [5]. Soils are a highly heterogeneous, essentially nonrenewable resource. If they are lost (e.g., due to erosion processes), their regeneration takes decades to centuries—thus, from the perspective of most societal actors, their loss is irreversible.

Historically, land and soils have mostly been treated as private property [6]. Since private property is highly protected in modern democracies, this may constitute a challenge for sustainability—if soil management generates externalities, their internalisation implies that property rights must be infringed to some extent. This is true for both spatial and intertemporal externalities. However, the status of land and soils as private property need not imply that they actually are rightly considered so [6,7]. For instance, it may simply be the result of the (prohibitive) transaction costs that would arise under a more nuanced property rights allocation [8].

In recent years the concept of ecosystem services has gained increasing interest [9]. It has also been related to soils via definition of soil ecosystem services [10–12]. The idea behind this perspective is to point at the diverse ways through which soils contribute to human well-being and to highlight the necessity of soil protection. Furthermore, the ecosystem service perspective can help identify and distinguish stakeholders, beneficiaries, and providers in the context of soil management. The fact that soils provide bundles of ecosystem services is useful in order to connect these considerations with design options of governance and institutions that seek to define an adequate framework to properly regulate soils.

The aim of the present paper is to suggest an answer to the question "who owns soils?" in order to discuss what this means in terms of governance. We use an institutional economics perspective and show that soils are multifunctional, and as such require a nuanced analysis of property rights. Here, the concept of ecosystem services is helpful for illustrating different beneficiaries of soil functions, which are the precondition for the provision of soil ecosystem services. Specifically, we build upon the application of Lancaster's attribute-based consumer theory [13] in property rights economics to (i) identify reasons for unsustainable soil management that result from imperfections in the definition of property rights and (ii) derive implications for an improved governance of agricultural soils. Our overall perspective in this paper is derived from New Institutional Economics (NIE), where the definition of property rights regimes is taken as a starting point for developing institutional rules and governance structures for soil management. Recently, the interrelation of the environment and economic transactions has received attention in NIE [14,15]; we build upon these insights and apply them to soil ecosystem services.

First, however, we will discuss some definitional issues, reviewing and refining existing approaches that framed the contribution of soils to human well-being in terms of the ecosystem service concept (Section 2). In the next step, we then turn to property rights issues that arise when soils are viewed through the lens of ecosystem services (Section 3). In Section 4, we derive from this discussion implications for the sustainable governance of agricultural soils, using two case studies in the EU context: the EU Common Agricultural Policy and the use of planning instruments to steer agricultural soil use in Germany. Section 5 offers a brief conclusion.

The analysis developed in Sections 2 and 3 is fairly general and should be applicable to most political and cultural contexts. The case studies in Section 4 are context-specific, but their results should be informative also for most developed country contexts.

## 2. Soils and Ecosystem Services

The application of the ecosystem service concept to soils has gained some prominence in recent years [8–10,12,13,16]. As already mentioned in the introduction, the ecosystem service concept is helpful in analysing the societal relevance of soils because of its emphasis on multifunctionality [17]—soils are not just supporting one function like agricultural production, nor are they relevant only because of the huge biodiversity they contain. Rather, they provide and support a bundle of ecosystem services or (an older but related concept) soil functions that provide benefits for human well-being.

One difficulty pertaining to the relationship of soils and ecosystem services is that virtually all terrestrial ecosystem services depend on well-functioning soils. What, then, are soil ecosystem services? In their influential classification, Dominati et al. [11] propose a long list of "ecosystem services from soil natural capital", which range from spirituality and knowledge through flood mitigation and carbon storage to provision of food and fibre. This is a rather imprecise classification, as some ecosystem services mentioned are directly provided by soils (e.g., carbon storage, water filtration, or the archive function), while for others soil is a basis but the actual "ecosystem-service-providing units" (SPUs) [18] are arguably different. For instance, while soils are essential for agricultural production, it is the vegetation above or below the ground that should count as the SPU. Of course, it can be argued that some vegetation-provided ecosystem services are determined by soils to a relatively larger extent (e.g., food production) than others (e.g., microclimate regulation). Nonetheless, there is a difference between *soil-provided ecosystem services*, where soil clearly is the SPU, and *soil-related ecosystem services*, whose provision depends heavily on soil but where soil is not the (only or main) SPU (an apparently related distinction between soil-provided and land-provided ecosystem services was made—but not elaborated upon—by Schwilch et al. [12]). Soil-related ecosystem services are effectively those services that are dependent on *supporting services* [19] provided by soil. For instance, crop production is dependent on the soil-provided supporting service of soil fertility; soil fertility itself, however, cannot be consumed or appropriated in any direct way and is thus not a *final* soil-provided ecosystem service [20]. While we are fully aware that the distinction between soil-provided and soil-related ecosystem services is challenging in practice, this distinction might help to better understand the relationships between soils and ecosystem services. Furthermore, an additional complication enters if we include *soil functions* [21] in the discussion, as they are the prerequisites for both soil-provided and soil-related ecosystem services. In the following, we focus on soil ecosystem services, which we use as a generic term encompassing both soil-provided and soil-related ecosystem services, and refer to this distinction explicitly only when it is relevant. On the relationship between the concepts of soil ecosystem services and soil functions, see Baveye et al. [16], Dominati et al. [11], and Adhikari and Hartemink [10]. Soil management influences both types of soil ecosystem services via its influence on soil functions [22].

With respect to management and governance, a further specification of soils might be helpful. According to Dominati et al. [11], who analysed soils as stocks with a focus on their sustainable capacity, soils have different types of characteristics. Some of them can be influenced by human activities, while others cannot. For example, landscape slope, soil depth, cation exchange capacity, and clay types can hardly be influenced by humans and are thus "soil-inherent", while soluble phosphate, mineral nitrogen, organic matter content, and others are shaped by human management practices and are thus called "soil-manageable properties". In an ecosystem service management concept, while acknowledging the character of soil-inherent properties, it is the manageable properties that deserve specific attention, as they provide entry points for farmers, agronomists, land managers, and other stakeholders to influence soils and their qualities and, thus, the ecosystem services that flow from soils [11]. In a similar vein, Vogel et al. [21] argue to focus on "functional soil characteristics", which are a result of internal soil processes and interactions (physical, chemical, and biological characteristics of soils) in response to soil management at a timescale of days to months. Contrarily, "inherent soil properties" represent rather stable soil formation characteristics (e.g., mineral composition, texture, layering, depth) which cannot be affected by soil management at a timescale of less than decades. Neither are observable "soil state variables", which are changing in minutes due to external forces (e.g., water content, temperature, redox potential) and are relevant for management because of their high natural fluctuation.

Soils are complex systems; from the point of view of society, they are highly multifunctional, providing different types of ecosystem services. The use of multifunctional systems usually involves trade-offs [17]; not all soil ecosystem services can be had at once. Each management approach will enhance the provision of some ecosystem services and negatively influence the provision of others; for instance, ploughing a field contributes to food production, but it undermines other soil ecosystem services, such as carbon storage or microbial biodiversity. On the other hand, no-till management leads to other problems (especially in terms of pest control). We still do not understand these relationships properly in the context of soils [21]. Yet, as soils are highly heterogeneous, with their heterogeneity not being easily observable, these relationships can be expected to be highly context-specific; their assessment needs to be spatially and temporally explicit, also for the purposes of governance [23]. This biophysical complexity is further aggravated by economic and social factors, including property rights. To this issue we turn now.

## 3. Soil Ecosystem Services and Property Rights

The questions "who owns the soil?", "who is responsible to manage the soils?", and "is public regulation of soils justified—and to what extent?" are questions that can be answered by applying a property rights approach. In the most general sense, property rights define the rights of particular actors to undertake actions towards clearly specified objects: "[t]he allocation of scarce resources in a society is the assignment of rights to *uses* of resources" [24]. The assignment of property rights and their enforcement by the state are a response to scarcity [8]. Note that not all types of property rights are/have to be enforced by the state. Common-pool resources are usually managed by the communities that use them—though it has been observed that the *recognition* of a common property regime by the state is supportive of the regime's success and sustainability [25].

Given the increasing scarcity of soils [26,27], the definition of property rights for soils appears highly important. Relevant actions related to land and soils are [28,29]

- access, i.e., the physical interaction with land/soils;
- withdrawal, i.e., enjoyment of the "fruits" provided by land/soils;
- management, i.e., modifying and regulating land/soils and their properties;
- exclusion, i.e., preventing others from access, withdrawal, and/or management;
- alienation, i.e., transferring the land to another person or entity (by selling or giving away).

The rights to these actions can be in the possession of a single person or entity, but it is also quite common that different persons or entities possess different rights towards an object. For instance, while the tenant may temporarily possess the exclusive right to cultivate a piece of land (access, withdrawal, and probably also management and exclusion), the landlord retains the right to sell the property in question (alienation). Property rights can be possessed by individuals, groups, or larger entities like the state (private, common, and public property rights). Also, some objects or resources are open access—no specific property rights are defined for them, usually because it is physically or politically difficult to do [25], i.e., due to high transaction costs.

Usually, property rights are understood as linked to specific (scarce) goods or assets or, more generally, objects, including land and soil [7]. However, as shown by Lancaster [13], people do not consume or demand objects, but rather their characteristics or attributes. In this sense, goods or assets are primarily bundles of valuable attributes—and for each of these attributes, (different) property rights can apply [8]. This perspective necessitates deviations from the Schlager/Ostrom [28] classification of "permitted interactions" resulting from property rights (see list of property rights actions above), as their focus was on physical resources, not on their attributes. Particularly, access and alienation can only be sensibly applied to physical objects or resources, while withdrawal (at least in the broad sense of enjoying the fruits of something), management, and exclusion are applicable also to attributes—at least if they are private goods. For collective-good attributes (e.g., soil biodiversity), exclusion from withdrawal is per definition impossible or at least prohibitively expensive.

All these considerations are summarised in Figure 1 below: while only land (and, to some extent, soil) can be accessed and alienated, exclusion is possible only from the enjoyment of private-good attributes such as soil fertility (this is linked to physical exclusion from "entering" land); exclusion is not applicable to collective goods (public goods and commons) by definition. Both private-good and collective-good attributes (e.g., biodiversity) can be enjoyed (derived utility from) and managed. From the perspective of the attribute-based property rights theory, Coasean [30] conflicts over resources can be viewed as resulting from undefined or poorly defined property rights or relationships between property rights and different attributes of a resource (Ronald Coase was one of the founders of new institutional economics; he argued that resource-use conflicts can be resolved through negotiation between the involved actors with the goal of assigning property rights). This is especially due to the fact that when it comes to natural resources such as soils, management is usually linked to the legal property title to the object (e.g., a piece of land); thus, while it is conceivable to manage *for* specific attributes, in practice, management is usually focused on only some of them—those that are in the interest of the managing actor. Other actors may enjoy other attributes, but it is difficult for them to influence the management: "[w]hile land may be parcelled out, many processes or 'services' linked to it cannot be easily demarcated" [31] (p. 171).

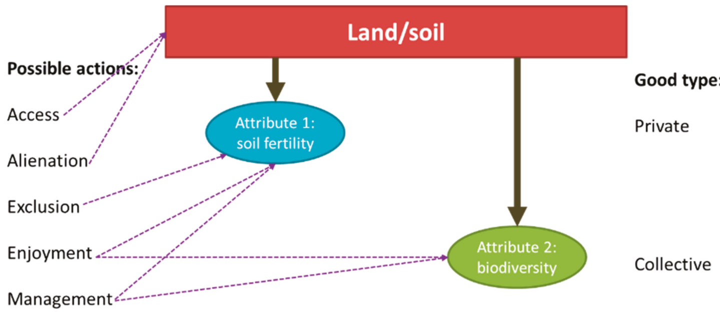


**Figure 1.** Conceptual framework of relationships between different types of attributes of land/soil and different actions that are influenced by property rights.

Furthermore, in this context the distinction of soil and real property for land is noteworthy [32]. Real property is a specific economic good that differs crucially from other economic goods. Physically speaking, real estate is a particular piece of land on the Earth's surface along with the things that are semipermanently attached to it, such as buildings, trees, and soil. In addition to the real estate itself, real property includes all the interests that are attached to the property, such as future use rights or tenancy rights. Real estate trade is strictly regulated all over the world. There is practically no other good whose property rights are so well defined and so strictly controlled, e.g., by zoning laws. On the other hand, at least for agricultural land, regulations are much less strict regarding other "transactions" [14], such as soil management. In Germany, for instance, there are no specific planning instruments for determining the use of agricultural land, while for nonagricultural land (e.g., urban areas), plans are quite specific and the regulator's discretionary power quite large [33] (see Section 4).

Even when considered as one resource or object, land (including soil as its main element) is special in terms of property rights [34]. As Bromley [6] argues in his historic essay, the perception of land has evolved from "general irrelevance" before the Neolithic Revolution, through "social ownership", "classical feudalism", and "centralized nation state", the latter generating (e.g., via enclosures) and protecting private property to land in a Lockean fashion (i.e., based on a contract theory between the state and private landowners), to today's growing recognition that land is, in a sense, public property and that private property rights to it imply social obligations. However, this is only limitedly reflected in the current property rights regime. In this sense, the abstract right to hold property should be distinguished from the reach of a specific property title, which cannot be viewed as absolute and inviolable [7]. In fact, the central German constitutional notion that private property implies social obligations (*Sozialpflichtigkeit des Eigentums*; Art. 14 Basic Law) is of particular relevance for land property. The Federal Constitutional Court on this [35]:

> Real estate is subject to special obligations with regard to its functional use in accordance with Article 14 (2) of the Basic Law. The inreproducibility of land prohibits its use completely being left to the free play of forces and the will of the individual [ . . . ]. The Constitution allows the legislature to promote the interests of the general public to a greater extent in matters of land management than in the case of other assets.

Multifunctionality of soils and the attribute-based perspective on property rights together help to substantiate this intuition.

At this point, the concept of ecosystem services can help in defining property rights. As was discussed above, soils are multifunctional complex systems—they contribute to the provision of multiple ecosystem services. As such, they cannot be sensibly viewed as one good implying one (type of) property right; rather, they are bundles of different properties/characteristics that generate different ecosystem services (attributes), implying different property rights and different potential property right holders. Thus, soil properties, soil functions, and the related ecosystem services determine the nature of *transactions* or activities related to their use and appropriation [14,15]; ideally, each of those should be considered separately.

This attribute-based perspective on property rights can help identify different property rights elements of soils. The above distinction in soil-provided ecosystem services and soil-related ecosystem services can help in defining different attributes of the good "soil". The focus on soil functions and soil ecosystem services can force decision-makers at various levels (agronomists, farmers, politicians who decide about land use, etc.) to explicitly take these attributes into account. This conceptual lens facilitates a focus going beyond selective soil functions and ecosystem services, instead focusing on the whole bundle of such services, including the often-neglected regulating and cultural services, but also the soil-manageable properties that influence their provision.

Of course, this is not always possible due to transaction costs—they are the main reason why only some soil ecosystem services are attributed legal property rights and, particularly, why these are usually reflected in property titles to land (or real estate, see above), which in the case of agricultural land do not distinguish between different attributes in the bundle. This property rights indeterminacy leads to land use conflicts and asymmetric focus in the management of soils on particular soil functions and ecosystem services, particularly biomass production. Most other ecosystem services related to soils exhibit public-good character and are thus underprovided under a private (Lockean) property rights regime. They can be considered externalities in need of internalisation.

In practical terms, the challenge is thus that usually property rights are defined with respect to land [6,7], which is actually a bundle of goods, the most important of which is soil—itself a bundle of properties, functions, and related ecosystem services. Furthermore, different ecosystem services and the different soil processes and components that are "responsible" for their provision are also different from a property rights perspective. Thus, of course, they are considered in different ways by the relevant actors. For instance, the "main" soil-related ecosystem service in agricultural landscapes—food—is obviously a private good. Soil biodiversity is on the other end of the spectrum, as it constitutes a public good with numerous positive externalities, such as gene pool or biodiversity's contribution to ecosystem functioning [36,37]. While it does provide benefits also to the property owner, e.g., as insurance [38] or a pool of options for future uses [36], its social value exceeds those benefits [39,40]. In between the two extremes there are numerous "grey cases" of soil ecosystem services that are only partly considered by those who manage soils directly (i.e., mostly farmers), at least partly constituting externalities. These externalities need not necessarily constitute public goods; in many cases, they can be private goods, but either the beneficiaries differ from those managing the soil (i.e., usually, the owners of land) or the (future) benefits are unknown or underappreciated by the beneficiaries–managers due to informational, cognitive, cultural, legal, economic, or other types of constraints [41].

This is additionally complicated by the fact that much agricultural land in developed countries is rented, so even the property rights to the whole bundle of attributes are not held by one person or entity, but are rather split among two or more persons and/or entities. However, they are split in a way that does not reflect the attribute-based nature of land- and soil-related property rights. It has been observed in both theoretical and empirical literature [42,43] that this creates disincentives to adopt a long-term perspective and to invest in those attributes that generate long-term *private* benefits. Therefore, even those ecosystem services that benefit soil managers—but do this only in the long term—are underinvested in and, thus, underprovided. The public benefits generated by these ecosystem services and others that are (approximately) pure public goods enter the calculus to an even lesser extent.

To sum up, we argue that the property rights for soils and their attributes (soil ecosystem services) are underdetermined due to (i) their being bundled together in bulk (private) property rights for land, and (ii) the public-good nature of many of them, which implies a lack of incentives for landholders to invest in them. The latter point is further aggravated by (iii) tenancy and the resulting disincentives for long-term investments even in private benefits. At the same time, discussions in the economic, political, and legal literature show that there are good reasons for the state to "infringe" private property rights in land to alleviate these problems [6,7,44]. In the following section, we derive from this implications for the governance of agricultural soils.

## 4. Governance Implications

Already some 20 years ago, the institutional economist Daniel Bromley argued that "[f]inally, we come to the contemporary setting in which property *rights* in land are giving way to the social *obligations* of property owners," which also implies the question as to "why those who own land should be granted special privileges as against those who hold other assets in their portfolio" [6] (p. 42). Today, in the face of an increasing severity of environmental crises, many of which can be linked to agriculture [45], societal demands for land management that is more oriented towards the common good (i.e., protecting biodiversity, securing ecosystem services) are increasing [46]. However, these interests and demands are currently not properly represented in the property rights regime in the context of agricultural land and soils. On the other hand, at least in the EU, where "agricultural exceptionalism" is still being practiced [47] and the state's influence on agriculture is large, there is (untapped) potential for improvement and alignment of agricultural practices with societal demands of sustainability.

In this broad context, a fully developed concept of soil ecosystem services could enlighten ways to identify societally important attributes of soils and the according definition of property rights. In what follows, we first discuss two general approaches to react to the imperfections of the current property rights regime. Second, we highlight the current deficits and suggest ways forward by using two case studies: (i) the EU's Common Agricultural Policy (CAP) and (ii) the differences between agricultural and nonagricultural areas in the German planning system. We chose these two case studies mainly based on our own expertise and because of the EU's pro-environmental rhetoric also in the agricultural policy context. In addition, Germany appears to be a particularly interesting case given the role of social obligations of land property as formulated in Article 14 of its Basic Law.

### *4.1. Two General Approaches for More Common-Good Oriented Soil Property Rights Allocation*

As discussed above, land can be conceived of as a "nested" bundle of attributes: on the first level, soil is the main attribute of land, along with other attributes like remoteness, land cover, local climate, infrastructure, etc.; on the second level, soil provides or contributes to the provision of a bundle of ecosystem services with different good characteristics (private vs. collective goods) and resulting different ideal-type property rights. Due to high transaction costs, the best solution of a clear disentanglement of the various property rights and their translation into legal property titles (implying a Coasean solution) is unavailable. There appear to be two generic second-best options to align agricultural management of soils with societal demands directed at the ecosystem services that are thus influenced: (i) the "Georgist" solution of implicit collective ownership of unproductive land expressed in land taxation to capture land rents (after Henry George; similar ideas have been voiced by the German *Freiwirtschaft* movement); (ii) an amendment of the current system with strong incentives regarding those attributes that would be assigned extra property rights in an (unattainable) best solution.

The "Georgist" approach is originally rather justice-oriented: it is based on the assumption that land is inherently a collective good, but that its private cultivation and management promises its efficient use. From this perspective, ownership of (a piece of) land is to a large extent the result of a set of random events in the past. At the same time, since land is absolutely scarce and of different quality (due to differences in the values of its attributes), its sole ownership generates rents, i.e., profits derived by landlords simply by virtue of the fact that they own land. Thus, Henry George famously called for taxation of land rents [48]. However, while it is interesting in its own respect, the consequences of such an approach for land and soil management are unclear; its basic tenet is that the owner of land retains the right to those fruits that she generates through its management. Consequences for the other fruits (attributes) that are affected by this management are uncertain and likely not captured by the land rent tax. As such, the Georgist approach may address a question of justice and the intuition also discussed by Bromley (see above) that land is inherently social property, but it will not solve the problem of soil-related externalities and the related property rights as a standalone. This leads us to a politically more promising and much-discussed option of incentive-based instruments that would target those soil ecosystem services (attributes of the resource soil/land) that are not taken into account by landlords and farmers because of their focus on private-good attributes—this option can be used both in the current system and in combination with a Georgist land reform. In the following we discuss two specific variants of this approach: agri-environmental measures within the EU's Common Agricultural Policy and agricultural land use planning in the German context.

### *4.2. Case 1: Soil Ecosystem Services and the CAP*

The Common Agricultural Policy of the EU in its historic and current form is largely incompatible with the notion of attribute-based property rights to multifunctional soils. Today, the largest share of CAP funds is distributed as area-based direct payments—i.e., indiscriminately on the basis of property rights to a piece of land. While reception of direct payments is linked to the fulfilment of some minimal ecological requirements (in the post-2013 CAP, cross-compliance and greening; in the current, 2018 reform proposal, conditionality and eco-schemes [49]), it has been shown that these requirements are largely toothless and do not have significant positive influence on the environment [50,51]. Direct payments are complemented by various instruments of the second pillar of the CAP, including agri-environmental and climate measures (AECM), but their overall environmental effects are limited [52]. With regard to soils specifically, the effects of European policies, including the CAP, have been found to be largely inconclusive [53]. Thus, currently, the large bulk of CAP payments benefits farmers and landlords [54], thus targeting only a small number of soil ecosystem services and ignoring the large part of the ecosystem service bundle that does not exhibit private-good characteristics.

To counter this and other environmental problems linked to agriculture, it has been proposed to replace direct payments by incentive-based payments for the provision of collective goods [55], i.e., those attributes of land/soil that are usually not taken into account by land managers (farmers, landlords). In a CAP system in which AECM (or similar instruments) would make up the large share of distributed funds, the legal property titles to land would remain unaffected; however, farmers receiving incentive-based payments would become *stewards* for the public, taking care of land/soil attributes that society at large demands but does not "own" because the best solution to the property rights problem is unattainable.

The attractiveness of incentive-based instruments in this context, particularly of result-oriented ones [56,57], lies in their flexibility: while it would be imaginable to steer land and soil management towards more sustainability and less negative environmental impacts by means of fostering, e.g., organic agriculture (the CAP already now includes payments specific to organic farming), this might lead to unnecessary and potentially problematic lock-ins and path dependencies [58]. Incentive-based instruments have the overall effect of strengthening the management for collective-good soil ecosystem services without generically forcing particular actions, which might actually be detrimental given the high heterogeneity of soils and also agriculture in general.

Another option that may complement centrally organised CAP payments of whatever kind may be in private contracts trying to establish implicit property rights (though not legal property titles) of the kind discussed above. In addition to the widely discussed payments for ecosystem services (PES) [59], which at least according to the original idea (but not necessarily in practice [31]) are based on contracts between private entities and would directly bring together beneficiaries of different soil ecosystem services, another option recently discussed in Germany is tenure contracts [60]. Here, landlords may be incentivised to include in land tenure contracts environmental management standards that the tenant is supposed to fulfil, over and above regulatory standards and voluntary instruments such as AECM. The downside of such a decentralised solution is, of course, high transaction costs. Thus, it can only complement a more coordinated AECM-like system, in which the state (or the EU) represents collective interests by means of incentive-based policy instruments.

While a political economy analysis is beyond the scope of our article, debates around the current plans to reform the CAP (post-2020) suggest that there is strong opposition against farther-reaching reform of the EU's agricultural policy. While there is strong evidence that the CAP does not deliver according to its goals [52], and the goals themselves are being questioned, a transformation towards a more explicitly public-good-oriented system does not seem probable in the short term. Nonetheless, a common-good-oriented agri-environmental policy would require a far-reaching reform of the CAP.

### *4.3. Case 2: Agricultural Land Use Planning*

The attribute-based property rights perspective on soils, together with the ecosystem service concept, indicate that there are reasons for societal restriction of property rights to agricultural land and soils, as the latter have attributes that are relevant primarily for the broader society. Since soil management affects them, there are reasons to incentivise farmers or even to restrict their option space so that their management activities reflect this complex property rights situation.

In this context, planning instruments are of high relevance due to the spatially explicit control options they provide. In Germany, there is a multilevel planning system which goes down to the communal level, where specific plans are defined. This follows the constitutional principle of communal self-government (*Selbstverwaltungsrecht*), as "The municipalities must be guaranteed the right to regulate all matters of the local community within the framework of the law on their own responsibility" (Art. 28(2) Basic Law). However, there is a surprising divergence in planning law between urban and agricultural land. Despite the already-mentioned constitutional "social obligation" of property (*Sozialpflichtigkeit des Eigentums*; Art. 14 Basic Law) that has historically been linked especially to land, the planning options for communes with respect to agricultural land are rather limited. In fact, while in urban planning, the local community (via communal administration) can determine by means of the development plan (*Bauleitplanung*, functional zoning), in a binding way, very specific restrictions of what may be built on the land, how much of its surface may be sealed, how high or large buildings may maximally be, etc., no such restrictions are present in planning for agricultural land use. In Germany, development plans and the more regional spatial plans mainly determine where and how nonagricultural activity (e.g., industry, housing, infrastructure, etc.) may take place, while agricultural land can only be designated as to be kept free from construction. No restrictions whatsoever are possible to steer agricultural activities in these plans. Currently, German law offers only the possibility to restrict agricultural land use in the case of a land consolidation procedure (*Flurbereinigung*) [44] and in areas designated as nature or water protection areas. However, this requires that these areas are particularly in need of protection. As a result, despite the constitutional principle of communal self-government, communes cannot control the type and extent of agricultural land use on their territory.

However, it is thinkable to use well-established instruments of urban planning and apply them also to agricultural areas by transforming and extending urban planning to comprehensive land use planning with external binding plans (*außenverbindliche Pläne*) for *all* land uses. This would allow the communes and their citizens to influence particularly beneficial use of land from a social point of view for all areas, without far-reaching legislative activities or the introduction of new planning instruments [33]. Different uses of agricultural land with restrictions to, say, monocultures or genetically engineered crops could be discussed like restrictions to height of buildings or industrial use in residential areas, or buffer strips to support biodiversity like minimum distance regulations or sealing maximums for light and noise protection of neighbours. This would not necessarily require detailed, comprehensive plans for the entire municipal area, but rather the designation of particular areas as requiring specific types of management (for a hypothetical example, see Figure 2). For instance, there could be restrictions along water bodies; in areas prone to soil-erosion, conservation agriculture or similar management approaches could be required; suitable areas could be reserved for grass- or woodlands, etc. Such adapted planning law would be much more in line with constitutional principles and would increase the level of participatory influence of citizens on the cultural landscapes in which they live [61]. It would also be very much in line with the argument developed in this paper, showing that legal property titles to land are not necessarily a perfect reflection of (idealised) property rights to the different attributes of land and soils. Planning could help to bring them closer to each other on a local level.


**Figure 2.** Actual (**left**) vs potential (**right**) reach of communal planning in Wiesenena, Germany; dashed lines: nonbinding plans, continuous lines: external binding plans, filled areas: hypothetical options [Map data: Google, DigitalGlobe].

Of course, opposition especially from farmers (and their associations), who would face additional restrictions on “their” land, can be expected to arise if the planning law would be transformed according to the suggestions formulated here. On the other hand, especially given Article 14 of the Basic Law, it is highly unclear “why those who own [agricultural] land should be granted special privileges as against those who hold other assets in their portfolio” [6] (p. 42). From a fairness point of view, there is a strong case in favour of adapting the planning law. A combination with the above-discussed incentive-based reform of the CAP would increase coherence of the agri-environmental policy mix and thus likely relieve some of the opposition.

## 5. Conclusions

Sustainable land management is challenged with inadequate consideration of the complexities and full spectrum of soil functions, which make up fertile, healthy, and well-functioning soils, and which are the basis for the many soil products demanded in modern (bio-)economies. This paper focused on the investigation of property rights related to soils, showing that common private soil ownership is likely accompanied with externalities which are not internalised in agricultural markets.

Applying New Institutional Economics and the ecosystem service concept to the analysis of soil property rights, we shed light onto a set of specific aspects. As an entirety, the individual parts are falling into place and illustrate how the ecosystem services approach can be applied to inform better soil governance that enables more efficient and sustainable agricultural land use decisions.

First, we have provided a characterisation of soils and ecosystems services. We pointed out the role of soil-provided versus soil-related services. Furthermore, we have emphasised the complexities, context-specificity, and heterogeneity of soils, which farmers can only partly influence by soil management and where trade-offs exist regarding the demands by different stakeholder groups. Soil ecosystem service assessment needs to be spatially and temporally explicit, also for the purposes of governance.

Second, in our reassessment of soil ecosystem services and property rights, we showed that multifunctionality of soils and the attribute-based perspective on property rights together help to substantiate the intuition expressed, e.g., by the German Federal Constitutional Court that land property is subject to special obligations towards public interests and the common good. The complex and nested setting of soil characteristics explains conflicts regarding the sustainable use of soils as resulting from imperfectly defined property rights or relationships between property rights and the different attributes of soil as a resource. Despite today's growing recognition that private property rights for land ownership imply social obligations, we find this only limitedly reflected in the current property rights regime. We have shown that the concept of ecosystem services is promising to support the identification of property rights that link more specifically to the bundles of distinct characteristics of soils that generate the different ecosystem services (attributes), implying different potential beneficiaries and (ideal-type) property right holders. The potential and limitations of the ecosystem service perspective to identify and distinguish stakeholders, beneficiaries, and providers in the context of soil management could be indicated. We have emphasised that the fact that soils provide bundles of ecosystem services is useful in order to connect these considerations with design options of governance and institutions that seek to define an adequate framework to properly regulate soils.

Third, potential governance implications have been outlined. As a first step, we discussed two general approaches in the form of either a "Georgist" solution of explicit collective ownership expressed in taxation of land rents, or an amendment of the current system with implicit assignment of additional property rights by means of incentive provision for farmers as *stewards*. Second, we focused on the latter approach, which we found complementary with the former, and discussed its implications using two case studies. For CAP, we have found implementation of the second approach in the form of more incentive-based payments for collective good provision as reflecting well the attribute-based property rights perspective adopted here. It implies motivating farmers to become stewards for the public and future generations, taking care of sustainable provision of the multitude of soil ecosystem services. Also, reform of tenure regimes is briefly discussed, pointing also to the challenges of lock-in effects and path dependencies as big hurdles. Agricultural land use planning approaches demonstrate that certain property rights can be kept with the state, e.g., in the form of land use restrictions in order to prevent unsustainable uses or foster sustainable ones. We show that in the German case, this would only imply applying the same standards to urban and agricultural planning. Both case studies demonstrate the applicability of the conceptual ideas developed in Section 3 to inform the assessment and evaluation of policy instruments.

Several questions arise from our analysis that require further investigation. These range from more theoretical to applied issues. On the one end, further discussion is needed to better understand how institutions involved at the intersection of the environment and economic transactions in the soil context are developing over time and how the ecosystem service concept can be applied to inform the transactions-linked emergence of nature-linked institutions. On the other end, the question is how to facilitate in practical conditions a shift of property rights regimes to ensure a better reflection of actual ecosystem service stakeholders from current and future generations—be it through instruments of planning, amended CAP, or other measures. Particularly, analyses from a political economy perspective and in transdisciplinary real labs would help uncover relevant transaction costs, interests, and interest conflicts as well as the trade-offs inherent to social–ecological systems that counteract the implementation of a more sustainable property rights regime for agricultural land and soils.

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# Identifying Gaps between the Legislative Tools of Soil Protection in the EU Member States for a Common European Soil Protection Legislation

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**Abstract:** To ensure an adequate level of protection in the European Union (EU), the European Commission (EC) adopted the Soil Thematic Strategy in 2006, including a proposal for a Soil Framework Directive (the Directive). However, a minority of Member States (United Kingdom, Germany, France, Austria, and The Netherlands) could not agree on the text of the proposed Directive. Consequently, the EC decided to withdraw the proposal in 2014. In the more than 10 years that have passed since the initial proposal, a great number of new evidences on soil degradation and its negative consequences, have proved the necessity of a common European soil protection Directive. This study is aimed at specifying the possible obstacles, differences, and gaps in legislature and administration in the countries that formed the blocking minority, which resulted in the refusal of the Directive. The individual legislations of the opposing countries on the matter, were summarized and compared with the goals set by the Directive, in three highlighted aspects: (1) soil-dependent threats, (2) contamination, and (3) sealing. We designed a simple schematic evaluation system to show the basic levels of differences and similarities. We found that the legislative regulations concerning soil-dependent degradation and contamination issues in the above countries were generally well defined, complementary, and thorough. A common European legislation can be based on harmonised approaches between them, focusing on technical implementations. In the aspect of sealing we found recommendations, principles, and good practices rather than binding regulations in the scrutinised countries. Soil sealing is an issue where the proposed Directive's measures, could have exceeded those of the Member States.

**Keywords:** soil degradation; soil functions; soil framework directive; soil policy; soil threats; contamination; sealing

## 1. Introduction

Soils are under ever-increasing pressure, since global population growth brings an increasing demand for food [1]. Although soils are one of the most important natural resources on the planet, their ecological importance is often greatly underestimated. On account of urbanisation, road construction, and pollution, three square kilometres of soil are destroyed every day in the European Union (EU) [2]. If nothing is done to stop soil erosion, by the year 2050 the world will lose fertile soil covering 1.5 million square kilometres, which is the land area of Germany, France, and Spain combined [3]. The 7th Environment Action Programme (EAP), which is guiding European environmental policy until

2020, recognizes that soil protection is a serious challenge. The EAP wants the EU to be a place where natural resources are managed sustainably, and biodiversity is protected and valued [4]. It requires the EU and its Member States to increase efforts to reduce soil threats and to remediate contaminated sites. The EAP, prescribes the integration of land use aspects into coordinated decision-making, involving all relevant levels of government. It also states that soil quality issues could be addressed using a targeted and proportionate risk-based approach, within a binding legal framework [5].

Despite the instructions of the EAP, the regulations on soils are not sufficient in all cases to ensure an adequate level of protection in the EU. Though protection provisions indirectly contribute to the protection of soils in the Community acquis in areas such as agriculture, water, and environment, there is no specific EU legislation on soil protection [6], and only a few Member States have specific legislation on it [7]. To better understand the situation, The Environmental Assessment of Soil for monitoring (ENVASSO) Project was launched [8] and the EC adopted the Soil Thematic Strategy in 2006 including a proposal for a Soil Framework Directive (the Directive), with the objective to protect soils across the EU. The EC had proposed the Directive with the objective of establishing a common strategy, for the protection and sustainable use of soil. This was based on the principles of integration of soil concerns into other policies, preservation of soil functions within the context of sustainable use, and prevention of threats to soil and mitigation of their effects; together with the restoration of degraded soils, to a level of functionality consistent with the current and approved future use. It included a requirement for Member States to identify soil protection priority areas within five years after the enforcement of the Directive, and take appropriate measures to protect against erosion, biodiversity loss, and other threats [9]. Member States would have been required to take specific measures to address soil threats, but the Directive left ample freedom on how to implement the legislation concerning these requirements.

However, a minority of Member States (The United Kingdom, Germany, France, Austria, and The Netherlands) could not accept the text of the proposed Directive. Subsidiarity considerations, excessive cost, and administrative burden [10] were among the reasons of refusal to accept the European law on soil protection. Consequently, the EC decided to withdraw the proposal in 2014. Thus, an opportunity was missed for the protection of soil based on a common legislative document within the EU, the targets of which are still vitally required.

In the more than ten years that have passed, since the initial proposal of a common European Soil Protection Directive, a great number of new evidences on soil degradation and its negative consequences have proved its necessity [11,12]. The areas of subsidiarity and administration have manifold legal implications. This study aims at specifying the possible obstacles, differences, and gaps between the goals set by the Directive and the legislature and administration in the countries that formed the blocking minority, resulting in the refusal of the Directive. The current study focuses on the legislative and administrative aspects present in the five countries and does not aim to make a comprehensive assessment for all EU Member States, nor an assessment of any political or economic motivation that may be present when regulating the protection of soil resources.

## 2. Materials and Methods

The materials used in the research part of the study include the Directive, and English citations of legal documents of the blocking five Member States at national, regional and local levels. The sources were the official governmental websites, the official website containing EU laws (EUR-Lex), online international law information services (e.g., Wolters Kluwer), and national legal experts' contributions (e.g., websites, articles, comments). The different types of legal acts (see also at Vrebos et al. [13]), such as: *Regulations*—binding legislative acts, which must be applied; *directives*—legislative acts that sets out goals; *decisions*—binding on those to whom they are addressed and are directly applicable; *recommendations; communications;* and *opinions* were assessed according to the level of legal obligation they represent.

The assessment is based on the categories of the Directive. We condensed the soil protection objectives of the Directive into three coherent groups: (1) *soil-dependent threats*—embracing erosion, organic matter decline, salinization, compaction, and landslides; (2) *contamination*; and (3) *sealing*. Grouping was based on the role of inherent soil properties in the degradation process. The threats classified in the first group were those where soil characteristics are important factors in the degradation process. Contamination (2) and sealing (3), typically do not depend on the properties of the affected soil and differ in their characteristics (i.e., driver, impact, etc.) among themselves too, therefore are considered separately. The study aimed at giving a clear view of these three aspects, within each examined country.

Regarding the national policies of the blocking five countries, the following: (i) responsible legislative and administrative bodies and (ii) legislative and administrative tools in effect, were assessed. Legislative bodies are those creating regulations and administrative bodies are responsible for the observation and implementation of these regulations. The different levels of implementation (national, regional, local) are clarified in the respective sections.

In the compilation and grouping of the researched material, we found that we can assess four categories concerning the gaps (i.e., differences and levels of similarity) existing between law making and practices of the blocking countries, and the proposals of the Directive. The four categories we determined were: (−−) no legislation available; (−) legislation exists, but with different conceptual approach and different implementation; (+) legislation exists with a similar conceptual approach but different implementation; and (++) legislation exists with a similar conceptual approach and similar implementation. It was also important for us to show the differences and similarities within the blocking five Member States (this is why we compared them in one table), to get a clear overview of the gaps this paper was aimed at identifying.

To place our research findings in the context of the current scientific discussion involving the necessity of common EU soil protection regulation, we briefly reviewed the main focuses of the ongoing dispute in the Discussion section. The research strategy for this assessment comprised of searches on legal, political, economic, and societal considerations of soil protection in the EU.

## 3. Results

### *3.1. Provisions of the Proposed European Soil Framework Directive*

#### 3.1.1. Provisions for Soil-Dependent Threats

Erosion, organic matter decline, salinization, compaction, and landslides were addressed within the legal framework. Within five years from transposition date, Member States should have identified the risk areas in their national territory, where there was evidence or suspicion that one or more soil degradation processes had occurred or would have been likely to do so in the near future. Member States may have based the identification of risk areas on empirical evidence or on modelling. The risk areas were to have been reviewed every ten years [14]. Under each risk area, Member States were to draw up a programme of measures including risk reduction targets, the appropriate measures for reaching those targets, a timetable for implementation, and an estimate of the funding allocation. Member States were encouraged to use their own existing monitoring schemes and improve them if necessary. Programmes could have built on measures already implemented at national and EU level, such as cross-compliance and rural development under the Common Agricultural Policy (CAP), codes of good agricultural practice and action programmes under the Nitrates Directive, future measures under the river basin management plans of the Water Framework Directive, national forest programmes and sustainable forestry practices, and forest fire prevention activities. These approaches to combat threats to soil could have been combined as well, benefiting in particular those Member States which had already been addressing soil loss [15].

#### 3.1.2. Provisions for Contamination

Local contamination would have been tackled at the regional or national level [16]. According to the Directive, Member States would have been required to identify contaminated sites in their national territory and establish a National Remediation Strategy, on the basis of a common definition and a common list of potentially polluting activities [17]. Each Member State was asked to designate a competent authority responsible for the identification of contaminated sites, and their status was planned to have been reviewed every five years [18]. Where containment or natural recovery were applied, the evolution of the risk to human health or the environment should have been monitored.

In the Directive, it became a state priority to create a sound and transparent system to ensure that contaminated sites would be remediated, and all entailed risks be reduced. Member States were also required to set up appropriate mechanisms to fund the remediation of the contaminated sites. To exercise control through terms of sale, it initiated the obligation for a seller or a prospective buyer to provide to the administration and to the other party in the transaction, a soil status report for sites where a potentially contaminating activity had taken place [19]. In cases when, the polluter pays principle cannot be exercised, namely the person responsible for the pollution cannot be identified or cannot be held liable under Community or national legislation or may not be made to bear the costs of remediation, the Member States have to refer to their own appropriate mechanisms for the funding of the remediation.

#### 3.1.3. Provisions for Sealing

In connection with sealing the Directive, it was clarified that Member States should take appropriate measures to limit it where it is carried out for the purposes of preserving the soil functions [20]. To achieve a more rational use of soil, Member States would have been required to rehabilitate brownfield sites, and to mitigate the effects of sealing using construction techniques and products that preserve as many soil functions as possible.

### *3.2. Soil Policies in the Blocking five Member States*

#### 3.2.1. United Kingdom

Soil protection administration has a complex structure in the UK and several pieces of legislation include provisions for soil protection, however, no single soil protection act exists. DEFRA (the Department for Environment, Food and Rural Affairs) has responsibility for overall soil policy in England, and it funds a wide range of research in partnership with other organisations. For example, the Environment Agency (EA) for environmental protection in England and Wales, and the new Department for Communities and Local Government (DCLG) for planning policy. Scotland, Wales, and Northern Ireland have separate, devolved bodies that deal with soil [21]. In Scotland, the Scottish Soil Framework [22] has been in effect since 2009, in Wales, the Environment Strategy for Wales [23] has covered the issue since 2006. England has existing programmes, such as CAP cross compliance, Environmental Stewardship, the England Catchment Sensitive Farming Delivery Initiative, and the new Code of Good Agricultural Practice. In accordance with current legislation, farmers need to comply with the cross-compliance soil management standards. These requirements are: Good Agricultural and Environmental Conditions (GAECs) and Scheduled Monuments Statutory Management Requirements (SMRs) [24]. These standards require landowners to identify and record any existing and potential problems with their soil and assess their risks of degradation, based on soil type, landform, rainfall, and present land use information. Furthermore, they need to carry out measures to prevent or reduce the problems and risks they have identified [25]. In the matter of legal penalties, landowners may have their scheme payment(s) reduced if they don't meet all the GAEC and SMR cross compliance rules, which apply to their holding.

Concerning the rehabilitation of contaminated land, there are two main statutes, the Environmental Protection Act 1990 (EPA) and the Environmental Damage Regulations 2015 (EDR). The EPA aims to ensure that contaminated land is identified and remediated, where it poses unacceptable risk levels.

The EDR relates to the prevention and remediation of environmental damage in the most serious cases. In 2012, DEFRA published a Statutory Guidance for England on dealing with contaminated land and radioactive contaminated land. In case of contamination, the principal enforcement authority is the relevant local authority. They must inspect their risk areas to identify any contaminated land and record them in public registers. Under the EDR, operators—land users—must take all practicable steps to prevent environmental damage if there is an imminent threat of damage. If environmental damage has already occurred, it is the operator's responsibility to prevent further damage. If the regulator considers that environmental damage has occurred, it can serve a remediation notice on the responsible operator setting out measures that must be taken. In cases of new developments on a site with contaminated land, planning authorities can impose conditions in the planning permission requiring remediation to be carried out before the development starts. Failure to comply with a remediation notice, without a reasonable excuse, is a criminal offence punishable by a fine. The regulator can carry out the remediation itself and recover the costs from the relevant parties. The liability for the remediation of contaminated land rests, initially, with those who caused or knowingly permitted the contamination. If neither of the above can be found, liability passes to the owners of the land, regardless of whether they were responsible for the contamination or were aware of its existence. Liability does not change when land is transferred. Unless one of the various exclusions applies [26], previous owners or occupiers who caused contamination, remain liable after the sale of the land. However, an owner who is not a polluter will no longer be liable when they cease ownership or occupation of the site [27].

According to the governmental soil strategy, since some degree of soil sealing is an unavoidable consequence of development, the environmental, economic, and social costs and benefits of the development and use of land should be balanced and the negative impacts of soil sealing mitigated, particularly in relation to urban drainage and maintaining green infrastructure [28]. Monitoring of soil sealing is consistent, even afforded by using airborne imagery [29].

3.2.2. Germany

Soil protection is carried out at the federal and local levels in Germany. The UBA (Umweltbundesamt) as Germany's main environmental protection agency and the Federal Ministry of Environment, are the main legal authorities which compile, assess, and provide information on soil status, soil conservation, and optimization of measures. The federal government lays down the legal frameworks, which are implemented by the regional states. One of the main regulations is the Federal Soil Protection Act (BBodSchG, 1998). It aims at sustainability by securing or restoring soil functions by administering safety measures and provisions against harmful effects on soils, with a focus on the rehabilitation of contaminated sites [30]. Farmers are required to comply with specified standards, called good agricultural practices [31]. These are based on the stipulation that any deleterious impact on natural soil functions is to be avoided insofar as possible [32]. The other leading code of practice is the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV, 1999). It lays down precautionary soil values for particularly important contaminants, contains hazard prevention and measurement values, together with soil investigation and assessment procedures [33]. The Federal Nature Conservation Act (BNatSchG) states that interventions in nature and landscape are to be avoided or offset. Article 15 (7) BNatSchG states that a statutory ordinance can regulate the details of offsetting interventions. In effect, this could introduce standards relating to interventions with soil and corresponding offsetting measures.

In Germany, contaminated-site remediation is based on a graduated concept. Suspected site contamination is verified by the existence and concentration of hazardous substances, and their impact on receptors and other natural resources. Official identification of site contamination, normally results from a definitive hazard assessment and forms the basis for protective and remediation measures [34]. If investigation or remediation actions on a site are required, liability is not limited to the person (or company) who caused the contamination. Those who own or possess the site or have owned it in the past, can be held liable by the authorities as well, even if the polluter is still present and solvent [35].

There is no regulation like a liability relief for small businesses or even private persons. There is no funding of clean-up or investigation, except for public authorities [36].

There are a number of laws that serve to reduce the extent of soil sealing (Federal Building Code §1a, Federal Spatial Planning Act §2 or Federal Soil Protection Act §1, §5, and the Federal Nature Conservation Act §1) [37]. At the regional level, building law and regional planning law also contain provisions relevant to soil. The Federal Building Code, states that land shall be used sparingly and with due consideration. This principle must be considered in urban planning in particular. Regional planning law contains regulations regarding overall area planning, and thus the use of land and soil. The relevant provisions at federal level are contained in the Federal Regional Planning Act (Raumordnungsgesetz). The Länder have corresponding Land legislation [38]. The Federal Government in 2017, adopted a Sustainable Development Strategy to clarify how Germany can achieve "land degradation neutrality" domestically [39]. In it, representatives of research, policy, and civil society agreed that soil sealing and land take need close monitoring, which relates to an existing policy goal (the "30-ha goal") [40] and could be extended towards other targets and indicators [41].

#### 3.2.3. France

In France, the national information system on soils falls under the leadership of "GIS Sol". The Members of the Organisation are the Ministry of Agriculture and of Environment, the Environment and Energy Agency (ADEME), the National Institute for Agricultural Research (INRA), and the Research Institute for Development (IRD). The objective of the GIS Sol is to answer the needs of soil information at regional and national levels, to public authorities and society through the coordination and realization of soil survey and soil monitoring in France, to manage an information system on the spatial pattern, properties, and quality evolution of the French soils [42]. At a local level, the local governments and Regional Directorates of Environment, Planning and Housing have general administrative enforcement powers, as well as derogatory emergency police powers in case of serious risks, including pollution like soil contamination from a factory [43]. In every one of the 101 directorates, a prefect representing the state is responsible for granting environmental permits and controlling compliance with regulations. French courts also play a critical role in soil protection. Administrative courts have jurisdiction over state and public authorities' decisions regarding soil protection. Civil courts hear civil liability cases, and criminal courts have the power to try and prosecute environmental criminal offences. The regulation of soil protection is substantially influenced by EU Law, the main statutes are the Environmental Charter of 2005, of constitutional rank; and the Environment Code, in which most of the relevant laws and decrees have been codified [44,45].

Regarding land contamination, environmental protection and waste regulations (ICPE [46] and Articles L. 541-1 of the Environment Code, and since 2014, the Chapter "Contaminated sites and land" of the Environment Code [47]) are in effect. ICPE regulation involves a proactive regulatory watch on soil problems, and there are also administrative and criminal sanctions provided by ICPE. Waste regulations can apply to non-compliance with clean-up provisions. Where known soil contamination justifies investigation and contamination management measures, in particular when the use of the land changes, the state classifies the land within a "land information sector" and publishes relevant information about the land [48]. In the event of soil contamination, the enforcing authority can perform of its own accord the necessary works, at the expense of the responsible party. If the site cannot be remediated because the responsible party disappeared or is insolvent, the state can entrust the ADEME with the remediation [49]. As far as liability goes, parties for the clean-up of contaminated land are, by order of priority, the last operator of the facility causing the contamination and secondarily, if no party is primarily responsible, the owner of the contaminated land can be held liable for negligence or contribution to the contamination [50]. An ICPE operator's liability is limited by the causal link between the permitted activities and the pollution. Concerning site remediation, barring migrating pollution, liability is limited by the future use of the site [51].

The National Strategy for Sustainable Development includes a new sustainability objective that defines the aim of land take reduction. The strategy for sustainable development puts emphasis on the reduction of sealing. Since 2010, the law Grenelle Environment has been enforced. Its most relevant action line for the reduction of land take and soil sealing, is the improvement of energy standards of buildings and harmonization of spatial planning, which stipulates energy efficient urban structures by supporting inner urban development and avoiding further soil consumption, mainly by brownfield redevelopment and urban renewal. France disposes of a network of more than 20 public land development agencies (EPF), who operate at the regional, but also at the local level to develop land for social housing [52].

#### 3.2.4. Austria

Soil Protection has been declared a national target with the Federal Constitutional Law on Comprehensive Environmental Protection, but there is no comprehensive federal law on soil protection in Austria [53]. According to the Constitution, governmental responsibilities for environmental issues are allocated to the federal state, the nine provinces, and the local authorities. The Ministry for Agriculture, Forestry, Environment and Water Management is the competent environmental authority. At the provincial level, the governments of the provinces and the district authorities are responsible for administering environmental law. The Federal Environment Agency deals with monitoring and documenting the Austrian environmental situation, and the regions are fully responsible for the central instruments of land management as spatial management laws, nature conservation laws, and laws concerning housing development aid. There is also a third, local, municipal level present in Austria. Land planning and development of land resources, and land-management by surface-dedication and development, lies in the hands of the more than 2000 municipalities. Specifically, soil protection lies in a mosaic of regulations. There are three principal systems of soil survey in Austria: On forested land the Forest Soil Survey, on agricultural land the Soil Taxation Survey, and the Soil Management Survey. In addition, there is an Environmental Soil Survey, a Soil Monitoring System, and a Soil Information System (BORIS) [54]. The assessment of soil quality is based on provincial soil protection regulations. Soil Protection Acts have been enacted in 5 provinces (Burgenland, Lower Austria, Upper Austria, Styria, and Salzburg), but with differing measurements of soil qualities and soil sensitivity classes [55]. Soil protection on both the federal and local level, is aided by the traditional cadastre updated into a modern monitoring system by GIS. Today, legal security of tenure and land-ownership is given by the system of the land register, covering the whole territory and involving the development and use of land-use indicators and related monitoring systems. Detailed land use descriptions are partially included in the cadastre, and in GIS applications. GIS is used for integrated planning and management of land resources. It integrates the spatially referenced information of land use and soil, and systematically captures, stores, and manages data. GIS is used both by federal and Laender authorities to support planning and policy implementation [56].

Concerning soil contamination there is no integrated regulatory regime, but applicable provisions are spread over a considerable number of laws and regulations (for example, the Trade Act, the Federal Waste Management Act, the Federal Environmental Liability Act, the Forest Act, and the Water Act). The Clean-up of Contaminated Sites Act and the Directive on Funding Clean-Up of Contaminated Sites 2008, stipulate provisions for the remediation of contaminated sites. The latter also sets out rules with regards to the public funding of remediation measures [57]. The main principle regarding the liability for contaminated land is the "polluter pays" principle. Under certain conditions, the property owner may also be held liable for soil contamination. If a site is identified as contaminated, the regulatory authority must first try to trace the polluter. Either the 'polluter or, if not traceable, the property owner may be held secondarily liable to take proper preventive or remediation measures or to bear the costs, or both. The same applies to the legal successor of the property owner, provided that the successor knew or should have known of the endangering activity. In terms of damage affecting the land, the Federal Environmental Liability Act requires that the land concerned, be decontaminated until there is no longer any serious risk of negative impact on human health. The costs must be met by the operator (the potential polluter). In case the operator is incapable, the competent authority will take preventive or restorative measures itself, and recover the costs incurred later. Where several instances of environmental damage have occurred, the competent authority may determine the order of priority according to which they must be remedied. Polluter liability is a strict liability. However, the blameworthiness of environmentally damaging conduct is decisive as to the eligibility for funding of remediation and safeguard measurements. Financial assistance may be available for remediation and safeguard measures, under the Directive on Funding Clean-Up of Contaminated Sites 2008. No financial assistance of clean-up measures is granted if the applicant caused the contamination in a premeditated or grossly negligent manner [58].

In 2002, the annual rate for soil sealing amounted to 9 hectares per day. The Austrian Strategy for Sustainable Development declared the target of a sealing rate below 1 hectare per day. The overall objective of this policy target was to stop the increasing fragmentation of landscapes, and to conserve soil functions as far as possible. Since then soil sealing is being monitored and published every two years in the Report on Monitoring Sustainable Development. The Strategy recommends enhancing inner urban development, to increase the efficiency of land use and the quality of living in small cities; to allow new land developments only along top public transport lines; and to re-develop brownfield sites and protect landscapes and recreational areas. All Austrian provinces have recently adopted their spatial planning regulations, efficient land use is a priority and new instruments are available to allow reduction of land take. Spatial planning follows a strong federal structure. At the national level, Concepts for Spatial Development (ÖROK) are published on a regular ten-year basis. The nine Austrian provinces dispose of their own spatial planning laws, which are regularly adopted and reflect the recommendations of the actual ÖROK document. Final planning decisions are made at the municipality level, under the supervision of the provincial governments [59].

#### 3.2.5. Netherlands

The Netherlands are divided into 12 provinces. The provinces form an administrative layer between the central government and the municipalities. In close cooperation with the central government, the municipalities, and the district water boards, the provinces usually perform duties in soil protection. Recently, the central government has transferred an increasing number of duties to the municipalities. Based on the Soil Protection Act (Wbb) and the Environmental Protection Act (Wm) some municipalities have more duties and powers than other municipalities with regard to soil policy and management. In general, these 'competent authority' municipalities are the large municipalities, such as Amsterdam, Rotterdam, and Utrecht. This means, for example, that duties normally performed by a province are instead implemented by the competent authority municipality [60]. The Ministry of Housing, Spatial Planning and Environment oversees making and enforcing soil protection policy and bears responsibility for the sustainable use of the soil. The Netherlands Soil Protection Guideline (NRB) for Industrial Activities (which has been confirmed at administrative level by the Ministry of Housing, Spatial Planning and the Environment; the Directorate General for the Environment (VROM/DGM); the Union of Water Boards; the Association of Provinces; and the Association of Netherlands Municipalities within the Soil Steering Party (Stubo)) has a powerful steering function, as it has the status of a harmonising tool, for assessing the need and reasonableness of soil protection measures and facilities. However, the NRB is not legally binding because it has no formal legal status. The NRB only becomes legally binding once it has been converted into conditions, in permits or general administrative orders [61]. An important body in soil protection is SenterNovem/Soil+. It is a task group in the SenterNovem agency, an agency of the Ministry of Economic Affairs. It pursues government policy in various policy areas, such as innovation, the environment, and sustainability. However, it is an assignment of the Ministry of VROM and acts as a link between policy formation by the central government, and the actual implementation of these policies by the provinces, municipalities (competent authorities), and district water boards [62].

Two of the most important laws that serve as the foundation for Dutch soil policy, are the Soil Protection Act and the Environmental Protection Act [63]. The Soil Protection Act contains general rules to prevent soil contamination. The Environmental Protection Act (Wm) is the most important environmental law, which establishes that permits must be obtained before certain activities may be performed. Under soil policy, this law means that permits must state the extent to which companies must make provisions to protect the environment and the land. A responsibility to return the soil to its original state may also be in force. In most cases, the permits are issued by the municipalities or the provinces. Important legislation in the current soil policy, for dealing with soil pollution and guaranteeing conscious and sustainable soil management includes the Soil Quality Decree [64]. The Soil Remediation Circular 2013, serves as a supplement to the Soil Protection Act. This circular is adapted to the new soil management policy as set out in the Soil Quality Decree, and applies to dry land. It contains guidelines for the use of remediation criteria and the determination of remediation goals in the case of soil pollution. Municipalities and provinces can use the remediation criteria to determine the severity of the pollution, and whether a site needs urgent remediation. The Cost Calculation Model (AOA), provides a standard to assist in an objective consideration of the costs for an area-oriented approach or the aftercare of soil remediation [65]. There are also some networks used as instruments regarding site investigation, soil sampling strategies, soil treatment and reuse, remediation technologies, chemical analyses, etc. [66].

National Spatial Planning Programmes are published approximately on a ten-year basis by the Ministry for Housing, Spatial Planning and the Environment (Rijksoverheid). The most recent development is the Nota Ruimte (NR) programme, which was enacted by the Dutch parliament in 2006. The programme gives guidance for the national spatial development until 2020 and provides a vision for the spatial development until 2030. The overall objective of the programme is decentralisation: the realisation of a polycentric society and a withdrawal of central structures. The issue of land take reduction is now under the responsibilities of the provinces. The objective of reducing sealing and landscape fragmentation is reflected in several spatial planning documents, like the Order on Council Spatial Planning (AMvB Ruimte), which reconfirms national aims to reduce urban sprawl and to establish a national ecological network; the Action Programme against landscape cluttering (Beautiful Netherlands), which aims to reduce development of new commercial zones by redeveloping the old commercial zones; or the long-range programme for habitat defragmentation (Meerjarenprogramma Ontsnippering). Brownfield redevelopment funding schemes have also been moved to the local authorities [59]. In 2008, the new Dutch Spatial Planning Act came into effect. It reflects that though spatial planning is rather flexible in The Netherlands, it has recently become overly detailed and easily outdated [67].

## 4. Discussion

At present, neither the preservation of soil functions nor the management of soil threats are comprehensively regulated by the EU legislator, and soil protection seems to be merely the by-product of different provisions which are mainly preventive, qualitative, and non-strictly binding [68]. The Directive would not necessarily have exceeded these in mandatory authority but could have provided a legal background for the enhancement of these issues and served as legal reference beyond national governments.

Results show (Table 1) that in the first two categories of legal acts ((1) soil-dependent threats, (2) contamination issues) the five blocking countries do have equally, or in cases even more binding measures. The legislative regulations concerning soil-dependent threats and contamination issues in the above countries were generally well defined, complementary and thorough, but because of their fragmented character may not serve sustainable soil use as sufficiently as they could. This is well demonstrated by the fact, that in some states, for example Austria, soil protection guidelines were not coherent among different administrative regions there being no concerning national law. While some federal states have very extensive soil protection legislation (e.g., Salzburg) or non-binding soil-focused instruments, such as the Soil Protection Concept Vorarlberg, there is no soil protection legislation in some other federal states [69]. In the aspect of sealing (3) the gaps are more significant. We found recommendations, principles, and good practices rather than binding regulations in this area. Sealing is not a separate issue, but is mainly incorporated into urban spatial planning, e.g., a planning system (UK), the National Strategy for Sustainable Development (France), Building Code (Germany), and National Spatial Planning Law (The Netherlands), as shown in Table 1. The current perception on sealing is that it is an unavoidable consequence of development [70]. Ecological sustainability considerations are often limited to the assessment of environmental, economic, and social costs and benefits of the specific land take, without considering the no-land-take alternatives. There are good initiatives too, which increasingly recognise the importance of mitigating the impacts of soil sealing, e.g., in relation to urban drainage and maintaining green infrastructure. However, as extensive literature suggests, these incentives are frequently pushed into the background by funding mechanisms and power configurations, which influence the implementation of spatial strategies integrated in strategic plans [71–73].

The Member States of the EU did not reach a political agreement about an overarching legislative control system over soil protection. The UK, Germany, France, Austria, and The Netherlands have argued that the new Directive would not respect the principle of subsidiarity and would interfere with domestic soil policy. Their objection was specifically about Member States' rights in the EU. The British and German governments claimed that unlike air and water, soil is not a cross-border issue and therefore the EU had no right to regulate it [74]. They were concerned about the extra costs of soil protection in other, possibly more problematic Member States and additional policy obligations, as well as a possible restriction on housing developments, and criticised the proposal on the grounds that it would lead to disproportionate cost with a negligible environmental benefit. As public concern over sovereignty and bureaucracy within the EU increased, these governments saw the proposed EU legislation as unnecessary meddling in an area best dealt with at the local level. Farmers lobbied intensely against the legislation too. It was also argued that soil is already protected under such EU legislation as the CAP [75].

On the other hand, the issue of soil degradation is widely accepted as having multiple cross border consequences. Soil degradation is also continuous in Europe, and the achievements in endeavours for a more sustainable use of soil diverges enormously between Member States [76]. Consequently, existing policies are apparently insufficient for preserving soil functions. There seems to be a need to ensure that all Member States are addressing all threats to which soils are confronted in their national territory, and do not do so in a partial way. On account of the national approaches, no common thresholds, monitoring targets, and priorities are in effect. There are strategic vision documents but they are mostly non-binding. Soil protection is regarded rather as a beneficial side effect, and not as a primary objective at present. In fractured legislation, the multi-functionality of soil may also be lost, since soil functions are addressed separately in different directives [77]. Many national governments insist that soil is a national issue, but they have passed almost no new national or regional legislation to protect the soil in recent years [78]. Moreover, there are national governments in the EU, which dispute the transboundary aspects of soil degradation [78]. Another argument against worries over sovereignty, is that the existing national soil protection laws of Member States would not be threatened by common EU legislation, as Member States may adopt laws that are more protective than EU legislation. Sharing best practice in soil protection at the European level would also be an asset, as a flexible and proportionate approach complements existing national action. A common European soil conservation policy would provide benefit to the EU by also addressing non-economical, societal challenges and in this way may better justify soil legislation. There are also other economic considerations which separate national legislations lack. Wide differences between national soil protection regimes, can in some cases impose on economic operators very different obligations, creating imbalance and a distortion of competition in the internal market. Acting at Community level would also greatly complement the quality controls performed at the national level to ensure food safety.

**Table 1.** Legislative acts of selected EU Member States on main soil threats and their relationships to the proposed Soil Framework Directive of the EU.

| | **Main Features of Legislative Acts (EU Member States) and the Proposed Soil Framework Directive (SFD) of the EU by Different Types of Soil Threats** | | | **Force of the Legal Instuments *** | **LEVEL of Similarity ** between the SFD and National Legislations** | **Possible Means of Harmonization towards Consistent Approaches between MS Legislation and the Proposed SFD ***** |
|---|---|---|---|---|---|---|
| | **Type I.** | **Type II.** | **Type III.** | | | |
| | **Soil-Dependent Threats (Erosion, Organic Matter Decline, Salinisation, Compaction and Landslides)** | **Contamination** | **Sealing** | | | |
| The proposed Framework Directive | Identify the risk areas (reviewed every ten years, Article 6)<br>For each risk area draw up a programme of measures (in place max. eight years after transposition date Article 8) | Limit dangerous substances in the soil (Article 9);<br>Identify contaminated sites and review every five years (Article 10);<br>Status report at transaction (Article 12);<br>National Remediation Strategy shall be published within seven years from transposition date (Article 23, 14) | Appropriate measures to limit sealing or to mitigate its effects (article 5) | | | |
| UK | CAP cross compliance, Environmental Stewardship, the England Catchment Sensitive Farming Delivery Initiative, and the new Code of Good Agricultural Practice<br>These requirements are Good Agricultural and Environmental Conditions (GAECs) and Scheduled Monuments Statutory Management Requirements (SMRs)<br>The Scottish Soil Framework, Environment Strategy for Wales | Environmental Protection Act 1990 (EPA): identification, remediation.<br>Environmental Damage Regulations 2015 (EDR): prevention and remediation in the most serious cases.<br>DEFRA: Statutory Guidance for England on dealing with contaminated land and radioactive contaminated land. | Planning system for considerations of mitigating the impacts of soil sealing, particularly in relation to urban drainage and maintaining green infrastructure. | Type I.<br>[B]<br>Type II.<br>[B]<br>Type III.<br>[NB] | Type I.<br>+<br>Type II.<br>++<br>Type III.<br>−− | Type I.<br>technical<br>Type II.<br>technical<br>Type III.<br>legislative |
| Germany | Federal: UBA main environmental protection agency and the Federal Ministry of Environment carry out compiles, assesses, and provide information on soil status, soil conservation, and optimization of measures.Sustainable Development Strategy to clarify how Germany can achieve "land degradation neutrality" domestically.<br>Federal Nature Conservation Act | Official identification, remediation system on both federal and local levels.<br>Federal Soil Protection Act, | Federal Building Code, Federal Spatial Planning Act The Federal Building Code in urban planning.<br>Federal Regional Planning Act (Raumordnungsgesetz)<br>30-ha goal | Type I.<br>[B]<br>Type II.<br>[B]<br>Type III.<br>[B] | Type I.<br>++<br>Type II.<br>++<br>Type III.<br>++ | Type I.<br>technical<br>Type II.<br>technical<br>Type III.<br>technical |

**Table 1.** *Cont.*

| | Main Features of Legislative Acts (EU Member States) and the Proposed Soil Framework Directive (SFD) of the EU by Different Types of Soil Threats | | | Force of the Legal Instuments * | LEVEL of Similarity ** between the SFD and National Legislations | Possible Means of Harmonization towards Consistent Approaches between MS Legislation and the Proposed SFD *** |
|---|---|---|---|---|---|---|
| | **Type I.** | **Type II.** | **Type III.** | | | |
| | **Soil-Dependent Threats (Erosion, Organic Matter Decline, Salinisation, Compaction and Landslides)** | **Contamination** | **Sealing** | | | |
| France | National information system:GIS Sol.<br>Ministry of Agriculture and of Environment, Environment and Energy Agency (Ademe)<br>National Institute for Agricultural Research (Inra)<br>Research Institute for Development (IRD). | ICPE, Environment Code a proactive regulatory watch on soil problems and administrative and criminal sanctions. | National Strategy for Sustainable Development, law Grenelle Environment | Type I.<br>[B]<br>Type II.<br>[B]<br>Type III.<br>[NB] | Type I.<br>+<br>Type II.<br>++<br>Type III.<br>− | Type I.<br>legislative<br>Type II.<br>technical<br>Type III.<br>legislative |
| Austria | Soil Monitoring System and a Soil Information System (BORIS)<br>Soil Protection Acts in 5 provinces. | No integrated regulatory regime, but applicable provisions are spread over a considerable number of laws and regulations (for example, the Trade Act, the Federal Waste Management Act, the Federal Environmental Liability Act, the Forest Act, and the Water Act).<br>The Clean-up of Contaminated Sites Act and the Directive on Funding Clean-Up of Contaminated Land | Austrian Strategy for Sustainable Development, Report on Monitoring Sustainable Development. | Type I.<br>[B]<br>Type II.<br>[B]<br>Type III.<br>[NB] | Type I.<br>+<br>Type II.<br>+<br>Type III.<br>− | Type I.<br>legislative<br>Type II.<br>legislative<br>Type III.<br>legislative |
| NL | Soil Protection Act (Wbb) Environmental Protection Act (Wm)<br>Competent authority municipalities<br>Netherlands Soil Protection Guideline (NRB),<br>Directorate General for the Environment (VROM/DGM),<br>Union of Water Boards Association of Provinces, and Association of Netherlands Municipalities | Soil Protection Act<br>Environmental Protection Act<br>Soil Quality Decree<br>Soil Remediation Circular 2013<br>Cost Calculation Model (AOA) | National Spatial Planning Programmes by the Ministry for Housing, Spatial Planning and the Environment (Rijksoverheid)<br>The most recent development: Nota Ruimte (NR) programme<br>Spatial Planning Act | Type I.<br>[B]<br>Type II.<br>[B]<br>Type III.<br>[B] | Type I.<br>+<br>Type II.<br>++<br>Type III.<br>++ | Type I.<br>technical<br>Type II.<br>technical<br>Type III.<br>legislative |

* Force of the legal instruments: [B] Binding instruments also called 'hard law' confer legal obligations, which can be enforced by a body of law. [NB] Non-binding documents, also called 'soft law', cannot be enforced, but provide guidelines of conduct, reflect principles and proclaim standards. They are intended to influence the development of national laws and practices mostly in the form of declarations, recommendations and resolutions and can be implemented through programmes and action plans. ** level of similarity: (−−) no legislation available; (−) legislation exists, but with different conceptual approach and different implementation; (+) legislation exist with similar conceptual approach but different implementation; (++) legislation exist with similar conceptual approach and similar implementation. *** possible means of harmonization: technical (technical solution would be adequate: in cases when legislation exists with similar conceptual approach but there are minor practical differences in the implementation, e.g., temporal terms, terms of monitoring); legislative (legislative measures would be required).

## 5. Conclusions

Most of the existing national environmental provisions recognize the problem of soil threats, and the importance of preserving soil functions. However, regulatory means of soil protection are mostly embedded into wider environmental legislation. Thus, soil protection, in many countries ends up as a by-product in measures often lacking the required authority to reinforce soil protection. Commonly, there is a lack of an overarching soil protection legislation and existing national policies are sometimes insufficient for preserving soil functions and combatting soil threats (halt erosion, soil sealing, etc.), as seen from the status of soil in the EU [79].

Nevertheless, we can state that in the five countries blocking the Directive soil protection, laws on soil-dependent degradation and contamination are often more restrictive than the proposed EU regulation. Therefore, the worries over sovereignty could not have reasonably arisen in this aspect. Soil sealing is an issue where the proposed Directive's measures, could have exceeded those of the Member States.

Liability implications were also included in the arguments opposing the proposed Directive, in cases when the liable party is not found, and the state would be responsible for remediation. In these subjects, technical solutions would be adequate to reach harmonised approaches for soil protection across the EU.

Results of our gap analysis suggest that—although legislation related to soil protection may be fragmented in some states—overall gaps in the contents of soil protection legislations are rather narrow among the EU member states. Thus, given that an agreement on the control of soil sealing can be reached, technical solutions are available to support the construction of a common political will to introduce a common soil protection legislation in the EU.

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# Arable Land Tenancy and Soil Quality in Germany: Contesting Theory with Empirics

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**Abstract:** Soils are under increasing utilization pressure, and soil governance is an important element to maintain soil functions and prevent the degradation of soil quality. However, scientific studies about soil governance are rare. In this paper, we focus on the governance mechanism of land rent. Here, a major theoretical assumption is that landowners have higher incentives to maintain soil quality than leaseholders. By using data for German arable land at the county level, we contrast theoretical assumptions about the relationships between landowners, leaseholders and soil quality with empirical evidence based on correlations between arable land rent prices, rent proportions and yield potential. The main finding is that the empirical data contradict the theoretical assumptions to a large degree, i.e., no clear relationship could be discerned between the three parameters of arable land soil quality, rent price and rent proportion. We discuss possible explanations for the revealed contradictions based on the state of research and highlight the need for future research to better understand the potential of arable land tenancy as a governance mechanism for sustainable soil management.

**Keywords:** landowner; tenant; rent price; rent proportion; yield potential; sustainable soil management

## 1. Introduction

A globally increasing population and a demand for biomass-based food, feed, energy and fiber is causing the intensified use of soils and requires corresponding actions of soil governance [1]. The current utilization pressure on soils might endanger their quality, i.e., their capacity to maintain their various functions and contributions to ecosystem services such as biomass production, nutrient provisioning and cycling, carbon storage, filtering and storage of clean water, providing habitats for biological activity, and climate regulation [2]. Because of this multifunctional and site-specific nature, soil quality is a complex phenomenon, for which no standardized assessment procedure yet exists [3]. Yield potential is a proxy for the inherent capacity of soil to produce biomass and is taken as an indicator for soil quality [4]. Soil degradation is a combination of processes that reduce soil quality and may thereby impede the achievement of societal targets such as those determined in the United Nation's Sustainable Development Goals [5]. Thus, there is a quest for sustainable intensification practices for soil management, which integrates the achievement of the highest productivity levels with the maintenance of soil functions [6,7]. Consequently, sustainable soil governance requires policies and regulations that support this quest [8]. In general, soil-related governance is far less understood than the governance of other natural resources such as water, air or biodiversity [9]. In addition, there is a general knowledge gap about the linkages between soil quality, soil/agricultural management and soil governance [10]. Therefore, complementary to our empirical study, we discuss propositions for more comprehensive research activities in the field of soil quality linked to management and governance.

Soil management in Europe is regulated by governance structures at several organizational levels through different mechanisms such as obligatory or voluntary policy instruments. At the European Union (EU) level, for example, policy instruments such as the agri-environmental measures of the Common Agricultural Policy (CAP) aim to compensate farmers for income loss associated with soil conservation management practices [11–13]. However, the proposal for a legally stronger binding Soil Framework Directive for the EU was rejected because some member states feared high costs for its implementation [14]. Thus, there is currently no European legislation that focuses exclusively on legally binding soil conservation regulations. At the national level, the German Federal Soil Protection Act aims to secure soil fertility [15]. However, similar to the agri-environmental measures of the CAP, most of the sustainable land use and soil conservation measures refrain from obligatory policy instruments and only apply incentive-based and awareness-raising instruments. Incentive-based and awareness-raising instruments aim to encourage farmers to implement additional soil protection measures on a voluntary basis [16,17]. For example, additional soil protection measures include the integration of additional crops that have the potential to improve soil quality through their root system, into the rotation scheme.

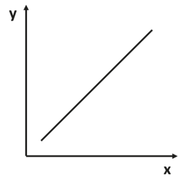
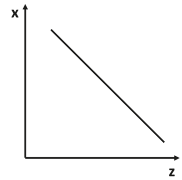
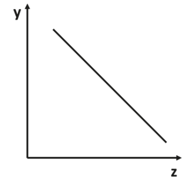
Farmers are assumed to have intrinsic reasons to protect soil quality because it secures their benefits arising from soil use. However, such an assumption might not be warranted when looking at the manifold forms of ownership and use rights on agricultural land that is often regulated through tenancy as a form of governance mechanism between private individuals. For example, leaseholders might have much less incentives to protect soils than landowners because the former may expect to stop using the land in the near future and thus aim for benefit maximization at the expense of soil quality. In this case, landowners have the opportunity to prevent such behavior by fixing obligatory soil protection measures in lease contracts that in turn might reduce rent prices to compensate for investments in soil quality [18]. Thus, property rights and tenure systems play a crucial role in the efficiency of soil protection governance. Germany, with a comparatively high land proportion of approximately 60% [19,20], is a prime location for investigating landowner and tenure relationships as governance mechanisms. Furthermore, Germany has a highly technologized agricultural system and faces demands for the highest level of productivity while preventing soil degradation. In this context, we focus on arable soils because soil degradation is more of a key issue here in contrast to, e.g., grassland.

Our objective is to investigate the influence of tenancy as a soil governance mechanism on soil quality by examining the relationship between landowners and leaseholders based on contrasting theoretical assumptions with empirical analysis, i.e., correlations between arable land rent prices, rent proportions and yield potential, the latter being used as an indicator for soil quality [4].

## 2. Theory of Land Price, Tenure and Soil Quality

Major theoretical assumptions about soil governance and economic behavior of farmers are rooted in the theory of rent by Ricardo [21] and in owner-tenant-relationships hypotheses [22,23]. We explain these theoretical assumptions from the perspective of soil governance through tenancy and connect them to the analytical dimensions of yield potential, rent price, and rent proportion (Table 1). Yield potential is used as an indicator for soil quality and represents the production function of soils [4] (compare Section 3). Yield potential estimates for arable land in Germany are available through the German Federal Institute for Geosciences and Natural Resources [24]. The arable land rent price represents the monetary value of arable land benefiting landowners in return for making assets available to a leaseholder. Leaseholders aim to exceed the costs for the rented land by agricultural production. Arable land rent proportion represents the rate of land leased to tenants in contrast to arable land being under ownership.

**Table 1.** Theoretical relationships between arable land yield potential, rent price, and rent proportion.

| (A) Rent Price and Yield Potential | (B) Yield Potential and Rent Proportion | (C) Rent Price and Rent Proportion |
|---|---|---|
|   |   |   |
| The higher the yield potential (x) is, the higher the rent price (y) because leaseholders can generate more and higher-quality products from soils with well-performing functions. | The higher the rent proportion (z) is, the lower the yield potential (x) because leaseholders have lower incentives than landowners to invest in soil quality. | The higher the rent proportion (z) is, the lower the rent price (y) because leaseholders have more choices to lease available land; this might result in decreasing soil quality. |

The theoretical background characterizing the relationship between arable land yield potential, rent price and rent proportion is as follows. First, following Ricardo [21], the rent for arable land arises because of the fertility of the soils that determines the productivity of the land. The difference between superior and inferior soils determine the rent price. Although subsequent researchers based the determination of rent prices on different underlying assumptions [25,26], the support for neoclassical rent theory is still strong and influences the scientific debate [27,28]. For example, farmland values are determined by expected returns that are demonstrated via land rents [29]. In addition, rent price formation is a complex process and depends on many factors. For example, rent is defined in standardized land values (taking into account productivity characteristics, soil characteristics, size, location, cultivation opportunities) or the demand and supply ratio of land, environmental factors, the presence of investors or governmental regulations influencing rent market processes and prices [30]. Since our research interest focuses on tenancy, the major theoretical assumptions would be that the higher the yield potential of soils, the higher the rent price because tenants or leaseholders can generate higher-quality products and returns from soils that exhibit a higher quality based on well-performing soil functions (Table 1A).

Second, the relationship between landowner and tenant is mainly described on the basis of classical-economic profit maximization approaches [31]. A number of studies have identified soil management differences between landowner and leaseholder [32–34]. The following perception prevails: land managed by its owner, who aims to secure high sale and option values of his property, is used in a more sustainable way compared to land tenure, where incentives are set up to invest in short-term production and less in long-term sustainable management strategy. It is often concluded that such a behavior is the consequence of insecure land tenure [17,35,36]. With the increasing trend of land tenure operations on farms in Europe, the problem of land tenure insecurity will remain, causing a decrease in the application of soil conservation measures [17,33,37]. From the perspective of soil management, this would mean that the higher the rent proportion (more land is managed by leaseholders), the lower the yield potential because leaseholders have lower incentives than landowners to invest in soils. This again would result in lower yields (Table 1B). This assumption needs to consider a dynamic relationship because the effect of leaseholder management on yield potential is time delayed.

Third, we apply a simple "supply and demand" assumption to assess the relationship between rent price and rent proportion. Within the natural limitations of a given amount of land, the relationship between rent price and rent proportion depends on a number of factors. For example, demographic, economic, regulatory and technological drivers influence the availability of land that is for rent and therefore influence the degree of rent proportion [27,38]. From the perspective of classic economic theory, the availability of land (e.g., scarcity or abundance) influences the rent price [21]. Thus, we assume that the lower the amount of land available for rent (rent proportion) is, the higher the rent price because leaseholders compete for renting land. In addition, the assumption that land leaseholders have lower incentives to apply soil-protecting measures than land owners would imply that a high rent proportion might result in an overall decrease in soil quality (Table 1C).

## 3. Materials and Methods

In this paper, we used data about arable land yield potential, arable land rent proportion and arable land rent price as indicators for soil quality and soil governance through tenancy agreements to test the abovementioned theoretical assumptions. We used the yield potential estimates for arable land in Germany of the German Federal Institute for Geosciences and Natural Resources [24]. They are based on the Müncheberger Soil Quality Rating (MSQR), which is a visual procedure for yield potential estimation, taking soil structure and soil degradation threats into account [4]. It integrates eight basic soil indicators with 13 hazard indicators into a rating of soil quality on an ordinal scale of 0 to 102, with higher values indicating higher yield potential. The eight soil indicators are: Substrate, A-horizon depth, topsoil structure, subsoil structure, rooting depth, profile available water, wetness and ponding, slope, and relief. The 13 hazard indicators are: Contamination, salinization, sodification, acidification, low total nutrient status, shallow soil depth above hard rock, drought, flooding and extreme waterlogging, steep slope, rock and surface, high percentage of coarse texture fragments, unsuitable soil thermal regime, and miscellaneous hazards (e.g., exposure to wind and water erosion) [4]. The procedure is an up-to-date, internationally acknowledged and applied method to assess soil quality [3]. Because of its focus on soil structure and soil degradation characteristics, most (albeit not all) of the indicators are sensitive to improper agricultural soil management, which makes it particularly useful for the scope of this study. Overall, the MSQR compiles parameters on a uniform basis that can be spatially processed. We combined the yield potential data with arable land rent price and rent proportion data. The source of both data sets is the German Statistical Agency of the Federal States, which provided German-wide data from the Agricultural Census in 2010 [20]. In Germany, the rent prices and the rent proportion rate increased constantly during the last decades, with significant differences between East Germany (former GDR) and West Germany (former BRD) [19,20]. Because of this situation, we analyzed the data for Germany in total as well as for East and West Germany separately. For all three indicators, we were able to access data on a uniform basis at the county level and therefore focus our empirical analysis at this level.

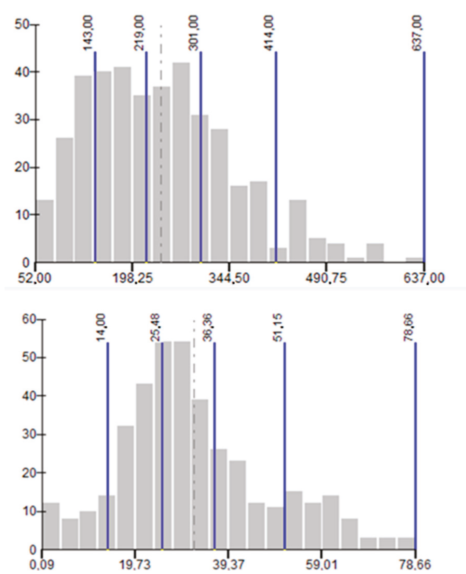
### *3.1. Data Acquisition: Arable Land Rent Proportion, Rent Price and Yield Potential*

The most relevant source for data on arable land rent proportion and arable land rent price is the Agricultural Census for Germany from 2010. It comprises data from the main Land Use Survey, the Survey on Agricultural Production Methods, and the Agricultural Structure Survey. It is commonly used for German and EU administrative purposes at different political and administrative levels and includes data with spatial information on Federal State-level, NUTS2- and NUTS3-level (the abbreviation NUTS is explained in the next paragraph) per farm operating business (according to a threshold of 5 ha or more and based on the locality of the operating business). The Agricultural Census comprises (based on uniform table formats) data on land use, livestock, labor forces, acquisition of agricultural production methods and "further survey characteristics" that constitute the legal form, place of farm operating business, owner and tenancy information, land under tenure and rent prices for arable land [18]. Comparisons with previous Agricultural Census data are difficult because of changes in data collection processes and definitions such as the size of farm operating business considered in the statistics [20].

For the purpose of this analysis, the smallest but nation-wide uniformly assessed spatial unit for Germany is the statistical unit NUTS-3 (county level). The "Nomenclature des Unités territoriales statistiques—NUTS" represents statistical regions within the EU and facilitates the supranational statistical comparison of such regions. NUTS-3 regions represent the statistically (based on the population) smallest regions. In Germany, NUTS-3 regions represent counties and corporate cities and number 402 in total [39,40]. To ensure a nation-wide uniform analysis of data based on the Agricultural Census from 2010, data were requested from the Statistical Agency of Germany. Statistical data from all federal states of Germany were requested with a response rate of 15 out of 16 (federal state statistical offices). After a data preparation and cleansing process, 389 out of 402 NUTS-3 regions were used for further analysis. In addition to four corporate city regions, the data for six NUTS-3 regions from one federal state were not available. For the purpose of our analysis, data on arable land rent proportion at the NUTS-3-level could not be derived directly from the acquisition, but data on rent prices could be derived directly for NUTS-3 regions.

Aside from the statistical data sources used to assess arable land rent proportion and arable land rent price, spatial data on the arable land yield potential was assessed with the aim to visualize the linkage and spatial distribution of those three variables. Here, two basic types of spatial datasets form the basis for the visualization, shapefiles and a raster dataset. The shapefiles mostly represent administrative borders. The raster dataset comprises data on arable land yield potential that is available for arable land in Germany at a scale of 1:1,000,000 (BÜK 1000) [24,41].

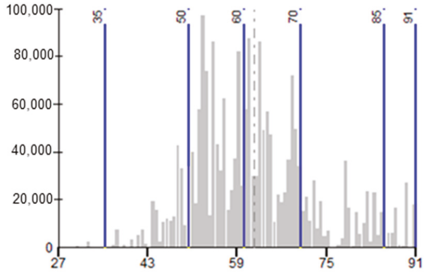
The arable land rent price as well as the arable land rent proportion were calculated and visualized for NUTS-3 regions, which reflects the highest spatial resolution that can be acquired at the national scale for these data. Rent proportion and rent price data were not normally distributed and thus were classified for the spatial visualization based on Jenks (natural breaks), which is a common and suggested method given an uneven distribution (Figure 1a,b). The method orientates itself on natural data gaps and classifies the data in such a way that variations within classes are as low as possible while differences between classes are as large as possible [42]. For arable land yield potential, the mean value has been visualized for NUTS-3 regions. Heterogeneities within those regions can therefore not be visualized. Figure 1c represents the frequency distribution and the breaks within the arable land yield potential data based on the classification of the BGR [24] (Table 2), reflecting heterogeneities among the raster data set of almost 2 million points for Germany.




(**a**) The frequency ($y$-axis) distribution of arable land rent prices ($x$-axis) (N = 389) with natural breaks (solid blue line) and the mean value (dashed line)

(**b**) The frequency ($y$-axis) distribution of arable land rent proportion ($x$-axis) (N = 389) with natural breaks (solid blue line) and the mean value (dashed line)

**Figure 1.** *Cont.*




(**c**) The frequency ($y$-axis) distribution of the arable land yield potential ($x$-axis) (N = 1,999,073 based on raster data) with breaks according to six classes based on BGR 2016 (solid blue line) and with the mean value (dashed line)

**Figure 1.** Frequency distribution of arable land rent prices (**a**), rent proportion (**b**) and yield potential (**c**).

**Table 2.** Classification of the agricultural yield potential ratings according to the BGR [24].

| Agricultural Yield Potential (Acc. to MSQR) | Evaluation |
|---|---|
| <35 | extremely low |
| 35–<50 | very low |
| 50–<60 | low |
| 60–<70 | medium |
| 70–<85 | high |
| >85 | very high |

*3.2. Data Calculation and Visulization: Arable Land Rent Proportion, Rent Price and Yield Potential*

The arable land rent proportion was determined by the share of rented arable land out of the total arable land (in %) at the county level (=NUTS-3 regions) from the Agricultural Census of 2010. Arable land rent prices were directly taken from the Agricultural Census for NUTS-3 regions. The calculated values for arable land rent proportion and rent prices as well as the average arable land yield potential for NUTS-3 regions were correlated with each other. The three variables were tested for normality in their distribution using the "Kolmogorov-Smirnov-Test", and the Spearman rank correlation $r_s$ was chosen as none of the variables are normally distributed (Figure 1a–c). In this method, the correlations are based on the rank of the values that are ranked beforehand [43]. The scatter plots provide a visual representation of the characteristics of the cases and support the identification of patterns and the description of correlations. They are not intended as an analysis in inferential statistical terms.

For the visualization of the data in a spatial map, the raster dataset was transformed into a vector dataset. The vector dataset allows for the attachment of the NUTS-3 information on arable land rent proportion, rent prices for arable land, and the average (mean) value for the arable land yield potential. The classification of the arable land yield potential (Table 2) guides the map of arable land yield potential of German soils by the BGR [24] (Figure 5).

During data processing, data for some NUTS-3 regions were removed and therefore do not appear in the map nor were they considered for the statistical analysis. The data set used therefore only includes data comprising information on arable land rent proportion and price. Where the arable land yield potential is not visualized (Figure 5), no arable land is determined by the MSQR. In these cases, the dominant land use type might be, for example, grassland.

## 4. Results

We have structured the results into three parts that describe the empirical findings of the relationships between the three variables, namely, the arable land rent price, arable land proportion and arable land yield potential. For each relationship, we interpret the results from the perspective of the theoretical assumptions presented in Section 2.

## *4.1. Arable Land Yield Potential and Rent Price*

There is a weak positive correlation between arable land yield potential and rent price in Germany ($r_s$ 0.235, Figure 2). This result supports the theoretical assumption only to a limited degree. A group of 23 cases (marked yellow in Figure 2) with rent prices between 400 and 600 € (aggregated at county level in 2010) has a solid effect on the weak correlation ($r_s$ excluding these cases: 0.303, N = 366). These outliers are counties located in the northwestern part of Germany on the border with The Netherlands (compare the map in Figure 5). These counties have a high density of livestock that increases the application of large amounts of farm manure. This group of outliers appears in the West German data points potentially explaining the correlation of $r_s$ 0.274 in an otherwise quite evenly spread data cloud. In contrast to West Germany, East Germany shows a stronger correlation ($r_s$ 0.585) that again concurs strongly with the theoretical assumption that high yield potential causes high rent prices. We discuss possible explanations for the limited agreement of empirical findings with the theoretical predictions between arable land yield potential and rent prices below in Section 5.1.

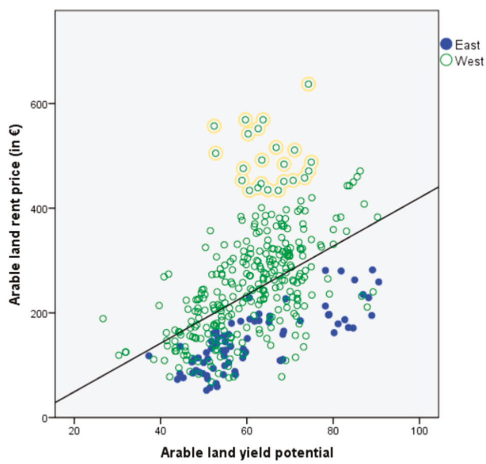



**Figure 2.** Correlation of arable land rent prices and yield potential in counties within Germany (N = 389); West Germany (N = 311); East Germany (N = 78).

## *4.2. Arable Land Yield Potential and Rent Proportion*

There is no correlation between arable land yield potential and rent proportion in Germany ($r_s$ 0.012, Figure 3). The scatter plot shows an evenly spread data cloud without clear groups of outliers. This also applies to the data from West Germany ($r_s$ 0.002). In contrast to West Germany, East Germany shows a weak correlation ($r_s$ 0.211). While the West German data show indifferent results, the East German data slightly contradict the theoretical assumption that high values of rent proportion cause a decrease in soil quality and yield potential. We discuss the possible reasons for the mismatch between the theoretical assumptions and empirical findings of the relationship between rent proportion and yield potential below in Section 5.2.

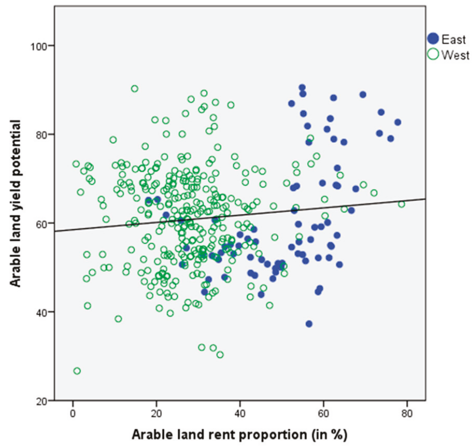



**Figure 3.** Correlation of arable land rent proportion and yield potential in counties within Germany (N = 389); West Germany (N = 311); East Germany (N = 78).

### *4.3. Arable Land Rent Proportion and Rent Prices*

There is a very weak correlation between the arable land rent price and rent proportion in Germany ($r_s$ 0.065, Figure 4). The scatter plot shows an evenly spread data cloud. The data make an even stronger case for the different degrees of correlations for West Germany ($r_s$ 0.001) and East Germany ($r_s$ 0.038). In all cases, we see no strong empirical evidence supporting the theoretical assumption that a high level of rent proportion decreases the rent price. We discuss possible explanations for the limited agreement between empirical findings and the theoretical predictions of arable land rent prices and rent proportion below in Section 5.3.

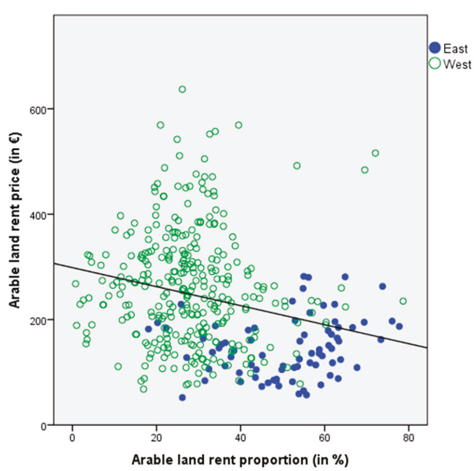
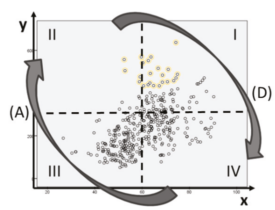
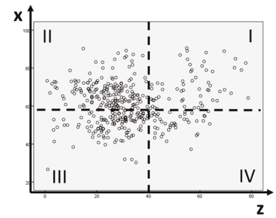
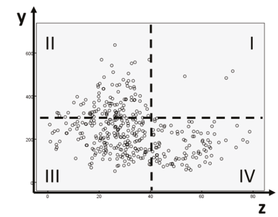



**Figure 4.** Correlation of arable land rent proportion and rent prices in counties within Germany (N = 389); West Germany (N = 311); East Germany (N = 78).

## 5. Discussion

We have divided the XY diagrams of all three combinations of arable land rent price, rent proportion and yield potential into four quadrants in order to more easily discuss possible explanations to the empirical findings (Table 3) and connect them to the spatial visualization of all three variables at the end of the discussion (Figure 5).

**Table 3.** XY diagrams of the relationships between arable land yield potential, rent prices, and rent proportion divided in four quadrants.

| (A) Rent Price (y) and Yield Potential (x) | (B) Yield Potential (x) and Rent Proportion (z) | (C) Rent Price (y) and Rent Proportion (z) |
|---|---|---|
|   |   |   |
| Quadrants I and III represent theoretically expected relationships (arrow A). | Quadrants II and IV represent theoretically expected relationships. | Quadrants II and IV represent theoretically expected relationships. |
| Quadrant II: almost no cases, thus, concurs with theory | Quadrant I: lower level of ownership on arable land in East Germany; soil resilience absorbs disturbances until tipping point of degradation; fixation of soil protection and/or rent security in lease contracts | Quadrant I: almost no cases, thus, concurs with theory |
| Quadrant IV: rent price fixation; internalized costs of soil protection or other issues in lease contracts might lower the rent price and increase yield potential (arrow D) | Quadrant III: low supply of or demand for less-productive land (original state or previously degraded) | Quadrant III: low demand for or supply of leased arable land; rent price fixation; internalized costs of soil protection or other issues in lease contracts |

### 5.1. Arable Land Yield Potental and Rent Price

Table 3A visualizes the relationship between arable land yield potential and rent price. The quadrants I and III represent theoretically expected relationships: arable lands with high yield potential have high rent prices (I), and arable lands with low yield potential have low rent prices (III). Quadrants II and IV represent relationships that are contrary to the theory: arable land with low yield potential have high rent prices (II), and arable land with high yield potential have low rent prices (IV). The empirical analysis revealed a weak positive correlation between yield potential and rent price ($r_s$ 0.235). Given the complex process of rent price formation, as indicated in the introduction, a number of possible explanations exist. Other than soil- and yield potential-related factors, the rent price is influenced by availability of land, distance to markets, compensation area for the application of farm manure, cultivation opportunities or competition on land markets [30,44] or non-agricultural attributes such as natural amenities [45]. A further potential explanation could be governmental interventions such as agricultural subsidies [46]. Focusing on the relationship between landowner and tenant, low rent prices for arable land with high yield potential might internalize costs for measures aimed at maintaining or increasing soil quality, e.g., fixed in lease contracts. However, there exists a research gap with respect to the relationship between tenancy agreements and soil governance mechanism. Viewing the relationship between both indicators, the theoretical assumption focuses on how the yield potential of arable land affects rent prices (A). However, the rent price might also explain the degree of yield potential (D) because low rent prices internalizing costly soil protection measures according to lease contract conditions increases the soil quality and, thus, the yield potential.

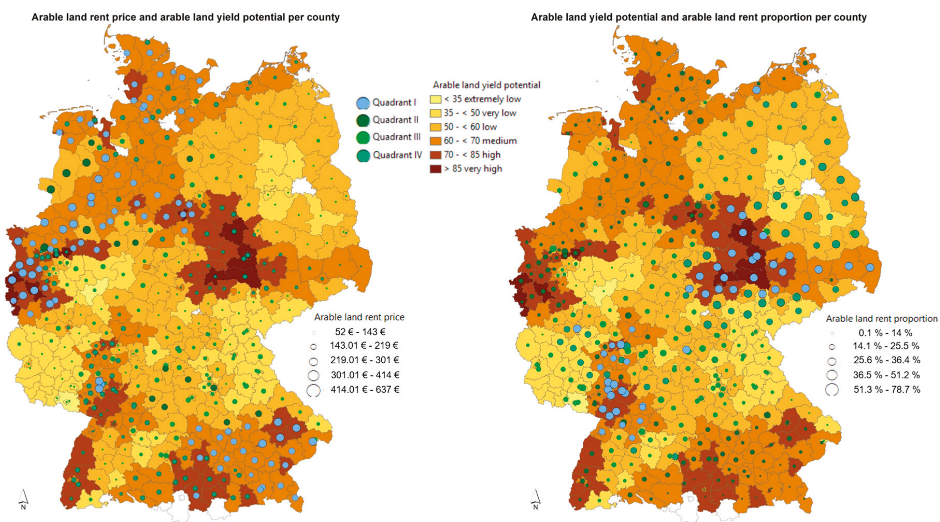
### 5.2. Arable Land Yield Potential and Rent Proportion

Table 3B visualizes the relationship between arable land rent proportion and yield potential. Quadrants II and IV represent the theoretically expected relationships: a low rent proportion exists on arable lands with high yield potential (II), and a high rent proportion exists on arable lands with low yield potential (IV). We observed a smaller number of cases present in Quadrant IV. A reason could be that non-productive arable land is not economically worthwhile for leaseholders [27]. The leaseholders' influence on soil quality in such cases is therefore restricted. Quadrants I and III represent cases that are contrary to the theory: a low rent proportion exists on arable land with low yield potential (III), and a high rent proportion exists on arable land with high yield potential (I). The empirical analysis revealed no correlation and many cases deviated from the theoretical assumptions stated about the relationship between arable land proportion and yield potential. Quadrant III represents a large number of cases where arable land with lower yield potential is not rented out to leaseholders. Similar to the situation in Quadrant IV, a reason could be that non-productive arable land is economically worthless to leaseholders and thus tend to be operated by landowners. Furthermore, the quality of soils and their productivity varies naturally regardless of the influence of owner or tenant operations. The data reveal no differentiation between the original soil quality status and the observed soil degradation process in determining the yield potential. It should be noted that the yield potential is averaged per county.

Possible explanations for cases in Quadrant I are rather intricate. First, many cases are East German counties, where before unification, cooperatives collectively managed arable land and large areas of arable land were state-owned. For more than 20 years, a privatization agency, i.e., the Land Utilization and Administration Company (BVVG), has been steadily selling areas of formerly state-owned arable land in East Germany on behalf of the German Federal Ministry of Finance, and this activity significantly affects the price formation in agricultural land markets [47]. Moreover, before contracts of sales are finally concluded, the arable land is leased out to tenants and, thus, explains the higher level of rent proportion in East Germany [19]. In addition, the farm size in East Germany is relatively large, and the larger the farm size is, the higher the rent proportion of arable land [48]. Second, the characteristics of soils might explain cases with high rent proportion and high yield potential. Soil resilience is the capacity of soils to cope with disturbances and to prevent significant changes in their functions [49]. This capacity maintains the soil's functional integrity until a particular tipping point or threshold is reached, which would then start a process of degradation. The time factor is crucial here because leaseholders can manage soils in an unsustainable way for some time until degradation and lower yields occur. Thus, arable soils usually have a high ecological resilience and can buffer impacts of tillage, harvest, agro-chemical applications before decrease of soil functional performance is detectable [49]. Third, the design of lease contracts might influence the way that leaseholders manage their soils. For example, a fixation of soil protection measures in tenancy agreements, enforced by landowners, might explain why arable land with high rent proportion have high yield potentials. Furthermore, a high level of rent security, i.e., long-term lease contracts or preferential lease rights, for leaseholders provide incentives for sustainable management of soils. A legally binding minimum term length, however, is not established in Germany [33]. Thus, establishing rent security is left to the contracting parties, where landowners have a high decision-making power in most cases. From the perspective of tenancy agreements, we call for further research about (a) the influence of the form of ownership on soil resilience over time, which should be directly connected to (b) the degree of detailed fixation of soil protection measures and rent security in lease contracts.

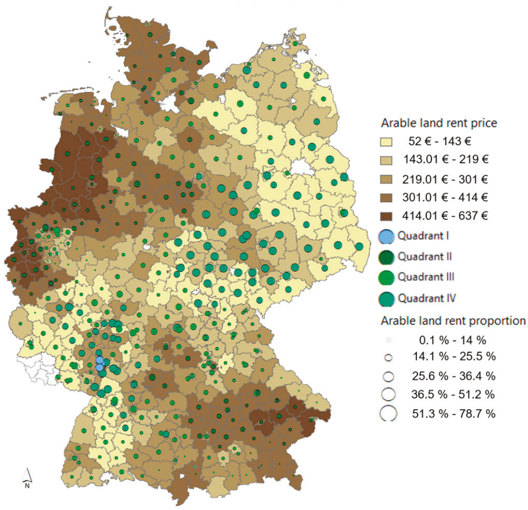
*5.3. Arable Land Rent Proportion and Rent Price*

Table 3C visualizes the relationship between arable land rent proportion and rent price. Quadrants II and IV represent theoretically expected relationships: a low rent proportion of arable lands is linked to high rent prices (II), and a high rent proportion of arable lands is linked to low rent prices (IV). Quadrants I and III are contrary to the theory: a low rent proportion coincides with low rent price (III), and high rent proportion coincides with high rent prices (I). Our empirical analysis revealed a very weak to no correlation. Although the almost empty quadrant I supports the theoretical assumptions, a high number of cases in Quadrant III deviate from the theory about the relationship between arable land rent proportion and rent price. The three cases in Quadrant I represent very specific urban-type counties with low levels of arable land. Possible explanations for the high number of cases in Quadrant III are a low demand for or supply of leased arable land [27]. Additionally, the abovementioned explanations of rent price fixation or internalized costs of soil protection or other issues in lease contracts might determine the correlation between low rent proportion and rent price. Another reason might be the isolated location of arable lands in counties with large areas of forests or mountainous regions that decrease the value of arable land for potential leaseholders, thereby enhancing farm operation by landowners. From the perspective of tenancy agreements, central research gaps concur with the abovementioned research needs, i.e., to clarify the details in the fixation of soil protection measures in lease contracts and its influence on rent price formation [50]. This is of crucial relevance for agricultural systems with high arable land rent proportions, such as those in Germany.




(**a**) (**b**)

**Figure 5.** *Cont.*




(**c**)

**Figure 5.** Maps of arable land rent prices and yield potential (**a**), arable land rent proportion and yield potential (**b**), and arable land rent proportion and rent price (**c**). Quadrants I-IV refer to Table 3. Rent prices and rent proportion are aggregated data for the year 2010. Yield potential is represented on an ordinal scale between 0 and 102 (see Chapter 3 for details).

## 6. Conclusions

The empirical analysis of arable land rent prices, rent proportion and yield potential reveals limited compliance and, in many cases, noncompliance of data with theory. This is due to a complex set of explanatory factors influencing rent price formation processes, the degree of rent proportion, and soil quality. From the perspective of tenancy as a governance mechanism, we suggest that an analysis of the particular designs of soil management measures incorporated in lease contracts in conjunction with the degree of soil quality would help to identify particular governance instruments for sustainable soil management. For example, rent security and preferential rights for new lease contracts are instruments that provide incentives for tenants to invest in soil conservation. Other crucial factors for such an analysis are the particular characteristics of soils that change over time and their capacity to resist disturbances by soil management measures over a particular timeframe (ecological resilience). For example, identifying the tipping points between different degrees of soil quality with respect to particular soil management practices would help to improve the design of precautionary measures in lease contracts. Furthermore, the effects of particular soil conservation designs in tenancy agreements on rent price development and the degree of rent proportion could be the subject of future research. For example, we propose investigating the internalization of soil conservation costs in rent prices. In addition, in this study, yield potential data were aggregated to county level and spatial heterogeneity within the county area was not accounted for. In heterogeneous landscapes, this confines the explanatory power for an assessment of specific relationships between land rent characteristics and soil quality. Nevertheless, the county-level analysis in this paper serves to identify the divergent and complementary cases for further detailed analysis of complex landowner and leaseholder relationships and their influence on the protection of soil quality. This could be the starting point for urgently needed research on tenancy as a soil governance mechanism or tool to enhance soil management towards sustainability.

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# Sustainable Land Use, Soil Protection and Phosphorus Management from a Cross-National Perspective

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**Abstract:** The scarcity of phosphorus (P) is a global concern that is not restricted to western industrialized nations. Until now, most countries in the world are highly dependent on importing mineral P fertilizers for agriculture. The industrialized nation of Germany, the emerging economy of Costa Rica, and the developing country of Nicaragua are examined with regard to their legislation in the field of environmental protection and agriculture, in particular with regard to soil protection and fertilizer law. Based on the structure of agriculture in each country, control weaknesses in legislation in the individual countries, which is largely determined by command-and-control law, are identified and compared. It becomes clear that soil protection in all three countries has not yet been adequately standardised in law and at the same time the efficient use of organic or recycled P fertilizers instead of (finite) mineral P fertilizers is inadequately regulated. In particular, frugality, i.e., the strategy of lower (and not only more efficient) consumption of P fertilizers, has so far played no regulatory role in land-use governance.

**Keywords:** phosphorus; legal comparison; governance; sustainable agriculture; fertilization; soil protection; Germany; Costa Rica; Nicaragua

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## 1. Phosphorus and Sustainable Agriculture-Problem and Methodology

Long-term availability of phosphorus (P), an essential nutrient for plants, animals, and humans, is a fundamental prerequisite for ending hunger worldwide by 2030 and achieving global food security, as intended by the United Nations Sustainable Development Goals (SDGs) [1]. In order to ensure the nutrient supply of plants with P, mineral P extracted by mining is still being used and to an increasing extent worldwide. In 2017, an estimated 263,000 tons of phosphate rock were mined worldwide, more than in any year before [2] (p. 123). In this context, it is interesting to take a comparative look at countries with very different agricultural and legal system requirements. Particularly, the research is intended to be an interdisciplinary study into sustainability research from a humanities perspective. Existing legal approaches of countries that differ in geographic and socioeconomic terms are examined, focussing on P resource conservation and the protection of related natural resources, such as soil, water, climate, biodiversity. The research aims to identify specific but above all recurring shortcomings in legislation as reasons for the unsustainable use of the aforementioned resources. Therefore, this comparative study can be seen as a first step to further develop effective governance for the sustainable use of P in agriculture and the protection of natural resources on national, supranational or international levels that are able to overcome the identified legal inefficiencies.

All countries in the world face the same future challenge: to develop sustainable agriculture systems which produce a sufficient amount of healthy food and at the same time preserve natural resources. SDGs have a universal character and apply equally to all countries [1] (p. 3); Nicaragua as a developing country, the emerging economy Costa Rica, and Germany as a typical industrialized nation have been selected for the legal comparison. While the use of mineral P fertilizers is tending to increase in Costa Rica and Nicaragua, it is rather stagnating at a medium level in industrialized countries such as Germany [3,4]. In 2015, Costa Rica had an average mineral P use per area of cropland of 41.23 kg $P_2O_5$/ha, well above the global average of 30.1 kg $P_2O_5$/ha. Nicaragua, on the other hand, is far below the global average at 9.74 kg $P_2O_5$/ha—although the climatic and biophysical conditions are largely the same as in Costa Rica—while Germany's consumption of 23.87 kg $P_2O_5$/ha is slightly below the global average [3]. For this reason, there is also a special interest in this comparative analysis of countries. The deposits of phosphate rocks, however, are firstly finite. There is a limit in the economic sense, i.e., phosphate reserves are (operationally) economically extractable according to the current state-of-the-art and at today's prices. According to data from the U.S. Geological Survey from 2017, the statistical range of phosphate reserves, which is the quotient of available reserves and the extracted phosphate rock, is 266 years [2] (p. 123). Secondly, phosphorus is limited to only a few regions of the earth, which results in an import dependency in the vast majority of countries [5–7]. This import dependency of P is already problematic because the highly monopolized market structure impedes effective price control for raw phosphates [8,9].

In the event of external shocks, such as the 2008 food crisis, the price of mineral P fertilizers may rise unexpectedly and disproportionately [10]. Particularly in developing countries and emerging economies where farmers tend to be poorer, price fluctuations are more difficult to deal with; as such, in a worst-case scenario, the supply of P to plants cannot be guaranteed and the risk of crop losses increases due to a lack of alternatives [11]. Above all, geopolitical risks with regard to export countries that are difficult to predict also endanger the secure supply of P fertilizers in industrialized countries. At present, a medium supply risk is assumed for P due to geopolitical instability in Morocco, one of the dominant exporters in the market [12].

In addition, the use of mineral P fertilizers in agriculture is directly linked to negative environmental impacts such as soil degradation, biodiversity loss, and global climate change. Firstly, heavy metals such as cadmium (Cd) and uranium (U) are increasingly being introduced with the mineral P fertilizer into the soil, which causes potential soil degradation [13]. Secondly, the predominant use of mineral fertilizers can lead to a long-term loss of soil organic matter. This is particularly true in connection with intensive, monocultural soil management with rapid crop rotation, lack of intercropping and continuously high removal rates of biomass from the field [14] (p. 45), [15]. Along with the loss of soil organic matter, soil biodiversity, water infiltration rate, and natural soil fertility decrease simultaneously [14]. At the same time, the lower water absorption capacity of the soil increases the risk of erosion, causing nutrients and pollutants to be more easily discharged into neighboring ecosystems, thus accelerating the eutrophication of water bodies [16–20]. Due to the loss of soil organic matter, the sink function of the soil as a global carbon store decreases as well, so that the potential to help mitigate global climate change is reduced [21]. Finally, the soil's ability to cope with crises—e.g., due to extreme weather events that are likely to occur more frequently in the future—is severely reduced [22–24]. The potentially mutual reinforcement of various environmental problems, which are also linked to fertilization, is already becoming clear. In the future, managing the soil sustainably also means circulating nutrients like P and replacing mineral P fertilizers obtained from mining with fertilizers from organic materials or recycled P fertilizers, preferably regionally produced using renewable energy [25–28].

On this basis, this paper asks to what extent legislation has so far effectively addressed this situation. Supported by a brief analysis of the natural scientific data, a methodical and comparative legal analysis of deliberately selected contrasting countries is carried out. Legal texts from different legislative fields are compared, whereby the basis for text comprehension are legal interpretation methods as practiced worldwide (the focus here is on the literal sense and systematics of legal norms) [29] (pp. 83–95). Comparative legal studies are a recognized method for gaining scientific knowledge [30,31]. The legal comparison provides "insights into the interrelationships, processes, causes and recurrent patterns of reality" [30] (p. 1084). In this way, lessons can be learned from the Latin American legislation [30] (p. 1084). In order to reflect the different contextualization of Latin American legislation [31] (p. 187), expert interviews were conducted in Nicaragua and Costa Rica during a three-month research stay from September to December 2016. Eight interviews were conducted in Costa Rica and six in Nicaragua with stakeholders from the agricultural administration, universities, agricultural associations and farmers. In particular, the openly structured interviews provided different perspectives, which served to better assess the actual implementation and application of existing legislation. The evaluation of the content of the interviews was therefore qualitative [32] and served as a supplement to the legal text analysis.

If the possible, ecological regulatory effects are considered, thus further extending the pure legal comparison in substance by aspects of legal effectiveness, control and governance research. This is limited in the present case to the extent to which the legal requirements laid down fit the officially pursued, overall objectives, in particular of international environmental law [29] (pp. 74–83).

## 2. Key Characteristics of the Agricultural Sector in Germany, Costa Rica, and Nicaragua

In German agriculture, the largest share of added value (almost 50%) is achieved through intensive livestock farming [33] (p. 8). Increasing export surpluses are generated for all types of meat [34]. An area-bound livestock farming—which would facilitate a recirculation of P—is mandatory in organic farming only (Art. 4 and Art. 14 Para. 1 lit. (d) No. (i) Regulation (EC) No. 834/2007). Although the total share of organic farming in Germany accounts for 7.5%, not all have integrated livestock farming [35] (p. 46). In total, only 14% of all agricultural holdings are integrated farms, which combine agriculture and livestock farming in different proportions [33] (p. 8). The number of farms fell by 40,800 to 280,800 between 2010 and 2015, with a particularly sharp decline in small livestock holdings [36]. In regions of intensive livestock farming, large quantities of animal feed must be imported, while remaining manure surpluses place a heavy burden on water quality (The European Commission has already initiated an infringement proceeding (Case C-543/16) against Germany due to high nitrate inputs into water bodies and groundwater bodies). Germany imports around 80 million hectares of virtual land each year for food and animal feed and thus indirectly tons of P [37]. Due to the overall increase in land use pressure, permanent grassland (29% of agricultural land) is also predominantly intensively used and fertilized, with negative consequences for soil, water, biodiversity and climate protection [38] (p. 9). Even though on average, P balance surpluses in German soils have been declining since 2000 by 5 kg P/ha annually, there are still nutrient hotspots often linked with spatially concentrated, intensive livestock farming. These hotspots stand in contrast to regions with nutrient deficits mainly due to low livestock density.

In the emerging economy of Costa Rica, about 47% of the total land area, which with 51,100 $km^2$ roughly corresponds to the size of Lower Saxony, is currently used for agriculture [39] (p. 24). Agriculture is particularly oriented towards exports. Currently 64% of agricultural land is used exclusively to grow export crops such as coffee, palm oil, sugar cane, bananas and pineapples [40] (p. 19). In particular, the small landholder subsistence economy has lost importance in favour of the export economy [41] (p. 7), [42] (p. 3). The number of agricultural holdings decreased by around 60% between 1984 and 2014, reaching 93,017 in 2014 [39] (p. 33), [43] (p. 185). Less than 5% of farms are dedicated to the production of basic foodstuffs [39] (p. 38). Cereals, beans and rice—at the expense of food security in the country—therefore largely need to be imported from the world market [39] (pp. 171–173). At the same time, Costa Rica is the world's leading exporter of pineapples and, with 63,383.2 kg pineapple production per hectare in 2014, achieved the highest yield in Latin America on average [44]. An extremely high use of mineral fertilizers (and pesticides) characterizes the intensive, monocultural cultivation of tropical fruits and is therefore an important driver for soil degradation and the destruction of neighboring ecosystems [45–47]. Accordingly, compared to Germany and Nicaragua, Costa Rica has the highest average consumption of mineral P fertilizers per hectare of agricultural land, which is accompanied by one of the highest levels of chemical pesticide usage in the world [3,48]. Pastures (43% of the agricultural area) are also increasingly intensively used and fertilized, using mainly mineral fertilizers. Costa Rica's soils tend to have a deficiency of plant available P. This is particularly true for soils of volcanic origin or deeply weathered red tropical soils, with active iron and aluminium oxides restricting plant available P [49] (p. 8), [50].

In the developing country Nicaragua, agriculture has traditionally been of great economic importance [51,52]. The share of agricultural products in Nicaragua's total exports from January to July 2017 was over 80% and is planned to be increased in the future [53]. The main agricultural export products are coffee, beef and sugar [54] (p. 4). Still, in terms of labor productivity and average agricultural yield per hectare, Nicaragua ranks last in Central America [55] (p. 36). Accordingly, the usage of mineral P fertilizer is the lowest in the countries compared in this study, even though average P use per area of cropland showed a rising trend in 2014 and 2015 [3]. Agricultural land is still distributed among more than 300,000 producers [56], of which over 80% are small farmers, who cultivate less than 5 ha of land and use mineral P fertilizers according to their financial abilities and depending on risk factors such as local weather conditions [57] (p. 69), [58]. In 2014, during the rainy season (May to November), up to 50% less rain fell locally than in previous years [59] so that many small farmers refrained from using expensive mineral fertilizers or changed their production (e.g., from peanuts to millet and sesame, which require less mineral P fertilizer) [60]. However, above all, uncertain land rights allow the almost unimpeded spread of industrial palm oil, sugar cane or peanut production by major investors because small scale farmers cannot adequately defend their ownership of land (which is partly only customary and not titled or registered in the cadastre) [57,61,62]. This industrial production is regularly accompanied by a high consumption of mineral fertilizers [62] (p. 4). Extensive livestock farming, which is characterised by extremely high land consumption, is spreading almost unchecked in Nicaragua as well [62] (p. 5) [63], even though the majority of pastures are not (yet) additionally fertilized. Nonetheless, livestock farming is, once again, largely decoupled from plant production at the expense of soil, forests, biodiversity and climate protection [63]. Overall, about 40 tons of soil per hectare are eroded every year due to farming methods that are not adapted to the site in Nicaragua [62] (p. 5). Regarding P, Nicaragua's tropical soils tend to be undersupplied with plant-available P [64], as is the case with Costa Rica.

## 3. Results from the Legal Comparison

### *3.1. International Level*

International, openly formulated, legally non-binding declarations of intent—such as the SDGs—dominate with regard to the sparing use of (P) resources in agriculture and soil protection. A binding international agreement explicitly aimed at limiting the use of mineral P fertilizers in agriculture and using P more efficiently does not exist. Nevertheless, on the basis of internationally binding agreements on environmental protection and on the basis of human rights obligations, the importance of improved P management in agriculture can be determined [29] (pp. 217–223). Germany, Costa Rica, and Nicaragua have ratified the following agreements:

- The Convention on Biological Diversity (CBD) [65], which came into force on 29 December 1993;
- The United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa (UNCCD) [66], which came into force on 26 December 1996;
- The Paris Agreement (PA) [67,68], which came into force on 4 November 2016.

Art. 1 of the CBD pursues the legally binding objective of conserving biological diversity and using its components sustainably. P losses from agricultural used soils and their leakage to inland and coastal waters are one major driver for the eutrophication of water bodies [69], thus restricting aquatic biodiversity [70,71]. In addition, soil biodiversity can be significantly decreased by intensive farming methods, which are accompanied by a high use of mineral (P) fertilizers and pesticides [72,73]. Thus, controlling the use of (mineral) P fertilizers in order to combat eutrophication of waterbodies and to preserve soil biodiversity becomes a major issue to fulfil the CBD. The UNCCD provides for combating desertification and mitigating the effects of drought through effective action at all levels to contribute to the achievement of sustainable development in the affected areas [66] (p. 6). Nicaragua and Costa Rica are among the affected countries specifically addressed by the UNCCD. The establishment of a sustainable, site-adapted, circular economy requires congruent agricultural systems to be generated for P [74]. Therefore, protecting the soil and preventing nutrient and pollutant leakage into neighboring ecosystems is directly linked to the fulfilment of these two international agreements. In particular, the circular economy concept in agriculture aims to stimulate the rational use of organic fertilizers from the farm or recycled from biowaste or other secondary raw materials [28] and thus helps to preserve biodiversity and healthy soils with a high natural soil fertility.

The PA obliges the international community pursuant to Art. 2 para. 1a PA to limit global warming to "well below" 2 °C (and if possible even to 1.5 °C) compared to pre-industrial levels; however, this requires globally timely and drastic emission reductions with the objective of achieving zero emissions on the one hand [25], [26] (p. 6), [27] (p. 36), [75] and the preservation of the soil's sink function as a carbon reservoir [20] on the other hand. Hence, a rather short-term exit from fossil fuels is also necessary in the agricultural sector [76]. Worldwide, the share of greenhouse gas emissions from agriculture, forestry and other land use (AFOLU) is about a quarter [27] (p. 47), [76]. Regarding mineral P, mining and transport are directly linked to the consumption of fossil fuels [77]. However, the climatic relevance of mineral fertilization is further exacerbated by the energy-intensive production of nitrogen (N) [78] (p. 74), [79], particularly because N is often applied in combination with P and/or potassium (K) as NPK fertilizer to the soil. In Germany, for instance, over 90% of mineral fertilizers are sold as complex fertilizers [80].

Most importantly though, zero-emissions and the preservation of biodiversity, water and soils require a drastic reduction of animal food production and consumption [73,81]. According to the Food and Agriculture Association (FAO) 33% of total arable land is used exclusively for animal feed production [82] (p. xxi). Raschka et al. even estimate the share of total arable land for the production of animal feed to be 71% in their study [83] (p. 21). However, the mostly monocultural, industrial feedstuff production is usually combined with a high mineral (P) fertilizer input [84]. According to the International Fertilizer Association, due to "firm demand from the livestock sector" [84] (p. 1) oilseed production will increase in the future and is therefore one driver for the expected increase in global demand for mineral P [84] (p. 2). Thus, by reducing demand for feedstuff, e.g., soy, mineral P fertilizer consumption may be reduced as well. Notwithstanding this, due to a minimised livestock production required in the future, the supply of organic fertilizers (including P) will be significantly restricted as well. This is especially the case since the general transformation of the energy sector towards renewables is also combined with the use of animal manure for bioenergy production [85]. Thus, in order to prevent a higher demand for mineral P fertilizers in the aftermath, mixed farming models with an area-bound livestock farming, that are optimally adapted to the site-specific conditions [86] (p. 160) and include practices like cereal/legume intercropping [87] that enhance natural soil fertility must be stimulated by appropriate policy instruments [88], [89] (pp. 40, 135). However, in order to achieve the necessary worldwide reduction in meat consumption, which, as has been shown, is closely linked to the challenge of closing P fertilizer cycles in the future, would require behavioural changes i.e. frugality, and must be triggered by appropriate policy instruments. The requirement for an overall reduction in livestock farming that is also optimally adapted to the area, is not contradictory, since intensive livestock farming systems keep livestock numbers far beyond the locally available farmland capacity (see also Section 2 the case of Germany) [77]. Overall, this indicates a total revision of previous agricultural concepts, which were rather based on further intensification and specialisation instead of site-adapted integrated crop-livestock systems [71,88,90].

### *3.2. Constitutional Anchoring of Environmental and Resource Protection Law at the National and European Level*

The adoption of frugality as well as efficiency (the more efficient use of resources) and consistency (the reuse of resources) includes the un-popular measure of lowering consumption and is thus politically complex. However, whether or not natural (P) resources must be sustained is not left to the political discretion of states. Besides a legal obligation to prevent climate change, a duty to prevent the loss of biodiversity and the degradation of soil and water pollution can be derived also from fundamental rights [29] (pp. 255–262). In particular, among the prerequisites for a free life in dignity are the sufficient availability of water, food and air [29] (pp. 255–262). Since P is an essential nutrient for plants, animals and humans and inappropriate P fertilization causes negative effects on the environment (eutrophication of water bodies, soil degradation, e.g., due to heavy metal inputs) the usage of P in agriculture is therefore linked to the fulfilment of fundamental rights. This applies in particular if intensive agricultural practices combined with a high mineral P fertilizer input could ultimately lead to a collapse of the Earth system by endangering its physical foundations, such as a stable climate, healthy soils, sufficient water, and biodiversity [29] (pp. 223, 328–330), [91].

Therefore, it has been shown repeatedly that in international, European, and national law, a relevant constitutional protection results from fundamental rights considerations regarding the right to life, health and a minimum subsistence level including a right to food [29] (pp. 194–375), [92–94]. However, legal practice has largely ignored this so far, since the problems caused by P have not yet been recognized. Among the less stringent objectives such as in the German constitution (Art. 20a GG) or the EU primary law in Art. 37 of the EU Charter of Fundamental Rights (CFR), and Art. 11 of the Treaty on the Functioning of the European Union (TFEU) [95] (p. 93), [96] (p. 173) statements such as those contained in Art. 191 TFEU (objective of prudent and rational utilisation of natural resources) can be found. However, no tangible restrictions on the use of scarce resources such as P or the soil exist.

Article 50 of the Costa Rican Constitution lays down the "right to a healthy and ecologically balanced environment" together with the right of individuals to report violations to the environmental tribunal. According to the 2015–2018 National Development Plan, the right to food and nutrition sovereignty is to be written into the constitution [97] (p. 291). Since fundamental environmental obligations have so far tended to be overlooked by a variety of states, it remains to be seen whether this will change anything in reality. Costa Rica's strong export orientation in particular runs counter to the right to food sovereignty, defined as "the right of people to produce, distribute and consume healthy food in and near their territory in an ecologically sustainable manner" [98] (p. 588).

The Nicaraguan constitution of 1987 was last reformed in 2014, enabling the reelection of the president (Daniel Ortega). At the same time, Art. 60 of the Nicaraguan Constitution was extended [99]. Based on Art. 60, the obligation arises for all inhabitants to maintain a clean environment and to protect it and its natural resources. In addition, "Mother Earth" (in Spanish "madre tierra", where "tierra" can have two meanings "world" and "soil") and all life-sustaining natural processes, thus also a healthy soil, next to the explicitly mentioned biodiversity is of particular importance. The earth is attributed dignity as an independent, living object. "It is to be loved, to protected and to regenerated" (Art. 60 Nicaraguan Constitution). The Nicaraguan people must adopt consumption and production practices that guarantee the vitality and integrity of the earth, with particular emphasis on the integrity of ecosystems and biodiversity. The social equality of people and responsible consumption based on solidarity and good coexistence must be achieved in accordance with Art. 60 of the Nicaraguan constitution. At the same time, Art. 60 of the Nicaraguan constitution refers to the Universal Declaration of the Common Good of the Earth and Humanity [100]. This Declaration (Declaración Universal del Bien Común de la Tierra y de la Humanidad) has been drawn up as a supplement to the Universal Declaration of Human Rights. The need to reduce means of production and goods of consumption, to reuse products and to collect and recycle waste is emphasized), which was signed by Nicaragua on 6 February 2010 (as the first country to do so) but has not yet become valid internationally due to a lack of states that have ratified the declaration [101]. Art. 102 of the Nicaraguan constitution obliges the state to protect natural resources and to use them rationally, but according to the national interest.

With regard to resource protection and the use of natural resources, it is interesting that although the obligation to protect resources has a human rights basis (due to the binding character of international treaties on human rights and the respective constitutions) it is still ignored more or less everywhere. With regard to the fact that the European and the German jurisdiction accepts environmental fundamental rights in theory but do not draw any consequences from these rights in reality, see Ekardt 2018 [102] and Calliess 2001 [93]. However, it can be derived directly from Art. 60 of the Costa Rican Constitution and was incorporated into Art. 102 of the Nicaraguan constitution as well. Furthermore, Nicaragua is the only country that has included the necessity to implement frugality in its constitution and therefore is very progressive in this respect. Due to the lack of enforceability by the courts in Nicaragua a targeted practical implementation of all this is again not discernible.

### *3.3. Environmental and in Particular, Soil Protection Legislation*

#### 3.3.1. EU and Germany

In addition to the above-mentioned binding international objectives in the climate and biodiversity sector, EU agricultural and environmental legislation has a major influence on national agricultural practices and thus on P use and the level of environmental protection in the member states. First, the EU Nitrates Directive [103] requires member states to encourage Good Agricultural Practices and to adopt action programmes in order to reduce water pollution from N compounds from agricultural sources and to prevent further water pollution [104] (p. 10). Good Agricultural Practices include inter alia periods during which fertilizers should not be applied to agricultural land or rules on procedures for the application of fertilizers (Annex II of the Nitrates Directive). In addition to the mandatory rules on nitrate fertilization, some EU member states, such as Ireland and the Netherlands, have also introduced limits for P. This has improved fertilization practice in some areas in recent decades, albeit with large differences between EU member states in both the P and N-balance [105] (pp. 4–5). Nevertheless, P is not specifically the focus of the directive. Besides the EU Nitrates Directive is an important instrument for implementing the EU Water Framework Directive (WFD) [106]. Art. 4 para. 1 WFD obliges EU Member States to achieve a good ecological and chemical status of surface waters and a good quantitative and chemical status of groundwater bodies by 2027 at the latest. The WFD also mentions P compounds as pollutants for water bodies [106] (p. 46), although, a clear reference to P fertilization is also missing here. P has been included in the WFD list of agri-environmental indicators describing the main impacts on water quality. However, due to limited data availability and methodological difficulties, the indicator is not yet considered applicable.

A further key component of European agricultural legislation is the Common Agricultural Policy (CAP). To receive direct payments within the framework of the first pillar of CAP, farmers have to comply with cross-compliance rules. According to Regulation (EU) No. 1306/2013 [107], these rules include standards for good agricultural and environmental conditions (GAEC) which potentially contribute to the reduction of P losses in agriculture [108]. For example, standards for better soil management reduce soil erosion and the loss of soil organic matter and thus minimize P losses [109] (p. 15). The regulations, however, are not explicitly aimed at P and there is no obligation for farmers to limit P use within the cross-compliance system [110] (p. 26). In fact, cross-compliance is merely a basic requirement for environmental and resource protection, which is not sufficient to develop truly sustainable and circular economy based agricultural systems. Hence, most subsidies continue to be paid for unsustainable farming methods and thus the CAP does not contribute adequately to the protection of natural resources such as soil or biodiversity [111,112]. This continues to remain valid after the reform of the CAP in 2013 [111,112]. The Greening introduced in this context aimed to make the EU agricultural sector more environment-friendly by having direct payments to farmers more closely linked to environmental services, in particular: crop diversification, the maintenance of permanent grassland, and the creation of ecological focus areas (Art. 43 para. 2 Regulation (EU) No. 1307/2013) [113]. But it is up to the EU member states whether or not they use their considerable scope for implementation of more sustainable agricultural practices. In particular, the political will of the EU member states strongly influences the design of agricultural environment programmes within the framework of rural development policy [114]. The second pillar of CAP can certainly contribute to reducing P losses in agriculture if an appropriate focus is set. So far, this is still lacking. In addition, the second pillar is chronically underfunded [115,116]. The extent to which the CAP can develop an enhanced influence on more sustainable P management in the future will therefore depend primarily on its further revision by 2020.

In addition to the national implementation acts of the CAP, various areas of environmental law show potential impact on the P problem in Germany. First of all, the Federal Nature Conservation Act (BNatSchG) [117] in § 1 para. 3 No. 2 BNatSchG initially stipulates that soils must be preserved so that they can fulfil their ecosystem functions. The BNatSchG is concretised by the laws for the protection of soils, water and air among other sector-specific laws [118]. However, the water protection provisions of the Federal Water Act [119], which implements the objectives of the European Nitrates Directive and the WFD, as well as the Federal Emission Control Act [120], which implements the European Directive on the reduction of national emissions of certain atmospheric pollutants (NEC Directive) [121] and the Air Quality Directive [122], are not applicable to agricultural land use. The same applies to the Federal Soil Conservation Act (BBodSchG) [123]. In the absence of an European Soil Framework Directive [124–126] the BBodSchG aims at the protection and restoration of sustainable soil functions (§ 1 BBodSchG).

With regard to agricultural soil use, the principles of Good Agricultural Practice are introduced in § 17 BBodSchG. Good Agricultural Practice includes, for example, site-adapted soil cultivation, and the promotion of biological activity through appropriate crop rotation management. Yet according to § 3 para. 1 BBodSchG, soil protection law is subsidiary and it only applies if the waste legislation, the sewage sludge ordinance, the fertilizer and plant protection legislation, the construction and planning law and the emission protection legislation, do not already regulate the effects on the soil. This makes the fertilizer law primarily relevant for P inputs (see Section 3.4), while subsidiarity keeps the steering effect of soil protection and other environmental laws with regard to P and sustainable land use low.

#### 3.3.2. Costa Rica

Already in the Basic Act on the Environment No. 7554 of 1995 [127], with the objective of maintaining a healthy and ecologically balanced environment, general requirements for the protection of biodiversity (Art. 46 ff.), forests (Art. 48 ff.), air (Art. 49), and water (Art. 50 ff.) are determined. In addition, requirements for the protection of soils are made (Art. 53 ff.). According to Art. 53a Law 7554, a balance between the natural potential for soil use and the economic production capacity of the soil should be established. Soil management practices that cause erosion (and thus also promote the discharge of P into neighboring ecosystems) or other forms of soil degradation must be controlled in accordance with Art. 53b Law 7554 as well as the use of chemical and radioactive substances (Art. 60f Law 7554). Agricultural practices that contribute to soil and water protection must be encouraged (Art. 53c Law 7554). The principles laid down by Law 7554 serve as a framework for the sector-specific laws and their implementing ordinances. An important tool is the Environmental Impact Assessment (EIA) for new projects that show a potentially negative impact on the environment. According to the definition in Art. 3 No. 3 ICW No. 16 of the Implementing Ordinance to Law 7554 [128], however, "new projects" in agriculture are only given in the case of land use changes. The purchase of small, formerly agriculturally used areas and their conversion into large, monoculturally cultivated areas, as is often the case with industrial pineapple cultivation, is not covered by this. Therefore, no steering effect can be achieved with regard to sustainable agricultural land use, in particular a possibly lower use of mineral (P) fertilizers and pesticides is not encouraged.

The Soil Conservation Act of 1998 No. 7779 [129] further specifies the regulations for sustainable land use and the restoration of degraded soils. Art. 2 Law 7779 provides for a regular inventory of soils to balance the natural soil potential and economic production capacity of the soil. Agroecology is also to be promoted in order to reconcile agricultural production with the protection of resources, soil, and water [130,131]. The Ministry of Agriculture and Livestock (MAG) should create a national land management and soil protection plan with binding guidelines on agricultural land use (Art. 7 ICW Art. 11 Law 7779). Every two years, the national plans are to be reviewed and adapted to current circumstances (Art. 14 Law 7779). Art. 12 of Law 7779 specifies the objectives of the national land management and soil protection plan. The aim is to achieve: an increased vegetation cover and water infiltration rate; an improved runoff regime and reduced soil contamination; a soil management system that promotes natural soil fertility by maintaining the organic matter of the soil.

These objectives are conducive to avoiding soil degradation, reducing nutrient leakage, and thus minimise the need for (mineral) P fertilizers in agriculture [132]. In addition to the national soil protection plan, regional soil protection and restoration plans are to be drawn up (Art. 15 Law 7779). Their objectives according to Art. 16 Law 7779 are: to define sensitive soils based on water catchment areas, to submit proposals for the best possible type of soil use, to carry out basic soil investigations for the soil cadastre, and to develop strategies that ensure adequate soil use in each case.

According to Art. 19 Law 7779, the practices for land use, which are to be made binding by the regional soil plans, must also include the handling of (mineral) fertilizers and pesticides in accordance with the technical recommendation of the MAG as well as strategies for organic fertilization and erosion control. MAG together with the Ministry of the Environment and Energy (MINAE) are also responsible for regulating and controlling agricultural inputs and machines and equipment used (Art. 30 Law 7779). It would therefore be conceivable—given the sensitivity of the site due to a high probability of soil erosion or the threat of nonreversible soil degradation—to restrict or even prohibit the use of rapidly soluble mineral (P) fertilizers (and pesticides) on the basis of the binding regional soil protection and restoration plans.

However, research into the implementation and application of the Soil Protection Act has shown that neither the national land management and soil protection plan nor regional soil protection and restoration plans—with the exception of the central region of Costa Rica—have been fully developed to date [133]. A steering effect with a view to a site-adapted agricultural land use and a reduced use of mineral P fertilizers thus cannot be achieved.

#### 3.3.3. Nicaragua

The Basic Act on the Environment and Natural Resources No. 217 of 1996 [134,135] pursues the overall objective of maintaining a clean environment (atmosphere, biodiversity, soil, and water) and protecting natural resources (Art. 1 Law 217). Soils should be used according to their natural conditions, such as physical and chemical properties and the resulting production capacity, while maintaining their natural balance (Art. 105 Law 217). Practices that promote soil erosion or degradation or negatively affect the topographical and geomorphological properties of soils should be avoided. In case of severe land degradation, the Ministry of Agriculture (MAG), in consultation with the Ministry of Environment and Resources (MARENA) and the governments of the autonomous territories of Nicaragua, may designate soil protection areas and restrict their use (Art. 107, Law 217). However, this optional provision applies only if land degradation has already occurred. Nicaragua does not have a sector-specific law for soil protection and thus also not for the prevention of soil degradation through agricultural use.

To achieve the objectives laid down in the Law 217, a national environmental plan, the designation of protected areas and national parks, environmental impact assessments, payments for ecosystem services, or subsidies from the National Environmental Fund [135], are named as instruments (Art. 11 Law 217). The Environmental Fund has been linked to existing sector-specific laws such as the National Forest Act [136] or the National Water Protection Act [137]. Since there is no specific national soil protection act, no corresponding connection can be established. As a consequence, with regard to soil protection, no concrete implementation, control or sanction mechanisms are formulated, although the obligation for sustainable use of the soil has been constitutionally reestablished. Thus, the principles of soil protection laid down in the constitution are not transposed into simple national law and therefore remain ineffective.

#### 3.3.4. Conclusions from a Comparative Legal Perspective

The legal studies of environmental law in the individual countries show that environmental and specifically soil protection law is de facto inadequate in all three countries. In particular, soil protection is severely neglected in Germany. Firstly, because unlike in the field of water protection, a European Soil Framework Directive does not exist [138]. Thus, national soil protection law applies, which however is subsidiary to various sector-specific-laws, such as the fertilizer law, that hardly protects agricultural soils due to a traditionally strong focus on economic productivity, disregarding the natural utilisation potential and sensitivity of soils [108] (see also Section 3.4). Secondly, European CAP has a major influence on practices of land management by German farmers and their (P) fertilizer use but is not yet sufficiently oriented towards environmentally friendly and resource-conserving agricultural practices. Other European directives only refer to individual pollutants such as N or do not consistently include appropriate agricultural land use in order to protect the soil or to encourage recirculation of the scarce resource P in the future.

In Costa Rica, a lack of implementation of the Soil Conservation Act renders soil protection law ultimately toothless, while other environmental protection provisions of the Basic Act on the Environment do not explicitly include agricultural land use. The corresponding preference for intensified agricultural production over soil protection becomes particularly evident in the recently created exemption for agriculturally used soils as new projects within the framework of the EIA However, the same can be observed for the EIA at the European level, which has been established since 1985 [139] and imposes no requirements for the articulation of alternatives to the project under consideration in case of agricultural land use [140] (p. 168) and the Nicaraguan EIA which does not include agricultural land use from the outset [141,142].

In Nicaragua, the overarching objectives for soil protection have not yet been sufficiently specified and thus cannot be applied. Soil protection measures can only be considered once harmful soil changes have already occurred—and are not even then mandatory. Agricultural land use, including (P) fertilization, therefore does not have to follow the maxim of soil protection.

It can be concluded that although the laws on soil protection are designed in different manners or are implemented to different degrees in the individual countries, soil protection is ultimately not lent the attention it deserves. In particular, agricultural land use and the use of (P) fertilizers as a major potential threat to soil quality are not consistently incorporated in soil protection legislation.

### *3.4. Fertilizer Legislation*

#### 3.4.1. Product-Related Fertilizer Legislation

Next, specific fertilizer legislation is considered. Mineral fertilizers require registration and approval in accordance with product-related fertilizer legislation. In Germany, the Federal Ministry of Food and Agriculture (BMEL) is entrusted with the approval of new fertilizers. The requirements of the Fertilizer Ordinance, DüMV [143] apply. The DüMV regulates the authorisation of fertilizers which are not designated as "EC-fertilizers", which are all fertilizers that are regulated by the EC Fertilizer Regulation 2003/2003 [144] (§ 2 Para. 1 DüMV). These must correspond to a type of fertilizer approved by the ordinance (§ 3 Para. 1 DüMV) and must comply with requirements regarding nutrient and pollutant contents. For fertilizers from waste streams, corresponding quality and hygiene regulations from special laws such as the Sewage Sludge Ordinance (AbfKlärV) [145] or the Biowaste Ordinance (BioAbfV) [146] apply. Furthermore, the new AbfKlärV requires larger sewage treatment plant operators to recover P from sewage sludge prospectively (§ 3 AbfKlärV). Mineral fertilizers can also be marketed under the already mentioned EC Fertilizer Regulation 2003/2003 [144], which is currently being extensively amended, inter alia, to include and promote fertilizers from organic materials, recycled bio-waste or recycled P from sewage sludge [147].

In Costa Rica, registration for mineral fertilizers is handled by the State Plant Protection Agency (SFE) in accordance with the Plant Protection Act No. 7664 [148]. In Nicaragua, the Institute for the Protection and Health Monitoring of the Agricultural Sector (IPSA) is responsible for the registration and quality control of agricultural inputs in accordance with the Basic Law on Animal and Plant Health No. 291 [149] as an independent institution (Art. 2, 37, Law 291). In addition, a Central American technical implementation regulation [150] exists, which regulates basic requirements for the registration of fertilizers in Costa Rica, Nicaragua, El Salvador, Guatemala, and Honduras.

Mineral P fertilizers extracted from mines are increasingly contaminated with heavy metals like U and Cd [151]. While no limit values exist for U, certain maximum values per kilogram of $P_2O_5$ are specified for Cd (see Table 1).

**Table 1.** Limit values for Cd in the case countries.

| Region | Regulation | Limit Value |
|---|---|---|
| Europe | EC 2003/2003 | no limit for Cd |
| Germany | DüMV | 50 mg/kg $P_2O_5$ |
| Central America | RTCA 65.05.54:09 | no limit for Cd |
| Costa Rica | RTCR 485:2016 [152] | 80 mg/kg $P_2O_5$ |
| Nicaragua | RTCA 65.05.54:09 | no limit for Cd |

In particular, phosphates from sedimentary phosphate deposits usually contain an average value of over 60 mg Cd/kg $P_2O_5$, with maximum values of over 80 mg Cd/kg $P_2O_5$ possible [153–155]. There is a relatively high risk of Cd being transferred to the plant or groundwater, especially in combination with Cd concentrations above 60 mg Cd/kg $P_2O_5$, low pH values (below 6.5) or low organic matter content in soil (below 1%) [153]—soil characteristics that regularly occur in deeply weathered tropical soils. Otherwise, the probability that Cd accumulates in the soil in the long-term increases [156].

Against this background, only the existing limit value of 50 mg Cd/kg $P_2O_5$ according to the German DüMV could displace most mineral P fertilizers from the market and thus indirectly promote organic/recycled P fertilizers. However, this potential steering effect is counteracted by the fact that the DüMV only applies to the marketing of fertilizers which are not declared as "EC-fertilizers" (§ 2 Para. 1 DüMV). The limit value of 80 mg/kg $P_2O_5$ decided in Costa Rica in 2016, on the other hand, is to be regarded as comparatively high and therefore still permits the usage of most mineral P fertilizers. In Nicaragua, there is no steering effect with regard to the limited use of mineral P fertilizers due to the lack of limit values. As a result, the use of mineral P fertilizers has not yet been significantly restricted in any of the three countries by qualitative approval requirements.

In the context of the current amendment process of Regulation EC 2003/2003, setting an EU-wide limit for Cd in mineral fertilizers—after its failure in 2003 [157]—is again discussed within the Circular Economy Package [28]. The European Parliament supports the proposal to introduce a limit value for Cd of 60 mg/kg $P_2O_5$ and to reduce it to 40 mg/kg $P_2O_5$ after six years and to 20 mg/kg $P_2O_5$ after 16 years [158]. Nonetheless, the long transition periods do not reflect the need for rapid change in the agricultural sector, which is unlikely to come of its own accord, as long as mineral P fertilizers continue to be available at reasonable prices. The EU-wide promotion of P fertilizers from secondary sources such as organic or recycled P fertilizers intended by setting limits for Cd must take place more quickly, especially in order to meet the international objectives in the area of climate and biodiversity protection. It remains to be seen whether the amended European Fertilizer Ordinance will finally set limits for Cd and what form this will ultimately take.

### 3.4.2. Applied Fertilizer Legislation

With regard to the application of fertilizers, the provisions of the Fertilization Act (DüngG) [159] and the Fertilization Ordinance (DüV) [160] apply in Germany. They were comprehensively reformed in 2017, not least in order to avert conviction of Germany under the European Commission's infringement proceedings for excessive N inputs into surface and groundwater bodies. This is also reflected in the extended purpose of the Fertilizer Act, which now includes ensuring sustainable and resource-efficient handling of nutrients in agriculture and avoiding nutrient losses into the environment (§ 1 DüngG). According to § 3 para. 2 DüngG, fertilization must be applied following Good Agricultural Practice. This is further specified in the DüV and comprises the application principles in § 3 DüV, in particular the location- and needs-based fertilization. The basis is the soil samples prescribed in § 4 DüV, whereby the available P-quantities must be determined at least every six years in accordance with § 4 (4) No. 2 DüV. Following the amendment, Annex 4 of the DüV contains more precise specifications for determining the plant's nutrient requirements, although the specifications only apply to N. In principle, the new DüV focuses significantly more on N than on P, which is reflected not only in the details for the plants requirements but also in the limitation of the absolute N input in accordance with § 6 (4) DüV. A corresponding regulation for P is missing. Specifically, for P fertilization, the new DüV provides in § 3 para. 6 that P fertilization in areas with >20 mg $P_2O_5$ per 100 g of soil may only be carried out up to the level of the expected phosphate removal. Appeals can only be made in individual cases or on the basis of the newly introduced country authorisation clause (§ 13 (2) s. 4 No. 3 DüV). In fact, the new § 9 para. 3 DüV halves the permitted average six-year P balances from 20 kg/ha/a to 10 kg/ha/a starting from 2023. Yet, P surpluses and thus potential P losses remain permissible. Overall, the new fertilizer law, with the obligation to apply P fertilizers in line with demand, the P limitation to highly supplied soils and the limitation of the maximum P balances as well as some application restrictions, certainly includes approaches for more sustainable P management, but does not make full use of its potential [132].

In Costa Rica and Nicaragua, a comparable applied fertilizer legislation does not exist. The handling or permitted quantity of P fertilizer used as well as permissible nutrient surpluses in soils are not prescribed by law. Instead, there are general guidelines on Good Agricultural Practice (Buenas Prácticas Agrícolas, BPA). The BPA was supported in Central America from 2009 to 2011 under the Protocol on Land-Based Pollution of the Caribbean. This legally binding protocol was concluded on the basis of Art. 4 para. 3 and Art. 17 of the Cartagena Protocol [161] as an initiative of the United Nations Environment Programme [162]. In this context, instructions on BPA for various crops, the preferred use of organic fertilizers and integrated pest management have been developed [163–166]. The objective of the BPA is to achieve a more efficient use of fertilizers and pesticides in agriculture. In a reference project on banana cultivation on the Caribbean coast of Costa Rica, the use of mineral fertilizers fell by 25% [167] (p. 28), [168] (p. 3). The complete renunciation of mineral fertilizers and pesticides is not foreseen and there is therefore considerable scope for the application of BPA.

However, the concept of BPA is based on the principle of voluntary certification. In particular, domestic small and medium-sized producers are addressed by the BPA. Due to the lack of domestic sales markets and high certification costs, the application of BPA has not yet been fully established, neither in Costa Rica nor in Nicaragua. Even though the certification costs in Costa Rica can be partially covered by the "Recognition of Environmental Benefits" programme [169]—a type of investment subsidy [170] (p. 142)—only 252 farmers applied the BPA in 2016 [40] (p. 4). According to Costa Rica's National Development Plan for 2015–2018, the objective is to integrate a total of 1600 farms into the BPA [40] (p. 4). During the last survey of the BPA in Nicaragua in 2011, about 750 producers applied the BPA [171] (p. 5).

In addition, Law No. 765 [172] in Nicaragua explicitly pursues the goal of promoting agroecological and organic agriculture. In Costa Rica, Law No. 8591 [173] and its implementing regulation [174] to promote organic farming was enacted in 2007. Again, certification for organic agricultural products is only desirable for the producer if corresponding markets exist. This has not yet been sufficiently achieved within Nicaragua and Costa Rica. The total share of ecologically certified production is 0.4% in Costa Rica and 0.7% in Nicaragua [35] (p. 46). Approximately 28,000 farmers in Nicaragua work according to agricultural-ecological principles, some of them however without certification [175] (p. 5).

Overall, the problem is that binding national regulations for the utilization of fertilizers valid for all farmers do not exist, and also the requirements for BPA have not been incorporated into national legislation or been improved with regard to efficient and consistent use of (P) fertilizers. In this respect, a governance gap exists in Costa Rica and Nicaragua [176]. In Costa Rica, Art. 19 of Law 7779 already provides the legal basis for the integration of binding regulations for the utilisation of fertilizers in the field of soil protection law. However, the lack of consistent implementation appeals to be a result of an ambition gap [177]. Riggs identifies an "ambition gap" [178] (p. 3) particularly with regard to the implementation of climate protection targets in accordance with the PA. This can also be applied to the missing establishment of national soil protection plans in Costa Rica, which would have to include rules for appropriate P fertilization practices (Art. 19 Law 7779) [129] and might also be applicable to the missing specification of soil protection legislation in Nicaragua.

Thus, from a comparative legal perspective, it can be stated that mineral P fertilizer use in agriculture remains either insufficiently regulated as in Germany or is not subject to any legally binding restrictions in Costa Rica or Nicaragua. In particular, Good Agricultural Practices—as it is understood and designed in each case—do not yet promote the closing of the P nutrient cycles and hence the protection of soils adequately; even though the German fertilizer law has recently been amended to improve nutrient efficiency. As a result, Good Agricultural Practice must be comprehensively reoriented in all countries to meet the future challenges with regard to sufficient food production as well as resource and environmental protection. However, increased and more intensive monitoring and enforcement problems [29] (p. 467) are likely to occur if strict and binding rules for Good Agricultural Practice are established. It may therefore also be necessary to create further, alternative legal instruments (see also Section 4).

## 4. Discussion and Concluding Remarks

Germany, Costa Rica and Nicaragua are each facing the challenge of overcoming dependence on imported mineral P extracted from mining and establishing sustainable agriculture with closed nutrient cycles, so that natural resources are protected in the long-term. A P-governance that consistently aims to reduce the amount of mineral P fertilizers used and promotes alternative fertilizers, and therefore also considers protection of soil, water, biodiversity, and climate is appropriate. So far, legislation in all three countries has not yet found the right answers to the existing challenges, even though obligations in the area of environmental protection can be derived from internationally binding agreements as well as from fundamental rights. In all three countries, agriculture is still essentially dependent on the use of fossil fuels and mineral (P) fertilizers. In each case, a strong export orientation, with far-reaching separation of livestock farming and crop production is evident, while permitting negative environmental effects on soils, water, biodiversity and climate, which may ultimately lead to irreversible environmental damage [29] (pp. 450–459), [90].

In order to close the P fertilizer cycles in the future, a better understanding of the process of P is necessary. In general, measures to increase the availability of P in the soil for plants are increasingly being investigated. Microorganisms, mycorrhization and crop rotation play a decisive role in this context [179]. This applies equally to Central European and tropical soils. Organic fertilization, mixed cultivation and intercropping—principles which contribute to increase the plant availability of P—have so far been most closely anchored in agroecological and organic agriculture. These practices are inadequately promoted. Legal initiatives in this regard have not achieved the desired results and are largely overshadowed by export-oriented agricultural policies. In non-European countries such as Costa Rica and Nicaragua, misguided subsidies under the CAP, which are insufficiently linked to environmental requirements or the utilisation of organic fertilizers within Europe, additionally increase the pressure to produce competitively [180,181], and in cases of doubt with a high use of mineral (P) fertilizers.

Soil protection is also inadequate in each case. In Germany, partly contrary special laws in the fertilizer legislation prevent comprehensive soil protection. In Costa Rica the lack of implementation of existing soil protection and in Nicaragua the general, inadequately specified requirements for soil protection law do not show any relevance in practice. At the same time, the use of mineral P fertilizers is largely uncontrolled or misguided in the individual countries. The respective product-related fertilizer legislation has already missed the possibility of restricting the use of mineral P fertilizers and thus indirectly promoting organic or recycled P fertilizers; for instance, through strict limit values for heavy metals such as Cd.

In addition, there are no control mechanisms which can consistently minimise the total quantity of mineral P used, and legislation in the individual states does not encourage any structural changes in agriculture. These should aim in particular at livestock farming practices that are optimally adapted to the site-specific conditions. In particular, it was shown that livestock production needs to be strongly minimized in total and at the same time much better distributed spatially than today [74]. In order to achieve this and to close P nutrient cycles in agriculture, efficiency and consistency (such as precision farming and P recycling) and in particular frugality, i.e., more modest consumption patterns, have to be included in P governance. So far, also the recovery of P from sewage sludge prescribed in Germany by the amended AbfKlärV [145] as an important consistency strategy neither encourages any structural changes in agriculture nor stimulates frugality and can therefore be seen as only one step on the way to close the existing governance gap. In this context, the potential steering effect of command-and-control law in agricultural legislation must generally be questioned, since—also in Germany—a large number of individual processes in agriculture make corresponding implementation difficult. In addition, there are fundamental governance deficiencies in the regulatory approaches such as possible rebound and shifting effects [29] (pp. 408–412). Command-and-control and subsidy approaches with their focus on a special place, action, or product have the disadvantage that they tend to trigger unwanted shifting effects of environmental problems to other countries and where possible, to other sectors. Reducing fertilization e.g., in Germany, could lead to intensified farming practices elsewhere. This also makes it hard to primarily focus on new approaches that are only established on a domestic level (e.g., meat tax). Also, there are potential rebound effects if e.g., fertilizer use is improved in a specific area, while at the same time the overall global trend of increasing land use continues. Frugality and the general need for quantity control for various resource and sink problems might require economic rather than regulatory approaches as the main instrument, which does not necessarily exclude the need for additional regulatory requirements. A cross-sectoral and ambitious cap on the availability or pricing of fossil fuels, land use or livestock farming as a first legislative action would be conceivable [76], [29] (pp. 459–470). In this respect, there is still a long way to go towards sustainable agriculture. One of the many steps towards this is closing the P governance gap [176].

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# Justifying Soil Protection and Sustainable Soil Management: Creation-Ethical, Legal and Economic Considerations

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**Abstract:** Fertile soils form an important basis for survival for humans, but also for animals, plants and ecosystems, on which all terrestrial organisms rely. Soil is not only of central importance to the global provision of food and in the fight against hunger; climate, biological diversity and water bodies are also highly dependent on soil quality. Soil conservation is therefore a decisive factor in the survival of humanity. Pope Francis also emphasized this in his encyclical "Laudato si'". However, increasing pressure is being exerted on soils, which poses an enormous challenge to the international community and thus also to the church. Against this background, in this article, which is based on a Memorandum of the German Bishops' Working Group on Ecological Issues, arguments and justifications for soil protection and sustainable soil management are developed from different angles—from a creation-ethical, a legal, and an economic perspective. All three perspectives point in the same direction, namely that in the use of soils public interests that serve the society and the environment should be given priority over private interests. These arguments may serve as an important reference point in political and societal debates about soils, and may support strategies for sustainable soil management.

**Keywords:** justifying soil protection; sustainable soil management; creation ethics; Laudato si'; property rights; German Constitutional Law

## 1. Introduction

Fertile soils form an important basis for survival for humans, but also for animals, plants and ecosystems and their services, on which all terrestrial organisms rely, for better or for worse [1]. Soil is not only of central importance to the global provision of food and in the fight against hunger; climate, biological diversity and water bodies are also highly dependent on soil quality [2] (p. 10), [3] (p. 397). Soil conservation is therefore a decisive factor in the survival of humanity. Pope Francis also emphasized this in his seminal encyclical "Laudato si'" ([4], the encyclical will be cited below using LS and the paragraph number). However, increasing pressure is being exerted on soils. Population growth, increasing urbanisation, and high requirements for food and energy are all associated with the degradation of soils in many regions of the world, destroying soil fertility that has arisen over thousands of years [5–8], [9] (p. 648). This all poses an enormous challenge to the international community and thus also to the church. Humankind is dealing with no less than a central element of creation and its contribution to life.

This article, which is based on the Memorandum "Der bedrohte Boden" ("The threatened soil") [10] of the German Bishops' Conference Working Group on Ecological Issues, deals with the necessity and justification of soil protection from a creation-ethical, legal, and economic perspective. Particular emphasis is placed on Pope Francis' encyclical "Laudato si'". All three lines of argument form a strong case for protecting soils through adequate policy strategies and measures. They underline that soil protection is indispensable for humankind in order to save the basis of our life. The presented arguments may serve as an important reference point in political and societal debates about soils, and may thus support strategies for sustainable soil management.

## 2. Justifying Soil Protection from Ethical, Legal, and Economic Perspectives

Soil conservation has long been a topic for normative reflection in virtually all human cultures and religions. As a prominent example, this can be shown on the Earth Charter, which sees itself as an inspiring vision of fundamental ethical principles for sustainable development, supported by religious and non-religious people from almost all cultures. The document underscores: "The resilience of the community of life and the well-being of humanity depend upon preserving a healthy biosphere with all its ecological systems, a rich variety of plants and animals, fertile soils, pure waters, and clean air. The global environment with its finite resources is a common concern of all peoples. The protection of Earth's vitality, diversity, and beauty is a sacred trust." [11]. Like other renewable resources the use of soil should therefore be managed in ways that do not exceed rates of regeneration and that protect the health of ecosystems. Main reasons are our responsibility to one another, to the greater community of life, and to future generations as well as the human rights, among these the rights to uncontaminated soil, to potable water and to food security (ibid.). In the following, our intention is not to unfold and reflect the entire ethical discussion about soils. Instead, the ethical and spiritual perspective on soil and soil conservation will be deepened through recent statements of the Magisterium of the Catholic Church.

### *2.1. Theological Considerations Relating to Creation*

#### 2.1.1. The Close Relationship between Humans and the Soil

In his environmental and social encyclical "Laudato si'", Pope Francis underlines that we humans are "dust of the earth". The human body is "made up of her elements" (LS 2). The Pope refers here to the second chapter of the Book of Genesis, which states that God created *adam*, the human, from *adama*, the dust from arable soil (Genesis 2:7). This is why humans are closely related to "our Sister, Mother Earth" (LS 1), as Francis states under reference to his patron saint, St. Francis of Assisi, and his "Canticle of the Creatures". God loves "each of his creatures" (LS 92), so he also loves the Earth and her important constituent, soil, and he is therefore not indifferent to humans plundering, mistreating and ravaging the planet (LS 2). Such behaviour is "a crime against the natural world ( . . . ) is a sin against ourselves and a sin against God" (LS 8).

For this reason, the Biblical Laws on the prescribed rest periods—the Sabbath (rest on the seventh day), during the Sabbath or fallow year (no planting in the seventh year) and during the year of Jubilee (restoration of the original ownership after seven times seven years)—command regular care and relieving of pressure, not only for humans and animals, but also for soils, for the salvation of all created by God (Ex 20:8–11; 23:12; Lev 19:3.30; 25:4 f.8–31; Dtn 5:12–15): That "they may have rest" (Ex 23:12; LS 71; 237).

#### 2.1.2. The Human Responsibility for the Earth

In the Bible, God is and remains the proprietor of his creation and thus also of the soil. For this reason, humans may work, plant and inhabit the land, but do not have the right to sell it. "The land is imprescriptible" [12] (p. 98). Only later, once the Israelites had mixed with the Assyrians in the North and with the Babylonians in the South and experienced the fact that land could also be bought and sold, was the following edict issued, simultaneously opening up and restricting opportunity: "The land shall not be sold in perpetuity, for the land is mine; for you are strangers and sojourners with me" (Lev 25:23; Ex 9:29; LS 67). But not only the land, all of the earth and all that is within and on it, are governed by God's sovereignty and jurisdiction (Ps 89:12; Dtn 10:14; [13] p. 1063): "The earth is the Lord's"; to him belongs "the earth with all that is within it" (Ps 24:1; LS 67).

Over the course of the modern history of emancipation, during which science and technology sometimes distanced themselves greatly from the church and theology, the Biblical position was queried more and more, to the point where humans even took the place of God. The historically influential philosopher, René Descartes, no longer regarded God, but humans as the masters and owners of the natural world (LS 75).

Counter to this position, Christian churches and theologies still adhere to the concept that God is and remains the proprietor of what he has created (LS 67). For example, the Catholic Church in Luxembourg emphasizes in its social declaration that humanity is only afforded the status of a guest on this planet: "The Earth does not belong to us as we are guests" [14] (no. 4.7). The Earth has been loaned to us, as the German bishops already outlined in 1980: "The world is a gift given by God to humanity, a gift that is to be passed on to the next generation. (...) Creation thus becomes an inheritance, with each generation owing this inheritance to future generations, prohibited from consuming all and from creating an unbearable burden of mortgage. (...) The human responsibility for Creation is thus a responsibility to care for the inheritance and not to leave behind a desert in place of a garden" ([15], no. I.5; LS 159). The generations living at any point in time are thus only "stewards" (LS 116; 236).

The term *steward* in the Christian ecological ethics used today to describe the required human relationship to the non-human earthly creation, originally referred to a person who was given the responsibility by the owner of the land of managing (*oikonomia*) the important resources and functions of the *oikos*, the household. When extrapolated to God's "household", the "living house" Earth, this means that humans, in their position as stewards, are entrusted with responsible management [16], (pp. 920, 922). Jesus is the model authentic steward for Christians: Sensitive towards all that is living and the requirements of others. Authentic management of the household necessitates reverence and veneration in the sense of a deep respect for life (LS 207 with reference to the Earth Charter). A Christian understanding of stewardship requires belief in the presence of God in all life and all creation (LS 87 p. 233; 246) and results in respect for the natural world and life in harmony with nature [16] (p. 921).

However, according to some critics, especially Lynn Townsend White Jr. [17], the Holy Scripture—condensed in the so-called *dominium terrae*—had served for centuries purposes that legitimize an exploitative, destructive relationship to nature. In his article entitled "The Historical Roots of Our Environmental Crisis", published in "Science", White Jr. vehemently criticizes Christian anthropocentrism and the "Christian arrogance toward nature" (ibid., p. 1207). Christianity had not only established a dualism of humans and nature, but had also insisted that it was *God's* will that humanity should exploit nature for its own purposes. Through its influence on science and technology, Christianity carried "a huge burden of guilt" (ibid., p. 1206). The state of the environment would continue to deteriorate if we do not overcome the Christian axiom, according to which nature has no other reason for existence than to serve man (ibid., p. 1207). Despite all legitimate objections to White's essay, it should be positively emphasized that his critique was (and still is) partly justified and has set in motion a fruitful inner-church and inner-theological clarification process. It also helped to overcome the mere anthropocentric perspective on nature and fostered a more holistic perspective that also includes the value of nature in itself.

For example, it is now a consensus in biblical science that Luther's influential translation and also the phrase "Macht euch die Erde untertan" (Subdue the Earth), which is based on it, are completely false. The original Hebrew text says, literally translated, "Set foot on the dry surface of the planet" (Gen 1:28). From antique representations, one knows that the gesture of foot-setting (hebr. *kābaš*) does not mean to trample down, but to protect something, here: the land. And "having dominion" (hebr.

*rādāh*), the other commonly misunderstood term (Gen 1:26.28), means in the context of the Bible a non-violent, caring guidance with wisdom and love—following the example of God, who reigns in love for his creation, and the good and just king, who should work for the well-being of the land and its inhabitants. Moreover, only these new translations, which are based on the original text, are compatible with the two divine assignments to the "first" genderless human being in Genesis 2 to serve (hebr. *ābad*) and preserve (hebr. *šāmar*) the Garden of Eden, the paradise, or in modern terms: the ecosystem (Gen 2:15). Who knows if the Christian exegesis, theology and ethics of the 1980s would have gained these important insights without the sharp criticism of White and others? However, even if the biblical belief in creation and the mandate for creation did not cause the exploitative attack on nature—"only the loss of the creation perspective made it possible in the end"—the church and theology would nevertheless have failed to object in good time and clearly to this misinterpretation and instrumentalization of the biblical texts [18] (p. 36). Unfortunately, recent German Bible translations, used in religious education and liturgy, have missed the opportunity to overcome the erroneous position of a (supposedly God-given) imperialist relationship of humankind to extra-human creation.

#### 2.1.3. The Principle of Universal Dedication of the Goods of Creation

The position outlined here was laid down in the theological and ethical principle of universal dedication of the goods of the Earth. Pope Francis includes this in the Principles of Church Social Teaching. According to the Compendium of the Social Doctrine of the Church the principle confirms "both of God's full and perennial lordship over every reality and of the requirement that the goods of creation remain ever destined to the development of the whole person and of all humanity" [19] (no. 177).

If we take the Biblical statements seriously, the legal human relationship with the Earth and other creatures on it can therefore not be determined by a proprietary relationship, and certainly not within the meaning of an *ius utendi et fruendi et abutendi*, i.e., the right to use something, to enjoy its fruits and to also be permitted to misuse it, that extends as far as the German Civil Code (BGB). In the first edition of the BGB, this right "to proceed at will and to exclude others from any influence whatsoever" has, however, already had a restriction imposed on it: What applied, and still applies, is "so long as this does not violate the Law or the rights of third parties" (§ 903 BGB).

In the first social encyclical "Rerum novarum", published in 1891, Pope Leo XIII wrote "that the blessings of nature and the gifts of grace belong to the whole human race in common" (RN 25). For this reason—so Vaticanum II, under reference to Pius XII and John XXIII—the Earth must yield up all it contains to all humans and peoples in a fair manner—"under the leadership of justice and in the company of charity" (Gaudium et spes 69). According to Oswald von Nell-Breuning, the fact that the council "has issued the purpose (dedication) of the goods of the Earth to humanity and not to the individual humans" and that the "so often blurred distinction" between the entitlement to use for all and the concrete administration and management was "heavily emphasized" is to be greatly welcomed here [20] (p. 505). Shortly after the Council Pope Paul VI points out that the principle of the common use of goods governs all other rights—such as the rights to property and free trade (Populorum progressio 22). His successor John Paul II repeatedly referred to this principle in his social encyclicals, emphasizing its central role in underpinning the responsibility of humans when handling the goods of creation. He calls it the "first principle of the whole ethical and social order" (Laborem exercens 19.2) and the "characteristic principle of Christian social doctrine" (Sollicitudo rei socialis 42.5). The Christian tradition has never viewed the right to property as "absolute and untouchable". Quite the contrary, it has always viewed it within the all-encompassing scope of the common rights of all to use the goods of creation overall; in other words, "*the right to private property is subordinated to the right to common use*, to the fact that goods are meant for everyone" (LE 14.2). So the right to private property carries a "social mortgage" (SRS 42.5), and we must amend this within the meaning of responsibility towards creation: also an *ecological* mortgage. Thomas Aquinas already justified private property only in a pragmatic manner and not based on Natural Law. His considerations emerge again in modern economic ethics: "The institution of private property overall is essentially ethically justified by the incentive provided by exclusivity to use scarce resources sparingly and efficiently" [21] (p. 650). This means that property, which excludes others from use, will normally be utilized more carefully than commons that are jointly used. In the latter case—especially in the absence of social controls—there is the danger of individuals behaving as free riders, who do nothing towards maintenance of the common good and over-exploit the resource.

In his Message for the Celebration of the World Day of Peace in 2014, Pope Francis writes that humans are permitted to use the natural world, but must respect, preserve, nurture and manage it responsibly [22] (no. 9). However, the relationship between humans and nature is currently shaped more by greed and the arrogance of dominion, possession, manipulation and exploitation. In contrast, the economic utilization of the natural world should aim to serve our fellow humans, including the generations to come. Above all, it is a "truly pressing duty to use the earth's resources in such a way that all may be free from hunger" (ibid.). The aim is that "all may benefit from the fruits of the earth, not only to avoid the widening gap between those who have more and those who must be content with the crumbs, but above all because it is a question of justice, equality and respect for every human being" (ibid.). In this context, Pope Francis reminds us of "that necessary *universal destination of all goods*" to ensure that all humans have "an effective and fair access to those essential and primary goods which every person needs and to which he or she has a right" (ibid.).

In "Laudato si'", Pope Francis enters into greater depth on these thoughts and, once again, emphasizes the "principle of the subordination of private property to the universal destination of goods" (LS 93). Until this encyclical, the interpretation of the mentioned principle by the Church was predominantly anthropocentric. In this tradition, creation seems to exist only for the sake of man. Now the Pope harshly criticizes "a tyrannical anthropocentrism unconcerned for other creatures"; humans "are called to recognize that other living beings have a value of their own in God's eyes" (LS 68). Humans have to ensure that the legitimate claims of animals are respected and protected (LS 68). In his address to the UN General Assembly on 25 September 2015, Francis furthermore stated "that a true 'right of the environment' does exist". This right "must be forcefully affirmed, by working to protect the environment" [23]. In this context it must be mentioned that Pope Francis has a large opposition within the Catholic Church. Many Catholics, priests, bishops, cardinals and even theologians are not committed to his views on environmental sustainability. A recent survey of Catholic seminaries in the United States, Canada, Rome, and the Holy Land concluded that only eight colleges out of sixty-eight offered courses on faith and ecology. This illustrates how far many Catholic colleges are from meeting the aspiration of Francis in Laudato si' [24].

Just like the climate, the soil is "a common good, belonging to all and meant for all" (LS 23). However, how can it be *fairly* distributed? Laying down *equal* rights of use for all would probably be the easiest of all possible solutions. However, is this also fair? In addition to soil quality, do we not also need to account for prior exploitation, destruction and pollution, on which the majority of current global, highly unevenly distributed, wealth is based? Furthermore, justice demands that "things that are essentially the same must be treated in the same way and things that are essentially different must be treated different ways" [25] (no. 25). Humans are equal with regard to their dignity and rights, but they have different needs that are, among other factors, dependent on (sometimes variable) individual characteristics. Above all, however, these needs depend on natural, largely unchangeable environmental conditions that most people can usually only escape from with difficulty, if at all.

Determining the needs of *future* humans is even more difficult, especially if we consider generations that are chronologically far away from us. Even so, based on constants that are associated with being human, it is extremely unlikely that in the future people will have fundamentally different basic needs. Virtually certain they will also have a requirement for uncontaminated soil, clean drinking water and healthy food. This results in two main demands. First: Current problems related to the fairness of global distribution must be solved *now* and not accumulated and postponed to the detriment of future generations. Second: Assumptions and estimates relating to technological developments, the available fertile soils and future consumption must be *realistic* and *not too optimistic* as subsequent generations may otherwise be placed at a disadvantage.

### *2.2. Economic and Legal Considerations*

#### 2.2.1. Exploitation of Soils—From Freedom to Responsibility

The problem of how soils can be protected and exploited more sustainably is also dependent on the question of to what extent ownership of land and soil can be regulated and its use limited. Land and soil use has varied greatly throughout the centuries. Within the history of economic thought there have been different strands of discussions ranging from explicit considerations of soils in early (classical) economic writings of Adam Smith, David Ricardo or Thomas Malthus, to a total neglect by (neoclassical) economics where the only sources of economic wealth are seen in labor and capital. "The history of the concept of land in economics shows an increasing narrow perception of the contribution of the natural world to human well-being. By the early 20th century interest in land was restricted to only those attributes that gave immediate economic value" [17], [26] (p. 6).

While in this article our intension is not to trace the entire economic discussion on soils, we specifically refer to property rights approaches. Property rights define the rights of particular actors to undertake actions towards clearly specified objects. In the soil context, the term property rights (also rights of use or control) makes clear that the proprietor of land holds all rights pertaining to the land and is (in an extreme case: fully) at liberty to make any kind of decision on how it is used: the proprietor can work and re-organize this property according to his personal ideas, can let it, sell it, create or prohibit access for others, etc. The peculiar aspect is that such a property rights approach can both explain soil regimes and give hints for the division of rights between landowners, soil managers, and society.

The relationship between humans and the natural world is essentially defined by how people live together in societies, through individual and social relationships, as well as by notions of acquisition and appropriation [27,28]. To clarify this, *Daniel W. Bromley* [29] (p. 21) refers to the "social construct of land". Farming of the land by groups of people progressively disappeared with the demise of feudalism in Europe at the end of the Middle Ages and the rise of centralized states. Instead, private property developed in the form of fenced-off land [30] (pp. 198, 327, 450). Hardly any open fields, meadows or fallow areas remained. This development was accompanied by an increase in freedom and autonomy for the individual. In particular, in the British Empire, this led to a requirement for the definition and development of *property rights* in relation to land. This process of parallel development of individual rights of freedom and comprehensive, unrestricted rights of use of property was (at least for the wealthy) an important milestone in emancipation and release from the power of the central nobility and rulers and in securing personal rights to freedom. Comprehensive rights relating to the use of the resource, land, were therefore regarded as a building block in securing the rights to freedom. This led to whoever first worked the land taking possession of it in the colonies of Africa, the Americas, Australia and New Zealand, a process frequently involving violent displacement of the indigenous population [29] (p. 35).

Only since the 19th Century the use of the land has once again become associated with duties towards the public good [29] (pp. 23, 35). Proprietors of land are increasingly issued with obligations on how they are permitted to use the resource, soil. Environmental concerns play a growing role in this. The imposition of restrictions on land use is often associated with compensation payments from the state. Today, land use in many states lies somewhere between orientation towards property and social obligation, whereby the balance between these two categories is encountered and must be revisited repeatedly from a social perspective. In modern times, Bromley sees a rise in socialization and a decrease in private rights of control [29] (p. 36). However, this is only limitedly reflected in the current property rights. Particularly the ecosystem services approach can be used for re-defining property rights regimes. Bartkowski et al. have developed a frame, where these shortcomings can be overcome by a re-definition of property rights, focussing particularly on social interests and the protection of soils [31]. This discussion is also well reflected in German Constitutional Law, which may serve as an example here to illustrate the division of property rights balancing between (full) private property and social responsibility from a legal perspective.

### 2.2.2. Social and Ecological Obligations Relating to Property under German Constitutional Law

Private property of soil and other objects is guaranteed by Article 14(1) of the German Basic Law (Grundgesetz—GG) within the catalogue of basic rights. According to current legal interpretation, basic libertarian and democratic order is essentially closely associated with this ruling, not only because there is a connection to the rights of freedom in the sense of proprietary law [32]—within the meaning of free and comprehensive power of disposition over assets—but also because it was recognized during engagement with socialism that private property formed the basis for careful and diligent handling of the property one was looking after—an insight that *Thomas Aquinas* had already formulated. The Basic Law emphasizes both the social obligation in relation to the property and the specificities relating to the possession of natural resources such as soils, as is made clear in Article 14(2) GG and Article 15 GG. According to Article 14(2) GG, property also carries obligations: "Its use should also serve the public good." This is of particular relevance to the property of land and soil, as was noted by the German Federal Constitutional Court over 50 years ago: "The fact that land and soil is a non-renewable resource and is indispensable prohibits its use from being left fully in the hands of impenetrable free market forces and subject to the will of the individual; rather more, a just legal and social order requires the interests of the public in the soil to be emphasized in far greater measure than for other assets. Ownership of land cannot be simply put on an equal footing with the value of other assets, either economically or with regard to its social importance; it cannot be treated like mobile goods in legal dealings. Article 14(1) sentence 2 GG in association with Article 3 GG can therefore not be interpreted to mean that the legislator is under the obligation to subject all assets of monetary value to the same legal principles. Furthermore, no discrimination is made between financial capital and capital that is invested in agricultural and silvicultural property" [33] (p. 82).

The specificity relating to the ownership of land—and therefore also the soil on the land—that arises from the nature of the issue offers the possibility of greater legal regulation and, in particular, justifies far-reaching restrictions on the use and trade in land. Land is not only a non-renewable resource, but also remains an integral part of the environment, landscape, and ecosystems, even as private property. Land areas are shaped by their surroundings, just as they themselves, and how they are used, shape the environment. The German Federal Constitutional Court derives a particular responsibility of the owner and holder of the land and a specific duty of care from this situatedness and the embeddedness of land. "Pursuant to the consensual jurisdiction of the Federal Constitutional Court and the Federal Court of Justice, regulations that restrict the use of plots of land for reasons associated with the protection of Nature and the landscape do not, on principle, constitute expropriation within the meaning of Article 14(3) GG, but are provisions on substance and limits relating to the property within the meaning of Article 14(1) sentence 2 GG ( ... ). This is based on the concept that each plot of land is shaped by its position and composition, as well as how it is integrated into its environment, i.e., through its given situation. This 'situatedness' may permit the legislator to impose restrictions on the proprietor's authority, with the legislator laying down the substance and limits relating to the property pursuant to Article 14(1) sentence 2 GG, and hereby ensuring a balanced relationship between the private and social benefits of the use of the property (Article 14(2) GG) ( ... ). This is because the stronger the social connection in relation to the proprietary object, the greater the proprietor's freedom of use pursuant to Article 14(1) sentence 2 GG; the properties and function of the object are crucial to this process ( ... ). When the natural circumstances or spatial landscape conditions of a plot of land are worthy of conservation in the interests of the general public and require protection, this results in a form of immanent restriction to the proprietorial authority, i.e., that is intrinsically linked to the plot of land itself, which is simply reflected in the regulations on nature and landscape conservation legislation” [34].

The high level of obligation that is associated with owning land is underpinned and extended by the national target of conserving the environment, as laid down in Article 20a GG since 1994. This Article expressly raises conservation of the environment to a constitutional level and thus declares it a target for the public good that is of overriding importance and permits the limitation of basic rights and other targets for the public good. The article simultaneously includes guidelines for assessment and a decree on optimization and offers indicators for a general increase in the level of protection for environmental resources—thereby also for the land use and the soil protection. In *Czybulka's* [35] opinion, this allows the derivation of an “ecological obligation” for the property. Therefore, in Germany, under consideration of the principle of proportionality, it is constitutionally permissible to restrict the options for use of land that is owned for ecological reasons without awarding compensation. According to the Federal Constitutional Court, e.g., it does not constitute expropriation if the use of surface waters and groundwater bodies in private properties is also subject to a public management regime [36].

#### 2.2.3. Internalizing External Effects: Strengthening the Polluter Pays Principle and Avoiding Disincentives

From an economic perspective, these legal arguments must still be expanded to include several aspects: Firstly, environmental and soil conservation is not just implemented for the natural world, for its own sake, i.e., for the plants, animals, communities and ecosystems, but equally, in the interests of humans: for their health and wellbeing, as well as their economic prosperity and, thus, ultimately due to “social concerns” within the meaning of Article 14(2) GG. The concept of ecosystem services, i.e. the services nature delivers to humans, clearly draws attention to this aspect. The natural world and the soil provide humans with numerous considerable services, as outlined above. These are not just visible benefits (such as traded on the markets), like food and feed, energy or drinking water, but also the hidden (as not traded on the markets) regulatory, cultural and supporting services, such as protection from flooding, purification of groundwater, recreation, habitat for numerous species, biodiversity, etc. [37] (p. 155), [38] (p. 456), [39] (p. 47).

Soil functions and services that cross the boundaries of plots of land underline the situatedness of land and soil and the resultant special responsibility borne by the holder and owner. From an economic perspective, pollution of the soils due to their activities constitutes a so-called negative external effect; uninvolved third parties are exposed to and harmed by these pollutants, without the perpetrator being held accountable. These “third parties” are not “faceless”: These are other people, future generations and the non-human natural world. Commercial gains from intensive cultivation that is associated with high levels of fertilizers and pesticides therefore contrast with the current and future overall costs to the economy, which are not, or insufficiently, considered in the perpetrators' calculations. Pope Francis calls this problem a serious injustice (LS 36).

A second required endorsement arises from the polluter pays principle (LS 167). This involves charging the perpetrators of soil pollution for the damages they are causing, so that their behaviour is changed to ensure that all soil functions and soil ecosystem services are preserved within the meaning of a sustainable development (LS 195). On the one hand, the polluter pays principle is targeting aspects of fairness: Whoever exploits natural and soil resources gains specific advantages, so that it is only fair that the user of the resources and emitter of the pollutants abstains from exposing the general public to pollution, or at least keeps this to a minimum and pays compensation for any damages. However, the polluter pays principle also constitutes an efficiency standard: Namely, people who use the environment and are holders or owners of the land often have greater insights and opportunities to stop the associated pollution or over-exploitation of the environmental resources and to address the negative consequences than those who are being harmed or the general public [40]. This requires a *social* decision on whether the costs of the negative external effects must be borne by the perpetrators alone or whether society should play a supporting role and, for example, grant the land user payments to contribute towards soil conservation. The (creation-)ethical and legal considerations touched upon above, but also the economic considerations that have been outlined, suggest a requirement for increasing the perpetrator's responsibility to ensure soil exploitation is oriented towards the common good. Of course, the application of the polluter pays principle is only possible if the polluter still exists and if he has the capacity to reduce the damages. The remediation of contaminated sites where contaminants were released in the past can often only be carried out by the general public.

## 3. The Responsibility of the Church

The responsibilities of the owners and holders of land and soil that have been described above from a theological, legal and economic perspective also apply to the churches, which belong to the largest non-state owners of land worldwide. Estimates assume that the Catholic Church owns over 716 m ha of land and soil world-wide [41]. Only a small portion of this is occupied by buildings such as churches, monasteries and other establishments. By far the majority is agricultural and silvicultural land that is either farmed by the church itself or leased to tenants. In Germany, the land assets of the Catholic Church are estimated at about 825,000 hectares [42] (p. 435), roughly two and a half percent of Germany. After the Nation (federal government, states and communes), the Catholic Church is thus the largest land owner in Germany.

Based on its own Christian values (LS 93, 216) and the demand issued by Pope Francis "Truly, much can be done!" (LS 180), the Catholic Church and its congregations have a social role model function in the ecologically sustainable use of its lands (LS 180, 200). The methods that allow the ecologically sustainable use of arable land, grassland and vineyards as well as forests are generally well-known. For arable land, the principles and methods of ecological farming are particularly well suited to the conservation of soils, water bodies and the remaining environment, including biodiversity [43] (p. 26), [44]. The yields are very often only slightly below those from conventionally farmed areas [45]. For many smallholdings in regions that are less intensively farmed, the insights from ecological farming may well even provide better protection for the harvests from annual variation and increase the yields [46] (p. 65).

Accordingly, the Catholic Church should either ecologically farm its agricultural and silvicultural land itself, or stipulate this type of farming practice in contracts for tenancies. In practice, this requirement is faced with difficulties. The proprietary structures in the Catholic Church are very heterogeneous not only worldwide, but also in the individual dioceses, monasteries and other religious orders and church establishments. The variety of independent legal entities makes uniform practice exceedingly difficult, even if the Vatican makes an order regarding this.

In Bavaria an association of monasteries and church institutions with ecologically managed agriculture and/or gardening shows a good practical example of how a sustainable management of church land can be reached [47]. In addition to a step-wise improvement in its own practices, the church should also dedicate itself comprehensively and with high levels of commitment to the problem of soil conservation and soil restoration and the associated required actions, given its responsibilities towards humans and the environment.

## 4. Final Remarks

More than ever, sustainable soil conservation requires (improved) social integration. Soil is not only part of God's creation, but also constitutes valuable "natural capital" from an economic perspective, that is worthy of protection. If this capital is used up, then the social proceeds in the form of ecosystem services will also disappear. The creation-ethical, economic and legal arguments that are presented in this article all point into the same direction, forming a strong case for soil protection and the sustainable use of soils. They also make clear that in the discussions about private appropriation of soils and the interests of the society a public balance must be found and that restrictions of private property of ground can be justified by the interests of public welfare, especially in the case of ecological reasons.

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# Leverage Points for Governing Agricultural Soils: A Review of Empirical Studies of European Farmers' Decision-Making

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**Abstract:** What drives farmers' decision-making? To inform effective, efficient, and legitimate governance of agricultural soils, it is important to understand the behaviour of those who manage the fields. This article contributes to the assessment and development of innovative soil governance instruments by outlining a comprehensive understanding of the determinants of farmers' behaviour and decision-making. Our analysis synthesises empirical literature from different disciplines spanning the last four decades on various farm-level decision-making problems. Based on a conceptual framework that links objective characteristics of the farm and the farmer with behavioural characteristics, social-institutional environment, economic constraints, and decision characteristics, empirical findings from 87 European studies are presented and discussed. We point out that economic constraints and incentives are very important, but that other factors also have significant effects, in particular pro-environmental attitudes, goodness of fit, and past experience. Conversely, we find mixed results for demographic factors and symbolic capital. A number of potentially highly relevant yet understudied factors for soil governance are identified, including adoption of technologies, advisory services, bureaucratic load, risk aversion and social capital, social norms, and peer orientation. Our results emphasise the importance of a broad behavioural perspective to improve the efficiency, effectiveness, and legitimacy of soil governance.

**Keywords:** agricultural policy; behavioural studies; literature review; soil functions; soil pressures

## 1. Introduction

Despite seed banks, in vitro meat production, hydroponic farming, or vertical greening, soils continue to be the essential basis for human health and well-being. They are not only indispensable for the provision of food, feed, fuel, and fibre; soil functions are also critical for water storage and filtration, carbon sequestration and storage, support of infrastructure, etc. [1,2]. In fact, most terrestrial ecosystem services are dependent on functioning soils, which provide many—often not recognised—benefits to people. However, soils are globally threatened by multifaceted processes of degradation [3,4]. Policies are needed for the effective protection of soils and their efficient use. Yet, current governance regimes are deficient in terms of protecting soils and ensuring their sustainable management [5–7]. To improve this situation, society is in need of (i) a thorough understanding of the drivers of soil degradation [8] and the societal impacts of soil management [9] so as to be able to properly assess the relevant trade-offs; (ii) an equally encompassing understanding of the processes within the soil that give rise to soil functions and ecosystem services and how they are affected by soil management [10]; and (iii) innovative governance instruments building upon a comprehensive understanding of the determinants of relevant actors' behaviour and decision-making. Although optimal governance would be based on knowledge regarding all three factors, in the absence of information on (i) and (ii), a second-best approach to inform governance under incomplete information is necessary as farmers make day-to-day decisions. Here, we focus on disentangling the decision-making determinants. Of course, questions to challenges (i) and (ii) are sought in research projects around the world; available results can be combined with our analysis to inform soil policy.

Agriculture is one of the most prominent and direct interfaces between human activity and soils. We are all consumers of agricultural products and, thus, (highly dependent) beneficiaries of the use of soil as a resource. Agricultural soils are both a private good and a public good. The group that most directly interacts and influences soils—both in subsistence economies of the global South and in industrialised countries of the global North—is farmers. Therefore, it is inevitable to look at farmers and their land-use practices when the goal is to identify ways and means to make soil management more sustainable through proper soil governance instruments. In other words, the determinants of farmers' behaviour and decision-making regarding soil management can be regarded as leverage points for soil governance, i.e., areas for easy interventions that can result in potential significant changes [11,12]; however, 'there is no precise assessment on how the existing policies have affected, and will further impact, the pressure on agricultural soils in Europe. Such assessment would require knowledge on [ ... ] how farmers' soil management responds to policy measures, and [ ... ] what impact these responses have on the state of soils in short and longer term' [13] (p. 241, emphasis added). Our key question is therefore: Which factors do European farmers respond to in their decision-making? What influences their behaviour related to soil management?

There exist a large number of empirical studies into these questions and a small number of synthesising studies with a focus similar to our research question. For instance, in an influential and widely cited large-scale study, Wilson and Hart [14] tried to disentangle economic from non-economic factors that influence participation in agri-environmental schemes (AESs) in the European Union (E.U.). Siebert and colleagues [15] synthesised a large corpus of empirical literature (including grey literature) investigating European farmers' participation in biodiversity policies, finding that financial incentives are important but not the only relevant factor that makes farmers participate. Lastra-Bravo et al. [16] conducted a meta-analysis of discrete choice experiment studies investigating drivers of farmers' participation in E.U. AESs, identifying economic and demographic factors as important influences in this context. In the specific context of soil conservation, an important though older review study is by Prager and Posthumus [17]. They used a theoretical framework inspired by innovation adoption research to synthesise empirical insights with a specific focus on adoption of soil conservation. As such, our paper can be viewed as extending and updating the knowledge generated in their study. Riley [18] synthesised the literature on farmers' participation in AESs mainly from a sociological and human geographic perspective, focusing on changes in farmers' attitudes and cultures due to AES participation. Burton [19] focused on the causal explanations of links between demographic variables (age, experience, education, and gender) and farmers' 'environmental behaviour'. In a recent study, Liu and colleagues [20] synthesised post-2008 applied economic research on the factors influencing farmer adoption of best management practices (BMP), with a particular focus on water pollution. Their study is an update of earlier studies by Knowler and Bradshaw [21] and Prokopy et al. [22]. All three studies had either a global scope or a U.S. focus. Liu et al. note that '[t]he majority of case studies [they] reviewed were [conducted] in the U.S. and Australia' (p. 3). Generally, it can be said that most existing literature reviews and syntheses had a narrow thematic and/or disciplinary focus, while usually having a broad geographical scope. In our study, the geographical scope is comparatively narrow, as we think that it is more sensible to keep the cultural and legal context relatively constant across analysed studies, particularly when the ultimate aim is to derive implications for soil governance in a specific cultural–political context. Conversely, our thematic and disciplinary foci are broad, which reflects the recognition that (i) soil management is influenced by many different decisions made by farmers, directly and indirectly; and (ii) the combination of different disciplinary perspectives can be very fruitful, as impressively shown by recent advances in behavioural research [23] and requested in the recent agenda for strategic research on land use and soil management in Europe [24].

Thus, our analysis differs from those attempts mentioned above in two ways: first, it synthesises empirical literature of various farm-level decision-making problems analysed from the perspective of different disciplines (including economics, social psychology, sociology, and human geography) with a geographical focus on the European Union and spanning the last four decades, noting that there has been a strong increase in publication numbers in this area in the last decade or so. Second, we use these insights to identify leverage points that will support the formulation of effective and efficient governance instruments aiming at sustainable management of agricultural soils. However, even though the focus is on agricultural soil management, the results have wider applicability to agri-environmental and natural resource policies.

We start in the next section by presenting the conceptual framework that will guide our analysis of the literature. Subsequently, in Section 3, we briefly discuss data and methods used for the literature review of empirical studies of E.U. farmers' behaviour. In Section 4, we present the results of the literature review, which are discussed in Section 5, where we point out particularly interesting results and put them into a broader perspective. In Section 6, we derive implications for governance of agricultural soils. Section 7 concludes.

## 2. Conceptual Framework

If we assumed that, agriculturally, used soils are merely a private good, thus focusing exclusively on their relevance for the production of food, feed, fibre, and fuel, and if we adopted the perspective of a hypothetical, naïve neoclassical economist, then there would be no need for explicit soil governance beyond the pure market mechanism. In such a simplified model, the rational farmer chooses an optimal soil management strategy so as to maximise the net present value of the stream of future income she derives from agricultural production. The factors relevant for decision-making are market prices of inputs and agricultural products. In this model, there are no soil-related externalities, information is either perfect or at least available at a calculable cost, and the future is deterministic. Of course, this model is too simple; however, it helps to identify the reasons why we need soil governance and why we need a more sophisticated model of farmers' decision-making (A first step would be, in order to make the model more realistic, to include as constraints existing regulations and non-market incentives, such as the Common Agricultural Policy (CAP) of the E.U. Most of them, however, are at best only loosely considering soils in an explicit manner [5]).

Farmers' decision-making has frequently been viewed through the lens of a simplistic behavioural model inspired by rational choice theory [25,26]. However, while economic motives are highly relevant for farmers' decision-making [14], a complex web of other factors also plays a role [26,27]. An overly narrow focus on economic factors involves the risk of ineffective or inefficient policies: governance instruments differ in terms of transaction costs, efficiency, and 'intrusion' into farmers' (or consumers') freedom of choice. Sometimes indirect, for example persuasive, approaches may be more effective (for instance influencing the image of a 'good farmer' [28]), but to apply those with efficacy, one needs a sound understanding of decision-making factors beyond purely economic considerations. Furthermore, an exclusive focus on economic motivation favours incentive-based policy instruments to influence behaviour; however, the necessary compensation payments (or, in economic terms, farmers' minimum willingness to accept compensation) may well be influenced by non-economic obstacles (for instance cultural factors); efficiency of such policy schemes may be increased by including and targeting other factors rather than simply increasing payments. Thus, in an ideal analysis all relevant factors that likely influence on-farm decision-making need to be taken into account. A realisation of this ideal is neither realistic nor necessary. However, behavioural research shows that increasing the complexity of behavioural models underlying environmental policies can increase their effectiveness and efficiency [23]. Therefore, we want to contribute to systematic analysis of available information about farmers' decision-making.

Figure 1 presents our conceptual framework for the analysis of the corpus of literature. It is assumed here that farmers' decision-making is influenced by six general groups of factors:

- 'objective' characteristics of the farm, including farm size, local environmental conditions, and technological facilities;
- 'objective' characteristics of the farmer, i.e., mainly demographic factors, such as age, education, gender, and household size;
- behavioural characteristics of the farmer, i.e., her attitudes, awareness, knowledge, beliefs, and perceptions;
- social-institutional environment, i.e., the external factors related to legal and institutional frameworks the farmer is faced with as well as her peers;
- economic constraints, i.e., the immediate economic pressures, such as availability of credit, cost of measures, etc. faced by the farmer as well as financial incentives and compensation payments;
- decision characteristics, i.e., factors that are inherently related to the specific decision, including the 'goodness of fit' [29] of the decision with the overall activities of the farmer, including the fit with existing legal restrictions.

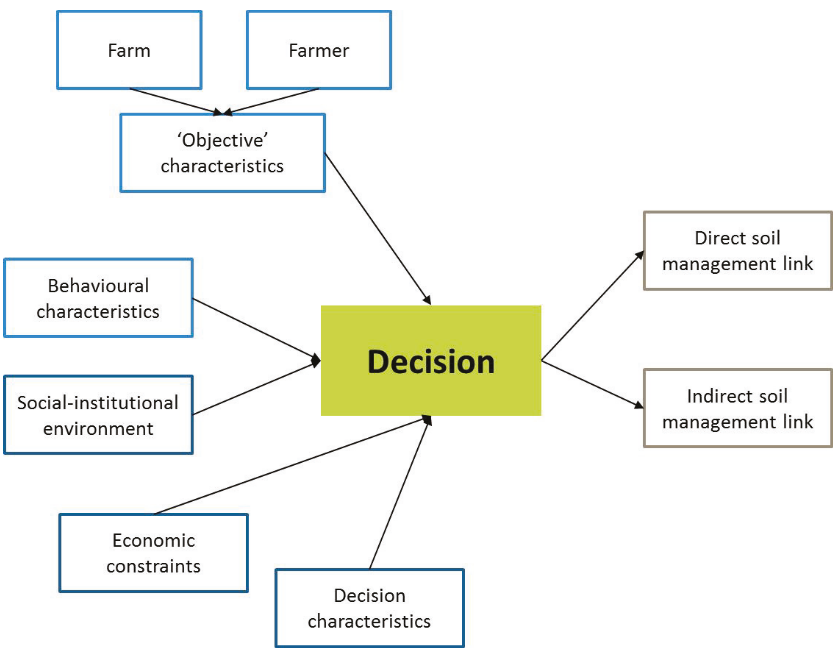


**Figure 1.** Conceptual framework of farmers' decision-making related to soil management.

The first three categories can be considered internal factors, which describe the decision-making farmer and do not vary across decisions; the latter three are external factors, which may vary across decisions, though to different extent (increasing in the order they are listed above) [30]. Of course, it is not always possible to clearly distinguish between those categories and there are overlaps. This part of the framework bears some superficial similarity with the basic conceptual framework of the Theory of Planned Behaviour [31]. However, it is kept more general and interpretationally flexible so as to do justice to the vast diversity of theoretical approaches underlying the studies included in our review, only some of which are based on the Theory of Planned Behaviour. Similar frameworks in a related context can be found for example in Greiner and Gregg's [32] study on the adoption of conservation practices by Australian farmers or in the above-mentioned review by Liu et al. [20]. Furthermore, the framework has been developed iteratively so as to fit the range of factors (decision-making determinants) identified in the literature reviewed here. The right-hand part of the framework presented in Figure 1 refers to the link between different decisions made by farmers and soil management. In some cases, this link may be quite direct; for instance, when the decision regards ploughing or fertilisation. In other cases, however, the link may be rather indirect; for example, when the decision is about which type of tractor to buy. This framework will guide the analysis of the empirical literature surveyed here.

## 3. Data and Methods

### 3.1. Literature Review

The literature review has the aim to identify a comprehensive selection of empirical studies investigating factors that influence the decision-making of farmers in European countries. Due to the heterogeneity of the reviewed literature and workload constraints, we refrained from conducting a fully comprehensive systematic literature review. However, comparison with earlier reviews focusing on specific decision types (see Section 1) suggests that our selection is fairly representative and captures the largest part of the literature. Pragmatic considerations dictated geographic restrictions; we decided for the E.U. and neighbouring countries (particularly Switzerland) due to their common political, economic, and cultural background (the search also included all European countries except Russia and small states, such as San Marino or Andorra; however, no studies were found nor included from outside the E.U. and Switzerland). A combination of keywords (see Appendix A) was used to identify studies that match the three basic criteria: empirical studies (i) focusing on farmers' decision-making (ii) in Europe (iii). The search string was applied to the Web of Science (All databases); all articles indexed by 10 September 2017 were included. A total of 308 publications matching the combination search terms was detected. In a second step, their abstracts were screened to exclude those that are not relevant for the purposes of this review. Reasons for exclusion and the frequency of their application in the screening process are listed in Table 1.

**Table 1.** Number of excluded papers by exclusion criterion.

| Exclusion Criterion | Number of Excluded Papers |
|---|---|
| Human/animal health/welfare | 73 |
| Non-European | 64 |
| No decision-making focus | 24 |
| Not empirical | 8 |
| Decisions clearly without link to soils | 5 |
| Covered in earlier publication(s) | 5 |
| Others (non-English, biology . . . ) | 12 |

The application of the exclusion criteria to the abstracts reduced the number of relevant studies to 117; of those, 3 were not accessible. The remaining 114 studies were then subjected to full-text analysis; during this process, another 27 studies were found to be irrelevant so that the final analysis is based on a total of 87 studies. Table 2 summarises the information extracted and coded from the publications included in the literature review. In addition to matching behavioural factors with the categories of the conceptual framework, we follow Floress et al. [33] in distinguishing between actual decisions ('behavior' in their nomenclature) and hypothetical decisions ('willingness or intent'). Where possible, we linked the decision-making problem to soil pressures based on Vogel et al. [10]: tillage, crop rotation, fertilization, pest control, irrigation, and compaction/traffic. Both decision types and influencing factors were grouped into generic categories for the purposes of further analysis.

**Table 2.** Description of information extracted from reviewed studies.

| Category | Explanation | Data Type |
|---|---|---|
| | **Publication Description** | |
| ID | Running number for each study, in chronological order according to Web of Science | Integer |
| Authors | Authors of the study (short) | Text |
| Year | Year of publication | Integer |
| Title | Title of publication | Text |
| Journal | Journal of publication | Text |
| DOI | Digital Object Identifier (if available) | Text |
| | **Decision Context** | |
| Production type | Type of agricultural production (livestock, food, biomass, multiple *) | Category |
| Production type specific | Specification of 'Production type' | Text |
| Agriculture type | Type of agriculture (conventional, organic, multiple *) | Category |
| Soil pressure | Soil pressure type related to the decision studied, if applicable | Category |
| Region | Region of study according to publication | Text |
| Country code | ISO 3166-1 Alpha-2 code | Category |
| Time period | Time when study was conducted according to publication | Integer (ranges) |
| Year | Latest year of 'Time period' | Integer |
| Sample size | Number of farmers or farms studied | Integer |
| Remarks | Additional remarks pertaining to study | Text |
| | **Behavioural Factors** | |
| Method | Method applied in study | Category |
| Theoretical background | Theoretical background of study (if explicitly mentioned) | Category |
| Inductive | Decision-making factors identified in study were inductively derived (versus: were preformulated as hypothesis, i.e., deductive) | YES/NO |
| Justification of relevance | Explicit relation to a specific societal challenge (e.g., sustainability, climate change, bioeconomy) | Category |
| Factor | Individual decision-making factor (generalised where possible) | Category |
| Framework category | Relation of the factor to a category of the conceptual framework | Category |
| Significant | Statistical significance of the factor in study, if applicable | YES/NO |
| Decision type specific | Type of decision analysed in study | Text |
| Decision type | Categorised type of decision | Category |
| Actual decision | Decision analysed was actual (behaviour) versus hypothetical (intention/willingness) | YES/NO |
| Direction of influence | Factor facilitating ('positive') or counteracting ('negative') behaviour under study, if applicable | Positive/negative |
| Remarks | Further information about the factor or its link to decision, incl. specification of 'Factor' where necessary | Text |

* 'multiple' includes unknown (it is assumed that if no explicit information is provided, no distinction was made in the study design).

Except for some descriptive statistics, the analysis of the 87 empirical studies is largely qualitative, other than, for example, Prokopy et al.'s [22] meta-analysis of the determinants of agricultural best management practices. The reasons for this are twofold. First, many of the studies analysed are themselves qualitative and little or no quantitative data pertaining to the question at hand could be derived from them. Second, the range of types of analysis in terms of disciplinary and theoretical background is very large, which means that a qualitative synthesis is more sensible. This means that it is impossible, on the basis of our analysis, to estimate the relative strength of the different factors in determining decision-making behaviour.

### 3.2. Bibliometric Analysis

Because of the diversity of the literature reviewed, it is worthwhile to review general patterns that connect or divide this body of literature. For such purposes, tools of bibliometric analysis are useful. In this paper, we use VOSviewer, Leiden University, The Netherlands [34] to visualise some basic patterns of relationship among the publications included in our review. The visualisations are based on the 'full records and citations' from Web of Science for all 87 reviewed publications.

## 4. Literature Review Results

### 4.1. Bibliometric Results

The choice of journals can be used as an indicator of the disciplinary background of studies. In total, articles from 48 different journals entered our survey. As can be seen in Figure 2, the most widely represented journals (with at least two articles in the review) include interdisciplinary (Land Use Policy, Journal of Environmental Management, Agricultural Systems, Journal of Environmental Planning and Management, Outlook on Agriculture, to some extent also Ecological Economics), economic (Journal of Agricultural Economics, Ecological Economics, Agricultural Economics—Czech), sociological (Journal of Rural Studies, Sociologia Ruralis), and applied ethics (Agriculture and Human Values) journals. The large category of 'others' contains further journals from above-mentioned disciplines, but also from agronomy, ecology, geography, management, and psychology.

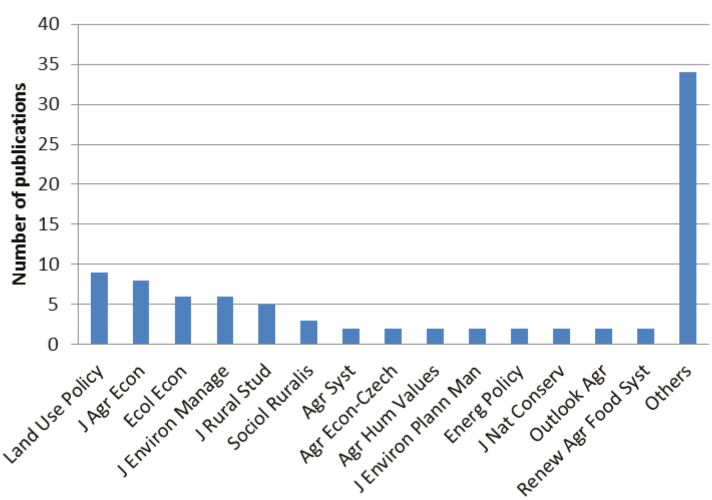


**Figure 2.** Distribution of publications across journals.

Despite this disciplinary diversity, there are many bibliographic links within the reviewed body of literature (Figure 3). The most widely cited study is Morris and Potter's [35] pioneering analysis of the adoption of AESs by U.K. farmers (15 citations within the reviewed corpus). The colours in Figure 3 indicate clusters identified by VOSviewer on the basis of cross- and co-citations [36]: the red cluster consists mainly of discrete choice experiments (CE) on AES participation; the dark blue cluster are predominantly economic (but non-CE) studies of AES participation, while sociological studies with the same (AES) focus form the green cluster.

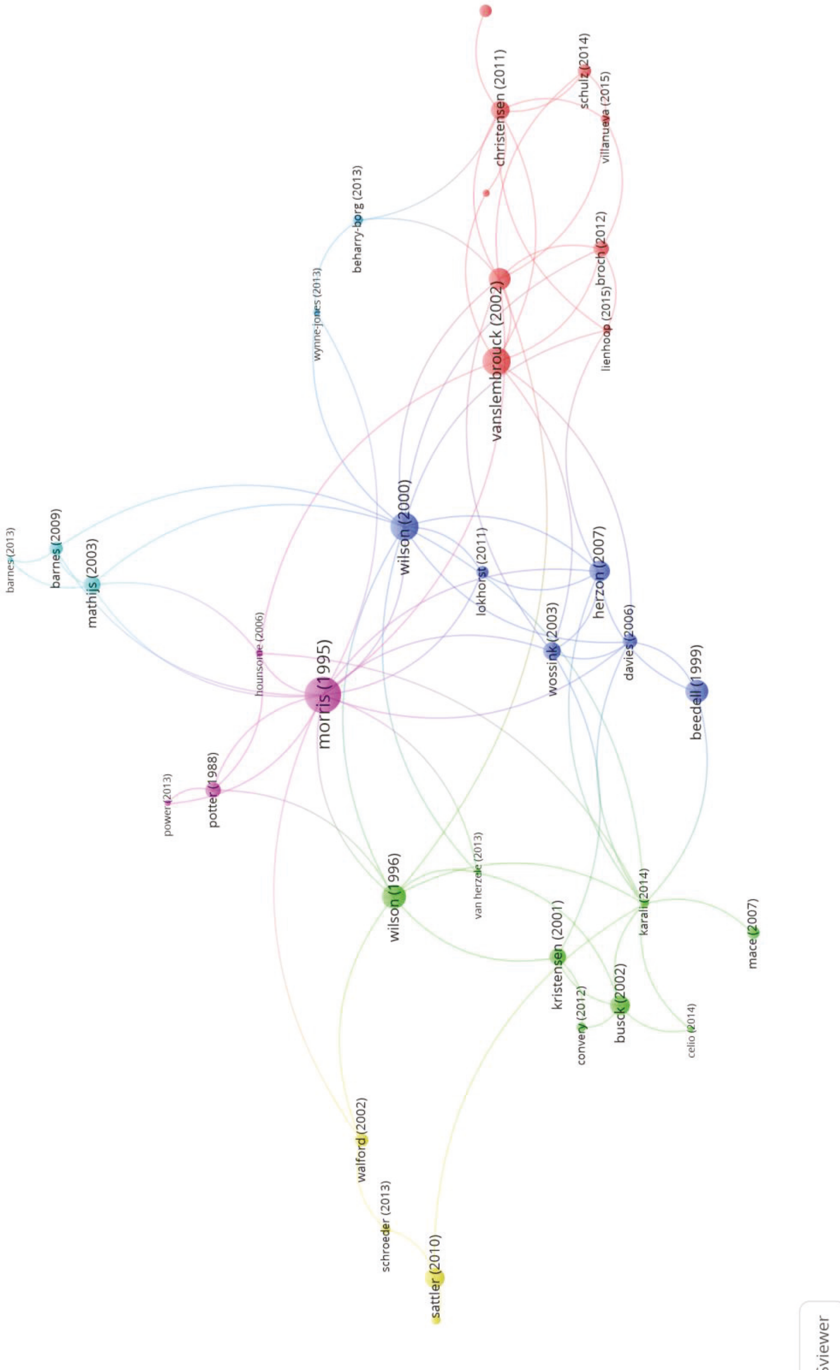


**Figure 3.** Cross-citations between publications included in review.

*4.2. Descriptive Results*

In this section, the main descriptive results of the review are summarised. With respect to the geographic distribution of the studies analysed, most were conducted in the large E.U. countries U.K., Germany, France, Spain, and Italy; among the smaller countries, Denmark, Greece, Belgium, Sweden, and The Netherlands are particularly well-represented (Figure 4). It is striking that eastern E.U. member states are heavily under-represented in this literature, despite of or maybe due to their relatively late accession to the E.U., offering an interesting context for decision-making analysis.

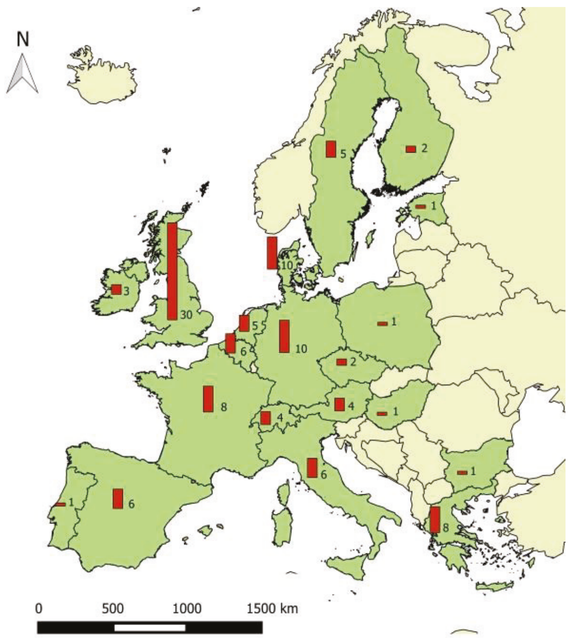


**Figure 4.** Distribution of studies across countries.

Most studies included in the review were conducted and published post-2008 (Figure 5); for 23 studies, no time frame was reported.

Table 3 matches categories of the conceptual framework with factors (decision-making determinants) identified in the review. It mainly illustrates the diversity of factors within each category and not the frequency with which each category was present in the studies analysed, as some factors were analysed only once or twice, while others were analysed in multiple studies each. The most frequently analysed factors were: economic considerations (analysed 55 times), pro-environmental attitude (36), age (34), education (28), farm size (27), entrepreneurial attitudes (21), perception of the problem (20), symbolic capital (18) (note that the term symbolic capital is used rather loosely here and does not correspond perfectly to its more specific use in the Bourdieu-inspired literature [29,37,38]; rather, here it encompasses all notions of perception by others, be it peers or customers or the general society), income-dependency on farm (16), and past experience (16). Note that some studies analysed some factors in more than one variant; for example, economic considerations were studied in 47 studies, but those generated 55 results for this factor.

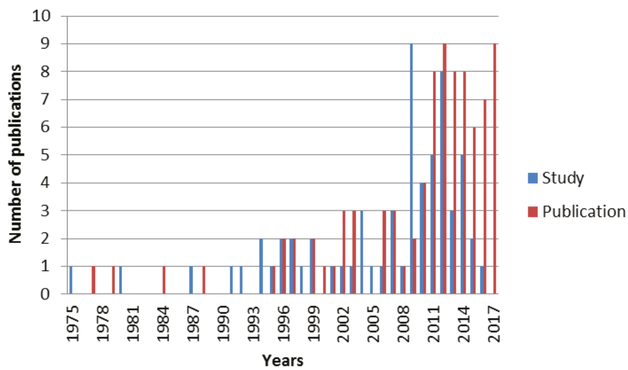


**Figure 5.** Temporal distribution of studies.

**Table 3.** Factors identified in review and framework categories.

| Framework Categories | Factors Identified in Review | # |
|---|---|---|
| Objective characteristics of farm | Accessibility of parcels, availability of resources, environmental conditions, farm diversification, farm location, farm profitability, farm size, on-farm technologies, own land of special interest, reduction farm activities, share of non-family labour, successorship, tenure, type of agriculture, var. farm characteristics, yield | 86 |
| Objective characteristics of farmer | Age, agricultural training, education, farming experience, gender, health, household size, income, income-dependency on farm, marital status, parent, past experience, path dependency, previous training | 125 |
| Behavioural characteristics | Attitude towards regulatory framework, awareness, beliefs, conservativeness, entrepreneurial attitudes, environmental awareness, general attitudes, identity, knowledge, lifestyle, loss aversion, peer orientation, perception of the problem, pro-environmental attitude, risk aversion, satisfaction, situational stress, symbolic capital, trust, values, vocation | 159 |
| Social-institutional environment | Advisory services, availability of information, dealers/representatives, local authorities, social capital, social norms | 32 |
| Economic constraints | Availability of credit, availability of labour, economic considerations, financial stress | 59 |
| Decision characteristics | Availability of advice, availability of leisure, bureaucratic load, collective participation, complexity of measure, context-specificity, contract length, contract specifications, measure efficacy, eligibility for further funding, environmental effects of measure, fit with existing legal restrictions, fit with existing practices, flexibility of contract, investment needs, labour intensity, monitoring, product quality, purpose of measure, self-employment | 74 |

The factors listed in Table 3 have been analysed in the studies included in our review in a number of different decision-making contexts. Figure 6 depicts the frequency of decision types within the body of literature. The most frequent decision types are participation in AES, choice of management (for instance, choice of pest control measures, decision between mowing and grazing, timing of manuring), local conservation (non-AES adoption of environmentally friendly management), (adoption or abandonment of) organic farming, adaptation to climate change, and water use choices (for instance irrigation) (see also Table 4).

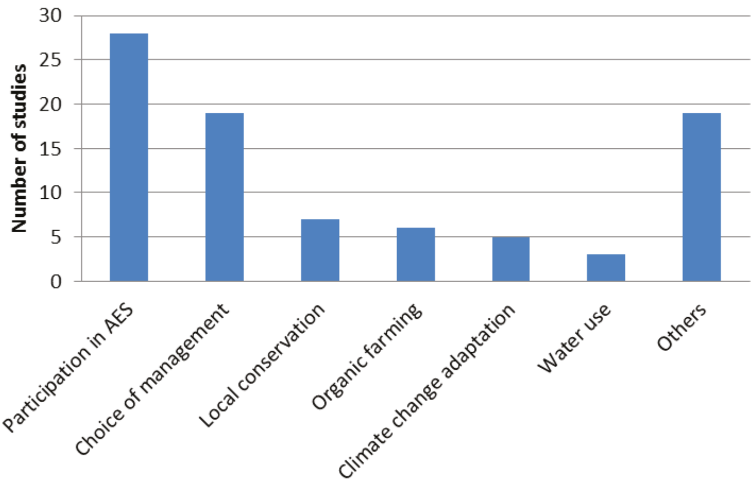


**Figure 6.** Frequency of decision types analysed across studies.

The decisions analysed in each study can be linked in some instances to soil pressures. The most frequent soil pressures are fertilization and pest control; however, since hardly any study had a specific focus on soil management, most decisions analysed had only an indirect link to soil and thus affected multiple soil pressures (Figure 7).

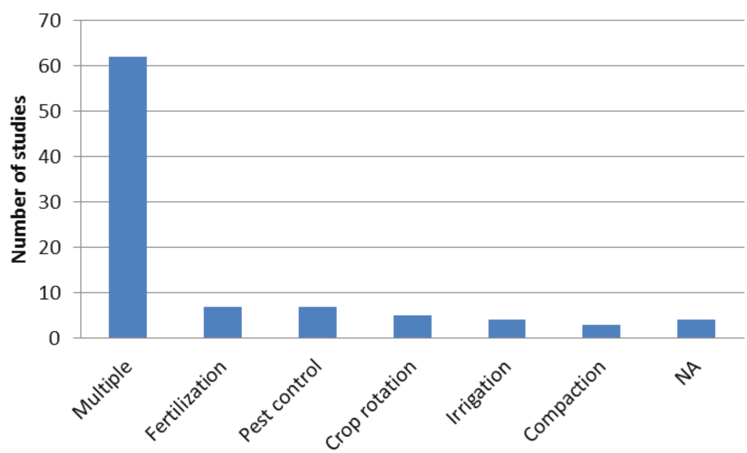


**Figure 7.** Soil pressures associated with analysed decisions.

Table 4 presents an overview of all decision types identified, the methods applied for each decision type, and the studies that analysed it. The frequency of each method class can be found in Figure A2 in Appendix B. In 54 studies, actual decisions were analysed, while 40 focused on hypothetical decisions (7 studies did both).

**Table 4.** Overview of decision types, methods applied, and studies.

| Decision Type | Methods Applied | Studies |
|---|---|---|
| Acceptance of cross compliance | Questionnaire survey | Davies and Hodge [39] |
| Adoption of renewable energy production | Questionnaire survey, interviews, focus groups | Convery et al. [40], Reise et al. [41], Tate et al. [42], Warren et al. [43] |
| Choice of management | Questionnaire survey, interviews, choice experiment, role-playing game | Bager and Proost [44], Mary et al. [45], Macé et al. [46], Ingram [47], Barnes et al. [48], Wright and Jacobsen [49], Papadopoulou [50], Sharma et al. [51], Morgan-Davies et al. [52], Pedersen et al. [53], Barnes et al. [54], Beharry-Borg et al. [55], Karelakis et al. [56], Damalas and Koutroubas [57], Jaeck and Lifran [58], Lamarque et al. [59], Bechini et al. [60], Macgregor and Warren [61] |
| Choice of machinery | Interviews | Foxall [62] |
| Climate change adaptation | Questionnaire survey, interviews, choice experiment | Holloway and Ilbery [63], Pröbstl-Haider et al. [64], Urquijo and De Stefano [65], Li et al. [66], Woods et al. [67] |
| Diversification | Questionnaire survey, interviews | Hansson et al. [68], Morris et al. [69] |
| Entering a new market | Interviews, questionnaire survey | Ambrosius et al. [70], Demartini et al. [71] |
| Environmental behaviour | Questionnaire survey | Vogel [72] |
| General decision-making | Questionnaire survey | Celio et al. [73] |
| Illegal wildlife killing | Questionnaire survey | Cerri et al. [74] |
| Investment decision | Internet-based experiment | Hermann et al. [75] |
| Job change | Choice experiment | Lips et al. [76] |
| Local conservation | Questionnaire survey, interviews | Beedell and Rehman [77], Kristensen et al. [78], Busck [79], Herzon and Mikk [80], Sattler and Nagel [81], Lokhorst et al. [82], Mills et al. [83] |
| Organic farming | Questionnaire survey, interviews, duration analysis, Bayesian modelling | Kirner et al. [84], Kallas et al. [85], Mzoughi [86], Tiffin and Balcombe [87], Mann and Gairing [88], Power et al. [89], Karali et al. [90] |
| Participation in agri-environmental schemes (AESs) | Choice experiment, questionnaire survey, interviews, contingent valuation | Potter and Gasson [91], Morris and Potter [35], Wilson [92], Wilson and Hart [14], Vanslembrouck et al. [93], Walford [94], Mathijs [95], Söderqvist [96], Wossink and van Wenum [97], Hounsome et al. [98], Ruto and Garrod [99], Christensen et al. [100], Lapka et al. [101], Broch and Vedel [102], Buckley et al. [103], McKenzie et al. [104], Schroeder et al. [105], Van Herzele et al. [106], Wynne-Jones [107], Karali et al. [90], Alló et al. [108], Lienhoop and Brouwer [109], Micha et al. [110], Villanueva et al. [111], Franzén et al. [112], Sardaro et al. [113], de Krom [114], Josefsson et al. [115], Schreiner and Hess [116] |
| Participation in cooperative | Interviews | Gasson [117] |
| Participation in greening | Choice experiment | Schulz et al. [118] |
| Risk management strategies | Questionnaire survey | van Winsen et al. [119] |
| Specialisation | Interviews | Ilbery [120] |
| Water use | Contingent valuation, questionnaire survey | Menegaki et al. [121], Bakopoulou et al. [122], Giannoccaro and Berbel [123] |

Further results can be found in Appendix B.

## 5. Discussion

Given the large number of decision-making contexts, investigated factors, and methodological approaches, we will focus in the discussion on pointing out particularly strong results and particularly interesting ones (which, of course, will be based on a significant amount of subjective evaluation of which results are interesting) in the literature focused on European cases. However, Figure 8 provides a more general overview by highlighting the most frequently studied (considered in at least 9 publications, i.e., 10 or more percent of the overall 87 studies) decision-influencing factors and their significance.

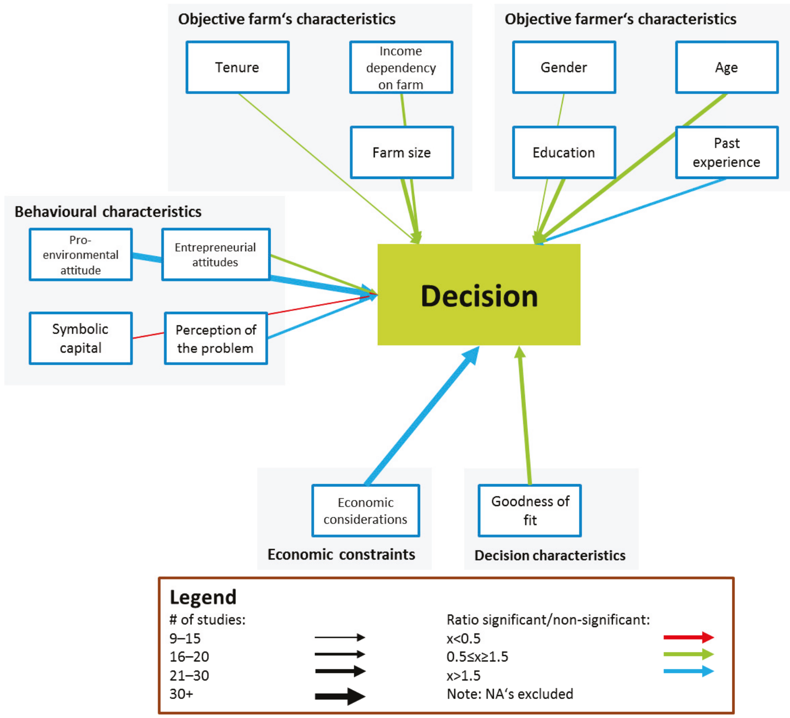


**Figure 8.** Most frequent factors sorted by conceptual framework categories.

It is immediately recognizable where the research gaps are located. Particularly, no decision-influencing factor of the category 'social-institutional environment' has been studied in 10 or more studies, the cut-off number for Figure 8.

The most frequently studied factor is, as already mentioned in the Results section, economic considerations (47 studies). In this broad category, various notions of changes in prices and costs as well as general considerations related to financial restrictions and monetary incentives related to the decision at hand are included. In line with the classic findings by Wilson and Hart [14], economic considerations have a rather strong influence on decision-making across studies, with only two studies finding this factor to be non-significant: Micha et al. [110] found that financial considerations do not influence farmers' willingness to participate in a subsidy scheme for organic vine growing; and in Lamarque et al.'s [59] innovative study of mountain grassland farmers, distance-related costs had no significant influence on their hypothetical decisions. Overall, however, the observation is quite robust across studies: economic considerations have a significant influence on all manner of decisions made by farmers. Given that farmers are, among other things, entrepreneurs, this is not surprising. In fact, it should be more interesting to see what other factors are influential, especially if they can be expected to counteract the effects of economic considerations on farmers' decision-making.

Another frequently studied group of factors was demographic characteristics of farmers, particularly age (29 studies) and education (26 studies). Here, the results are mixed, with similar numbers of significant and non-significant studies. This is very much in line with the results of the excellent study by Burton [18], who provides a number of possible explanations for the seemingly contradictory results across different studies. In contrast, another demographic characteristic—gender—has been studied much less frequently (nine studies); here, too, both significant and non-significant effects have been found (four and five times, respectively). While most farmers in Europe are male [124], the proportion of women in the agricultural working force ranges between 30 and 50 percent in most E.U. countries, so if women behave differently than men, as some of the studies analysed here indicate [86,108,112,121], it would be interesting to understand why this is the case, especially given the societal dynamics towards more equal representation of genders across sectors.

Farm size is another quite frequently studied decision-influencing factor (27 studies). We find 14 studies where farm size is a significant determinant (10 non-significant), showing mostly a positive influence on decision to participate in AESs [93,96,97,105,108], to participate in cooperatives [117], impacting pesticides use and pest management [50,51], and the willingness to adopt renewable energies [42]. Although economies of scale and space to try new options might be the key for the implementation of new practices, several studies found no clear link of farm size to factors such as adoption of organic farming [87], renewable energies [42], climate adaptation [67] or local conservation measures [82], cross compliance [39], participation in AES [95,112,116] or in CAP greening [118], or regarding the specialization on hop [120], indicating that farmers' decisions are not merely correlated with or dependent on the available field size in the European context.

Behavioural factors have been studied quite intensively, with pro-environmental attitude and entrepreneurial attitudes being the most frequently studied ones (33 and 17 studies, respectively). Interestingly, the effect of a pro-environmental attitude on decision-making has been consistently significant in most studies, which is a striking result as compared to the well-known attitude–behaviour gap found in studies of consumers [125]. This may be due to the fact that farmers generally have a more direct influence on the environmental effects of their behaviour than consumers; moreover, in the E.U. they are provided with incentives to live up to their attitude (organic farming payments, agri-environmental and climate measures, etc.). On the other hand, Tiffin and Balcombe [87] found no significant effects of pro-environmental attitude, measured by the membership in an environmental organisation, on the adoption of organic farming. Many studies in this context employed qualitative methods, so they do not report significant effects in the statistical sense. However, the qualitatively identified effects of pro-environmental attitude are consistently pointing towards pro-environmental behaviour: it plays a role in the participation in AES [35,90,106], counters incentives to abandon organic farming [84], and has positive influence on more general environmentally friendly on-farm practices [54,77,83].

In contrast to pro-environmental attitude, entrepreneurial attitudes—particularly the classic distinction between productivist and post-productivist attitudes [126], but also more general attitudes towards the goals of farming (e.g., purely profit-oriented versus 'landscape stewardship' versus production of healthy food)—have very different effects on decision-making. Significant influences have been found regarding decisions to participate in AESs in environmentally sensitive areas [92], but against AESs related to field margin or in animal-welfare programmes [97,116]; by tendency in disfavour of adopting organic farming [87,89], yet positively related to adopting renewable energies [42] as well as investing in a hog barn [75]. However, several insignificant results are documented, too, related to participation in country stewardship schemes and in field margin programmes as part of AESs [95,97], to acceptance of cross compliance [39], or on adoption of integrated crop protection or organic farming [86–88]. Further studies investigated the role of entrepreneurial attitudes related to decisions on intercropping [45], manure management [48], switching to biomass production [40], and generally on diversification of business [69]; however, without clear generalisable conclusions. The diversity of the factor makes it difficult to conclude, yet a notable degree of entrepreneurial spirit seems to be a potential trigger of farmers' behaviour to explore and adapt to new practices.

Symbolic capital is a notion developed in the context of Pierre Bourdieu's sociological theory of capital(s) and has been much discussed in the context of farming [29,37,38]; here, we use this term in a broader sense, encompassing any considerations by farmers that are related to how they are perceived by others: be it farmer colleagues, consumers, or the general public. There is partly a strong similarity between this factor and 'entrepreneurial attitude', as in both cases one's self-image as a farmer plays a strong role. The results here are mixed, partly because of the large differences in what was measured specifically, from the importance of 'clean fields' [53] to 'farm image' [14], but also the influence of 'symbolic capital', for example on participation in AESs, depends strongly on which type of image is important to the farmer. However, it seems that overall symbolic capital has some influence on farmers' decision-making, though this influence varies depending on context.

One of the few factors with a consistent effect across studies is past experience (usually in the context of participation in AESs): farmers who already once participated in a scheme or measure are more likely to participate in similar schemes or measures in the future. This statistical effect finds strong support and thorough sociological explanation in the recent study by Riley [29], who re-interviewed participants of an older study regarding AES participation after circa 10 years to find that they had grown accustomed to the scheme and developed an understanding for its rationale and an identification with it. However, this of course does not answer the question of how farmers can be incentivised to join such schemes and measures in the first place, i.e., how individual path dependencies may be best overcome [46].

Another rather strong and important factor is 'goodness of fit', both in terms of fit with existing management practices and fit with legal obligations. Particularly, the former dimension has multiple aspects; of course, easily implemented measures are preferred by farmers, as they minimise effort [106]. However, oftentimes the measures discussed in the studies simply did not fit the orientation of the farmers' activities; for instance, in Warren et al.'s [43] study of willingness to introduce short-rotation coppice, an important obstacle was that many interviewed farmers focused on animal husbandry, not arable farming. On the positive side, in Bechini et al.'s [60] study, the incorporation of crop residues to improve soil quality appeared to be attractive where burning of the residues was prohibited, thus restricting the space of alternative options. Overall, it appears that goodness of fit is consistently influential for farmers' decision-making, a result that has some intuitive appeal. This is particularly important for the design of policy instruments meant to incentivise sustainable management practices (see next section).

Institutional economics suggests that property rights are a very important determinant of resource management [127]; therefore, it is often assumed that tenure status is an important factor influencing decision-making behaviour of farmers [22,128]. However, the results in this respect are rather mixed, with significant and non-significant effects found equally frequently. The literature on the relationship between tenure prices and land rents resulting from CAP direct payments demonstrates that the effects of tenure are much more complex than simple economic models suggest [129]; similar complexity can be expected in the context of their influence on farmers' decision-making. Therefore, we can only repeat Prokopy et al.'s [22] 10-year-old call for more research in this area.

There are a number of factors that have been studied only in very few studies each, some of which appear potentially highly relevant and interesting. In what follows, we briefly comment on a few such factors that deserve more research attention as they are potentially relevant for governance:

*On-farm (adoption of) technologies*: given that precision (or smart) farming is increasingly considered an important option that may help achieve more sustainability in farming generally [130] and in agricultural soil management specifically [8], the lack of insights into how on-farm adoption and use of technologies, both agricultural and general-purpose (for instance broadband internet), interacts with decision-making is bothering and an important research gap. In one of the few studies in this context, Morris et al. [69] found a relationship between use of technologies (decision-support systems, broadband internet, farm website) and diversification of and beyond farm activities.

*Advisory services*: Knowledge and information are preconditions to action. Surprisingly, we found only a few studies on the role of advisory services. Even more surprising is that we do not find a clear link but again a mixed picture related to the significance of the impact on farmers' decision-making, for example to facilitate best management practices, new ideas, and new technologies [44,47,70,83,116]. Bager and Proost [44] illustrate that advice as a voluntary measure to influence farmer behaviour can be effective alongside compulsory regulation by supporting farmers in the search and readiness for new technical solutions and through influencing farmers' priorities and attitudes. It is noteworthy that the efficacy is linked to habits of interaction, for example a tradition of strong study groups as found in the Netherlands. Ingram [47] emphasises that group activities with empowerment and reorientation are a more effective form of advice than mere provision of information, while also pointing out that the advisor's motivations and values play a key role. Mills et al. [83] point out that advisory services will be effective only if they cope with the heterogeneity of farmers' beliefs and values. Hence, more research is needed to understand the effective co-creation of credible and trusted partnerships enabling a co-production of knowledge and understanding [47,83].

*Bureaucratic load*: as agriculture in the E.U. (and most OECD (Organization for Economic Co-Operation and Development) countries) is heavily regulated and farmers are highly dependent on CAP direct and other payments [131], the bureaucratic load can be expected to play a major role in decision-making, particularly with respect to voluntary participation in measures such as AESs or organic farming [14,84,90,99,100,118]. Curiously enough, studies of the actual extent of bureaucratic work as part of overall farm-related workload seem to be non-existent; the few available studies of time allocation by farmers focus on allocation between on-farm and off-farm labour [132,133]. Relatedly, there has been little research so far on the attitude of farmers towards their own subsidy-dependence, though some indications can be found scattered in the literature that subsidy-dependence is met with discontent [69,107].

*Social capital, social norms, peer orientation*: we already discussed above the broad and diverse influence of 'symbolic capital' on farmers' decision-making. A related set of so far understudied factors are social capital, social norms, and peer orientation. These are difficult-to-capture factors that may, however, have large relevance for decision-making. The extent to which farmers have social networks [73,108,116], how open they are to those [95], and the type of norms and how they respond to them [83] are important influences on on-farm decision-making. Particularly, in the face of movements such as community-supported agriculture [134], it is no longer only relationships towards other farmers and advisors that are relevant, but also social interactions with consumers gain increasing importance.

*Risk aversion*: there is a growing literature on the opportunities to alleviate (downside) risk involved in agricultural practices not only by means of financial instruments but also management practices that increase biodiversity [135–138], and while there are studies on the influence of risk and risk aversion on farmers' decision-making, with rather consistent results indicating that risk plays a large role, there is still much need for further investigation, including specifically in the context of biodiversity-increasing management practices.

One striking result of our literature review is that there are hardly any studies of farmers' decision-making behaviour that can be clearly linked to soil management and soil pressures. This is also reflected in the under-representation of particular decision types. For instance, the already mentioned issue of adoption of technologies, particularly choice of machinery—so crucial in the context of smart farming [130]—is vastly understudied. In our selection of studies, only Foxall's [62] 1979 study of tractor choice was explicitly devoted to this topic. Bukchin and Kerret's [139] recent literature review suggests which 'personal resources' (behavioural characteristics in our nomenclature) influence technology adoption. While the authors transfer these findings to the adoption of 'green technologies' by farmers, there is a need for more empirical research specifically targeting farmers' decision-making in this context. It is striking that decisions for specific machinery have not been examined despite an increasing practitioners' debate on more flexible tools to cater to smaller field owner requirements [8].

Another area that deserves more investigation is climate change adaptation: climate change is increasingly affecting European agriculture, with significant consequences for example in terms of soil moisture [140,141]. How European farmers adapt to climate change and what influences their decisions in this context is still a largely open question. Soils and their management play a major role in this context [142]. More generally, farmers' willingness to diversify and engage in non-farming activities, to go beyond traditional farming identities exemplified by the figure of 'good farmer' [28], thus overcoming path dependencies, enlarging individual option space, and possibly also contributing to making agricultural landscapes more multifunctional [143] is currently not well-understood.

Inevitably, due to challenges in optimizing the search string for the literature review, some literature might have been missed in our analysis. For instance, Prager and Posthumus [17] include some relevant studies not covered by our review (we thank a reviewer for pointing this out); their overall results, however, are largely consistent with ours.

## 6. Implications for Soil Governance

The main message of the literature corpus reviewed and synthesised above is probably not very surprising: economic constraints are an essential determinant of farmers' decision-making behaviour. However, economic constraints are not all there is, and this is a highly important insight. It means that a sole focus on economic factors in designing soil governance instruments can lead to inefficiencies; if, for instance, an AES provides significant remuneration, but ignores cultural opposition to the thus incentivised practices, it may be necessary to offer an inefficiently high payment in order to overcome cultural barriers and achieve a sufficient coverage by the scheme. However, if the cultural opposition (or other non-economic factors present) is tackled directly in an appropriate way, the cost of the governance instruments need not be inefficiently high. For this, however, there is a general need for information about both economic and non-economic factors that are determinants of farmers' decision-making in terms of their distribution among target populations for policy and governance so that targeted instruments can be designed.

Specifically, in our review, we have identified multiple relevant factors that influence farmers' decision-making alongside prices, (opportunity) costs, and financial incentives. These factors should be taken into account in designing agri-environmental policy instruments both in the context of soils and beyond. Not all of them are equally relevant for governance purposes, of course. For instance, empirical results across studies show the importance of demographic factors [19], but these are a datum that cannot be easily influenced. Knowledge of their importance has mainly the role of informing which farmer groups may be targeted differently and how, but the age structure or gender representation among farmers can hardly be affected by means of agri-environmental policy (though, of course, there are attempts to influence these factors in a more long-term way by means of other types of social and agricultural policy, for example through payments to young farmers within the CAP).

Conversely, the significant influence of pro-environmental attitudes on farmers' decision-making suggests an avenue for fostering sustainable soil management. Although attitudes are not easily influenced, approaches targeting them—for instance, by means of education, information provision, exchange with other farmers (field days etc.)—can be used to support the effect of other types of incentives, including economic instruments. Recent psychological research provides crucial insights into how attitude change is triggered by, for instance, social media and social networks [144]. This research shows, among other things, that the influence of peers ('buzz agents') is large and has already been harnessed in both marketing and public policy.

One important result of our review, particularly in the context of soil management, is the decisiveness of 'goodness of fit'. Soils are highly heterogeneous and multifunctional, which makes generic governance solutions potentially ineffective. Thus, context-specificity and spatial explicitness of instruments are generally required in soil governance. This insight is strengthened by the widespread observation that farmers prefer adopting measures that are consistent with their own status quo activities; understandably, they prefer incremental changes in practices rather than large-scale, uncertain overhauls. This suggests that on top of being context-specific, soil governance instruments should be flexible so as to allow for step-by-step adaptation of practices.

In the previous section, we discussed a number of interesting but understudied factors influencing farmers' decision-making. Three of those appear to be particularly relevant from the point of view of (soil) governance. First, there is the role of extension services and agricultural/agronomic advisors. The vast diversity of advisory services available to farmers and the complex interactions between the two groups suggest that their role in facilitating sustainable practices, including sustainable soil management, should be carefully considered [47,83,145]. Innovative formats, such as collaborative extension services that bring together farmers with potentially different perspectives (note the link to the above discussion of fostering pro-environmental attitudes), may have particularly large potential in this respect [44], but there is a need for more research into the role of advisory services. Second, many existing agricultural policies lead to a significant bureaucratic load faced by farmers. However, modern technological developments, such as precision farming and the thus generated data, may lower this load if the information currently provided by farmers could be generated, stored, and transmitted (semi-)automatically and with higher precision [130,146]. Furthermore, this and the technologies involved may allow us to make soil governance instruments more context-specific and spatially explicit, for instance by overcoming the measurement and attribution barriers that have so far largely prevented the adoption of result-oriented AESs [147,148]. Third and relatedly, use and adoption of technologies is a highly understudied issue, which, however, is highly important against the background of the opportunities offered by precision farming and related technological developments for soil management and governance.

## 7. Conclusions

Effective, efficient, and legitimate natural resource and agri-environmental governance requires a thorough understanding of the natural system in as much as flexibility to adjust rules and (formal) institutional settings to new knowledge. One element to leverage governance is the knowledge of the behavioural characteristics of the involved actor groups. In this paper, we focused on sustainable governance of agricultural soils and on farmers as the group with the most direct relationship to this particular resource. In our synthesising analysis of existing empirical studies of farmers' decision-making, we found that while economic constraints and incentives are very important in this context, other factors also have significant effects. Particularly strong and consistent effects have been found for pro-environmental attitudes, goodness of fit, and past experience. Conversely, we found mixed results for demographic factors and symbolic capital. We also identified a number of interesting yet understudied factors, including adoption of technologies, advisory services, bureaucratic load, risk aversion and social capital, social norms, and peer orientation. These are factors that are potentially highly relevant for soil governance, particularly against the background of recent technological developments, but robust empirical evidence is still missing (though existing studies give hints at the possible effects). From those results we derived implications for governance, which boil down to the main message of the paper, namely that the non-economic factors influencing farmers' decision-making should not be easily brushed aside, as their consideration in combination with economic factors may well improve the efficiency, effectiveness, and legitimacy of soil governance.

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## Appendix A

Search term combination:

TITLE: ((decision* OR adoption OR behavio* OR involvement OR participat* OR accept* OR practice* OR willingness* OR preference* OR response*) AND farmer*) AND TOPIC: ((“q method*” OR “q-method*” OR delphi OR interview* OR “focus group*” OR “group discussion*” OR experiment* OR survey OR participatory OR questionnaire* OR workshop* OR “case stud*”) AND (Europ* OR Portug* OR Spain OR Spanish OR France OR French OR Ireland OR Irish OR “United Kingdom” OR Brit* OR Engl* OR Wales OR Welsh OR Scot* OR Belg* OR Dutch OR Netherland* OR Holland OR Swiss OR Switzerland OR German* OR Ital* OR Austria* OR Denmark OR Danish OR Norw* OR Swed* OR Finland OR Finnish OR Icel* OR Poland OR Polish OR Czech OR Slovak* OR Sloven* OR Lithuan* OR Latvi* OR Eston* OR Hungar* OR Croat* OR Serb* OR Bosn* OR Bulgar* OR Romania* OR Moldav* OR Moldova OR Ukrain* OR Belarus* OR Greek OR Greece OR Cypr* OR Malt* OR Macedon* OR Makedon* OR Montenegr* OR Alban* OR Andor* OR Luxemburg* OR Lichtenstein*)).

## Appendix B

Further information from literature review:

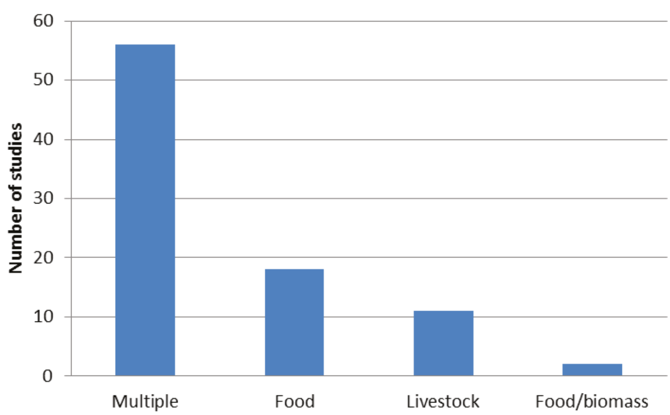


**Figure A1.** Production systems analysed.

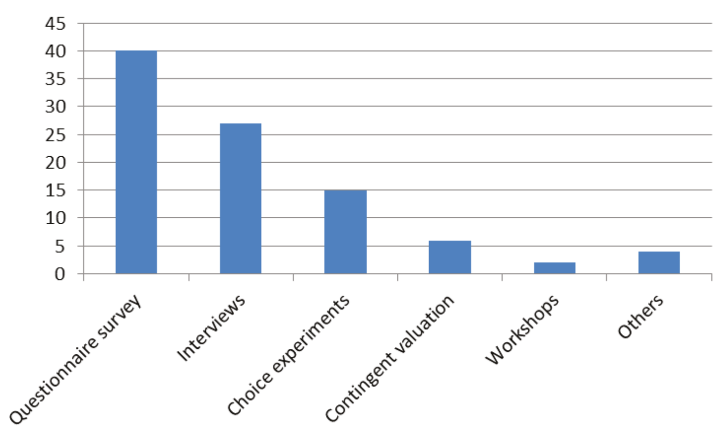


**Figure A2.** Methods used.

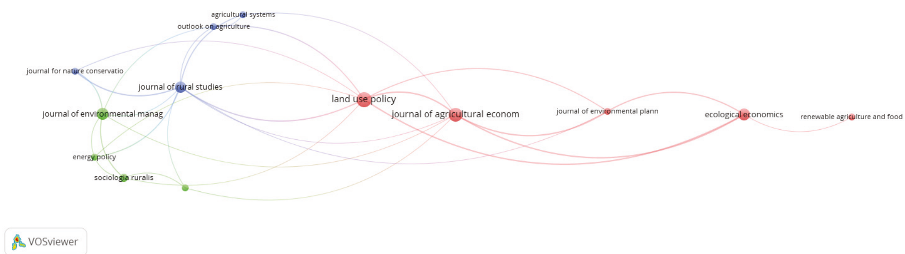


**Figure A3.** Cross-citations between journals (journals with minimum 2 articles).

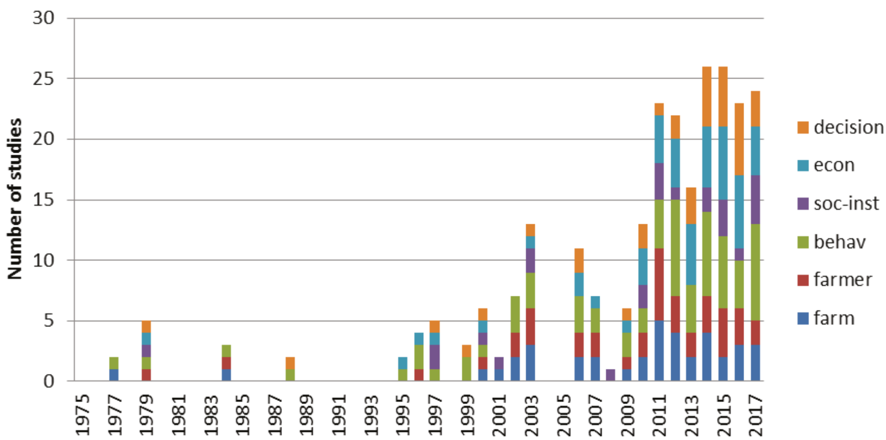


**Figure A4.** Factors belonging to different conceptual framework categories over time.

**Table A1.** Methods versus conceptual framework categories.

| Methods/Categories | Interviews | Questionnaire Survey | Choice Experiments | Contingent Valuation | Workshops | Others |
|---|---|---|---|---|---|---|
| Objective characteristics of farm | 9 | 18 | 7 | 5 | 0 | 4 |
| Objective characteristics of farmer | 9 | 16 | 8 | 5 | 0 | 3 |
| Behavioural characteristics | 19 | 34 | 10 | 5 | 2 | 4 |
| Social-institutional environment | 8 | 12 | 2 | 0 | 0 | 2 |
| Economic constraints | 13 | 21 | 13 | 0 | 1 | 2 |
| Decision characteristics | 11 | 13 | 13 | 1 | 1 | 2 |

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# Assessing Impacts of Soil Management Measures on Ecosystem Services

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**Abstract:** Only a few studies have quantified and measured ecosystem services (ES) specifically related to soil. To address this gap, we have developed and applied a methodology to assess changes in ecosystem services, based on measured or estimated soil property changes that were stimulated by soil management measures (e.g., mulching, terracing, no-till). We applied the ES assessment methodology in 16 case study sites across Europe representing a high diversity of soil threats and land use systems. Various prevention and remediation measures were trialled, and the changes in manageable soil and other natural capital properties were measured and quantified. An Excel tool facilitated data collection, calculation of changes in ecosystem services, and visualization of measured short-term changes and estimated long-term changes at plot level and for the wider area. With this methodology, we were able to successfully collect and compare data on the impact of land management on 15 different ecosystem services from 26 different measures. Overall, the results are positive in terms of the impacts of the trialled measures on ecosystem services, with 18 out of 26 measures having no decrease in any service at the plot level. Although methodological challenges remain, the ES assessment was shown to be a comprehensive evaluation of the impacts of the trialled measures, and also served as an input to a stakeholder valuation of ecosystem services at local and sub-national levels.

**Keywords:** soil; ecosystem services; land management; soil remediation; Europe

## 1. Introduction

Ecosystem services (ES) specifically related to soil have recently become increasingly important to justify and support sustainable soil management for the mitigation or prevention of soil threats. However, the extensive literature on ES contains only a few studies that have quantified and measured soil-related ES [1–3]. Rutgers et al. [4] developed a method to quantify soil quality indicators on arable farms, with land users and experts giving scores to various ES indicators. Schulte et al. [5] identified proxy indicators for five soil functions based on agro-environmental indicators from current policy debates on interactions between agriculture and environment. Dominati et al. [6] worked with a comprehensive list of proxies for each service and units for measuring them, but omitted cultural services due to their non-biophysical nature and the related challenges of quantifying them. Van Oudenhoven et al. [7] applied the cascade model of Haines-Young and Potschin [8] to a multifunctional rural landscape in the Netherlands for the assessment of land management effects.

Although these frameworks reflect the specific contributions soils make to ES, they are unable to reveal the changes in ES that are introduced by soil management measures. Additionally, there is a lack of methods on how to quantify the changes in ES based on measured changes of soil properties, which would allow us to assess and compare the impacts of different measures on ES. Our research attempts to fill this gap by developing and applying a methodology to quantify changes in ecosystem services that were stimulated by soil management measures. To this end, we have reviewed the current scientific debate and, in an earlier step, proposed an adapted framework for soil-related ES that is suited for practical application in the prevention and remediation of soil degradation across Europe [3]. The framework we proposed in [3], see Figure 1, is an adaptation of existing frameworks, achieved by integrating components of soil science while introducing a consistent terminology that can be understood by a variety of stakeholders. The rationale is that changes in the properties of natural capital influence soil processes, which in turn support the provision of ES. The benefits produced by these ES are explicitly or implicitly valued by individuals and society. Their valuation influences decision-making and policymaking at different scales, potentially leading to a societal response, such as improved land management.

In the 17 RECARE ('Preventing and remediating degradation of soils in Europe through land care'. EU FP7 project 2013–2018. www.recare-project.eu [9]. The main aim of RECARE was to develop effective prevention, remediation, and restoration measures using an innovative transdisciplinary approach, actively integrating and advancing knowledge of stakeholders and scientists in case studies, covering a range of soil threats in different bio-physical and socio-economic environments across Europe) case study sites across Europe, various soil management measures—selected by local stakeholders in a participatory workshop and targeting prevention, remediation, and restoration of a range of soil threats on various land use systems—were trialled (Table 1). The resulting changes in manageable soil and other natural capital properties were assessed and quantified. In this paper, we present how we developed a methodology to assess changes in ES based on these measured and estimated changes in soil properties. The aim was to develop and apply a methodology to provide a comprehensive appraisal of the impact of each measure on ES, including cultural ES, which have largely been under-represented in ES assessments to date [10]. We then present the results of the assessment of 26 different measures from 16 case study sites and discuss their interpretation as well as the methodological challenges. The ES assessment presented here served as an input to enable stakeholders at the local and subnational levels to determine and negotiate their valuation of ES in a deliberative process.

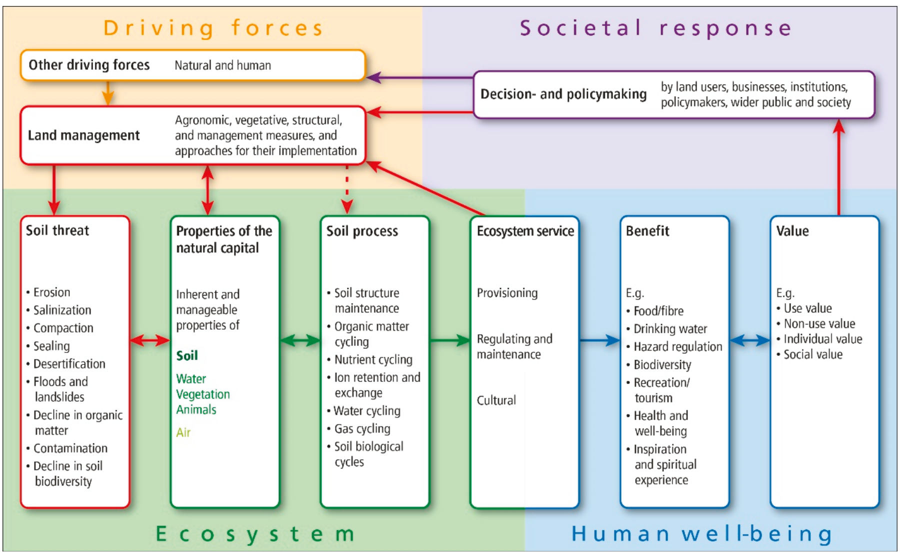


**Figure 1.** Ecosystem service framework for RECARE. Reprinted from *Ecological Indicators*, Vol. 67, Schwilch et al., Operationalizing ecosystem services for the mitigation of soil threats: A proposed framework, 586–597, 2016, with permission from Elsevier [3].

**Table 1.** List of the 16 case study sites and their 26 trialled measures—sorted according to their main soil threats addressed. Further details about the trials and their results can be found in the papers cited in the last column. Most of these papers are part of the CATENA special issue "Quantifying the effectiveness of stakeholder-selected measures against individual and combined soil threats" [11].

| Study Site no. | Study Site Name | Country | Trialled Measure | Main Soil Threat | References |
|---|---|---|---|---|---|
| 01 | Frienisberg | Switzerland | Dyker on potato fields (shovels digging holes into the bottom of the furrows) | Soil erosion by water | [12] |
| 02 | Caramulo | Portugal | Mulching—Low application rate (2.5 Mg ha$^{-1}$) | Soil erosion by water | [13] |
| 02 | Caramulo | Portugal | Ploughing | Soil erosion by water | |
| 03 | Peristerona | Cyprus | Terrace rehabilitation | Soil erosion by water | [14,15] |
| 04 | Timpaki | Greece | Rainwater harvesting system installed in greenhouses | Soil salinization | [16,17] |

**Table 1.** *Cont.*

| Study Site no. | Study Site Name | Country | Trialled Measure | Main Soil Threat | References |
|---|---|---|---|---|---|
| 04 | Timpaki | Greece | Application of T. harzianum in tomato rootstock for alleviation of high soil salinity effects | Soil salinization | [16,17] |
| 06 | Wroclaw | Poland | Regulations limiting soil sealing | Soil sealing | |
| 07 | Canyoles | Spain | Straw mulch | Desertification | [18] |
| 08 | Gunnarsholt | Iceland | Land reclamation | Desertification | |
| 09 | Vansjø-Hobøl | Norway | Flood retention ponds | Flooding and landslides | |
| 09 | Vansjø-Hobøl | Norway | Stream bank vegetation | Flooding and landslides | [19] |
| 10 | Myjava | Slovakia | Changes in crop and land use management | Flooding and landslides | [20,21] |
| 10 | Myjava | Slovakia | Small wooden check dams | Flooding and landslides | [20,21] |
| 10 | Myjava | Slovakia | Changes in vegetation cover | Flooding and landslides | [20,21] |
| 11 | Veenweidegebied | Netherlands | Submerged drains (positioned below the groundwater level) | Loss of organic matter in peat soils | |
| 12 | Broddbo | Sweden | Different grass crops | Loss of organic matter in peat soils | [22] |
| 13 | Olden Eibergen | Netherlands | Local Biomass (from e.g., tree pruning, mowing applied on/into the soil) | Loss of organic matter in mineral soils | [23] |
| 13 | Olden Eibergen | Netherlands | Grass undersowing of maize | Loss of organic matter in mineral soils | [23] |
| 14 | Veneto | Italy | Cover crops (CC) | Loss of organic matter in mineral soils | [24] |
| 14 | Veneto | Italy | Conservation agriculture (CA) | Loss of organic matter in mineral soils | [24] |
| 15 | Guadiamar | Spain | Amendment addition: biosolid compost | Soil contamination | [25] |
| 15 | Guadiamar | Spain | Use of tree species: plantation of Olea europaea var. sylvestris | Soil contamination | [25] |
| 16 | Copşa Mică | Romania | Inorganic soil amendments (bentonite, zeolite, dolomite) | Soil contamination | [26] |
| 16 | Copşa Mică | Romania | Organic soil amendments | Soil contamination | [26] |
| 17 | Isle of Purbeck | UK | Elemental sulphur treatment | Soil biodiversity | [27] |
| 17 | Isle of Purbeck | UK | Ferrous sulphate treatment | Soil biodiversity | [27] |

## 2. Materials and Methods

### 2.1. Developing a Practical Methodology to Assess ES

Several authors have reviewed available methodologies to assess ES. Turner et al. [28] reviewed methods, data, and models assessing changes in the value of ES from land degradation and restoration, providing a good overview of the current state of the art. Bagstad et al. [29] evaluated 17 tools for ES quantification and valuation of their usefulness in decision-making processes. Adhikari and Hartemink [1] conducted a global review linking soils to ES: They retrieved key soil properties related to ES and confirmed that the number of studies that directly link soil properties to the services is limited. Existing tools focus on land use planning (see also [30]) rather than on local-scale land management (e.g., tools used by the OpenNESS project, www.openness-project.eu/). They vary from simple to complicated and time-consuming models, e.g., Multi-scale Integrated Model of ES (MiMES, afordablefutures.com; [10]). There are tools designed for landscape-scale or larger spatial area, such as the land utilization & capability indicator LUCI/Polyscape (lucitools.org; [31]), which builds on a GIS-based model, as well as a few addressing the local scale, such as TESSA toolkit [32], but focusing on biodiversity sites only. Moreover, some studies focus on monetary valuation, such as Ghaley et al. [33], quantifying marketable and non-marketable ES of diverse production systems and management intensities. Concurring with Baveye et al. [2], we are convinced that non-monetary, deliberative ways of dealing with the multifunctional nature of soils are more appropriate than assigning price tags to aspects of soil management that we do not yet sufficiently understand. Volchko et al. [34,35] have worked on analyzing soil functions as part of a holistic sustainability appraisal of remediation alternatives. Their soil quality index was an arithmetic mean value of the sub-scores, without weighting.

Our main challenge was to define the linkages of soil properties to ES, something that hardly any study did [1]. In our process to come up with a workable methodology, we used some ideas and elements from the reviewed tools and literature. The methodology was developed in cooperation with a multi-disciplinary group of soil-related scientists and went through various iterations. Feedback from the international science, policy, and practitioner community was obtained at European science and policy events (Global Soil Week [36], European Geosciences Union [37], and Ecosystem Services Partnership conference [38]).

Furthermore, we evaluated whether we should quantify the ES before and after implementation of the trialled measure, or only evaluate the changes in ES. The first would conceptually be simpler and would also be in line with other studies, where the reference situation refers to a maximum ecological potential, often taken from a less managed agricultural landscape than the one at stake [4]. However, an assessment to quantify all ES before and after implementing 26 different measures across Europe was not feasible within the RECARE Project. We thus decided to focus on the changes only. Furthermore, focusing on changes resulting from trialled measures helped to identify the most effective measures and to keep the focus on the effects/impacts of soil threats as well as land management.

To delineate the zone to consider, we agreed to focus on the local plot area, where the measures were tested and monitored (such as the field level of the farm), as well as a wider area (such as a watershed), represented by the area for which a land use and degradation mapping was available at the case study sites.

In order to assess changes in the properties of the natural capital, we complemented the list of inherent and manageable properties published in Schwilch et al. [3] with properties monitored during the trials. The final list is shown in Figure 5, which depicts the number of properties assessed by the case studies. For ES that can be assessed directly, we decided to work with the MAES 'Best available indicators for assessment of ES across different ecosystems' (Mapping and Assessment of Ecosystems and their Services; [39,40]), acknowledging some of the limitations of legitimacy and validity as presented by Heink et al. [41]. The most difficult issue was the question of how to calculate changes in ES based on measured changes in properties of the natural capital. While looking for methods on how to quantify the impact of the changes of the various properties on the provision of ES, we realized that most studies only look at which soil (and management and environment) properties play a role in the provision of the ES, but they do not quantify the relative contribution of each property [1,6,42].

*2.2. RECARE ES Assessment Methodology*

As we aimed at a comprehensive perspective integrating all ES potentially affected by soil management, we evaluated available lists of ES, such as CICES ([43]; www.cices.eu) and TEEB ([44]; teebweb.org). We decided on CICES, because it was the most detailed and had a hierarchical structure of section, division, group, and class. We used CICES 4.3 but simplified it and changed some of the terms for easier comprehension to stakeholders. We then defined 15 ES that were relevant for RECARE case studies, all of which had been mentioned as being affected by the trialled measures in one or more case studies. They are a combination of the division and group from the CICES classification, as presented in Supplementary Material S2. For the methodology, the columns 'RECARE Division & Group' and their associated 'Class' were used.

To assess the impact of the trialled measures on ES we developed an Excel-based tool with final visualizations programmed in R (see Figure 2). The tool contains four steps which were taken to determine short-term and long-term changes of the 15 ES we defined.

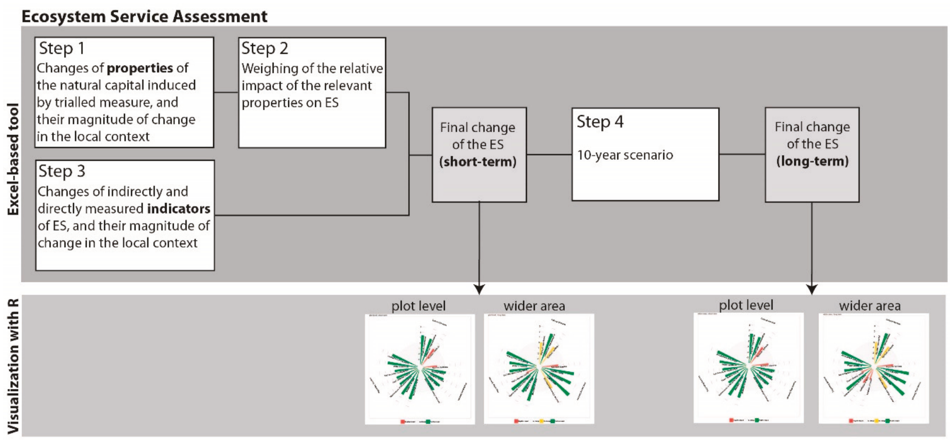


**Figure 2.** Framework and processes of the ecosystem service assessment tool.

In Step 1, the values of the measured or estimated properties of natural capital with and without trialled measures were entered for the whole implementation period. The list of 50 properties (see also Figure 5) originates mainly from Dominati et al. [6]. It was extended by the 16 case study partners during the methodology development phase and kept fixed for all assessments afterwards. The data for any property for which a change was measured, observed or estimated was entered. The magnitude of change of the selected properties was then appraised and rated in the local context from −3 (strong decrease) to 3 (strong increase) by considering seasonality and velocity of changes. Whether a certain increase is considered low or high within the local context represents the interpretation of the researcher involved.

In Step 2, the 'impact dependence' (positive impact +1 or negative impact −1) was defined for each property with an impact on the identified ES, for the plot level and the wider area (regional scale). Thereafter the relative impact of each property on each of the 15 specified ES was weighted for the plot level and the wider area. The total impact of all properties with an impact on an ES was always 100%. Figure 3 shows an example of the relative weight of properties explaining changes in the nutrition biomass ES. The default weights, as presented in Figure 3, were used for 12 measures. The main explanatory factors considered for nutrition biomass production thus include soil organic matter (SOM), soil moisture, and infiltration, with some importance for 'weed amount/species' and 'soil fauna and microorganisms'. This was partly adapted from Adhikari and Hartemink [1], leaving out most of the inherent properties. The 'grass undersowing' trial in the Netherlands at Olden Eibergen assigned equal weights to four properties, namely mineral nitrogen, SOM, infiltration, and 'soil fauna and micro-organisms' (see Figure 3).

With the estimated impact of the measured change (from step 1), the impact dependence and the weighting of the properties (from step 2), the Excel-based tool then calculated two impact values between −3 and +3 for each ecosystem service, one for the affected area (plot level) and one for the wider area. The calculation was done by multiplying the 'magnitude of change' and the 'impact dependence' with the 'weight'. If a specific ES was not relevant for the case study, it was set as N/A.

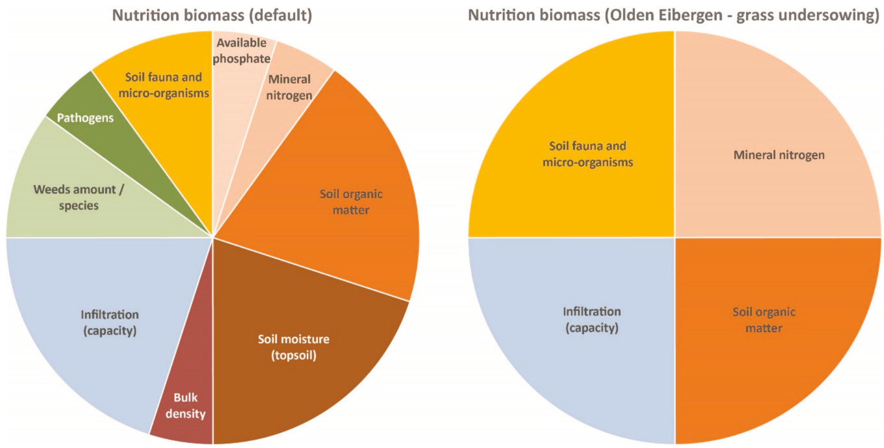


**Figure 3.** Relative weight of properties explaining changes in the nutrition biomass ES. (**Left**) default. (**Right**) NL—Olden Eibergen trial 'grass undersowing of maize'.

Some of the ES can be measured directly (such as crop yield), or assessed using other indicators than those related to a change in properties of the natural capital (such as number of visitors). In Step 3, these measured or estimated indicators were entered into the tool and their magnitude of change was again appraised and rated in the local context from −3 (strong decrease) to 3 (strong increase) for the affected ES, one for the plot level and one for the wider area. A challenge was how to combine the directly measured ES with the ones based on changed properties, as these would also have an effect (e.g., many properties have an impact on yield). Due to a lack of scientific evidence, we simply averaged the two. In many cases, however, no directly measured ES indicators were available. This average of the calculations in Step 2 and Step 3 then resulted in the final change of the ES due to the trialled measure between −3 (strong decrease) and +3 (strong increase). In addition, the case study partners also identified benefits (positive impacts, advantages) and drawbacks (losses, negative impacts, disadvantages) that the trialled measure may have for people and nature, such as increased yield, clean water, or increased workload.

In Step 4, we assessed for each ES, for plot level and wider area, whether the assigned short-term value from Step 3 will still be the same in 10 years or whether the changes in ES will increase or decrease. The case study partners also identified benefits and drawbacks of the trialled measure for this 10-year scenario.

In order to present the results to stakeholders we also investigated effective visualization approaches. Different studies suggest various forms of visualizing ES, e.g., the spatial relationship between service production area and service benefit area [45], or the relative provision of services in spider diagrams [46]. We developed an R script to generate four different graphs for each trialled measure for both short-term and long-term scenarios at both plot level and the wider area (Figure 4). The values on the axes indicate the magnitude of change in the 15 ES compared to the situation without the trialled measure. The grey circle of 'no change' reflects the supply of the ES before the implementation of the trialled measure. The values of the radial axes signify a strong increase (+3), moderate increase (+2), small increase (+1), no change (0), small decrease (−1), moderate decrease (−2), and strong decrease (−3). Green bars indicate that the ES has been increased compared to the situation without the trialled measure (the value is above zero); red bars that the ES has been reduced compared to the situation without the trialled measure (the value is below zero); yellow bars that the ES have not changed due to the trialled measure (the value is zero); and grey bars that the trialled measure has no relevance for this ES. In contrast to a standard bar chart, this kind of visualization has the advantage of also highlighting ES with no change, in addition to showing their increase or decrease. However, it makes the positive impacts (green) look larger than the negative ones (red), although this does not mean they are more important.

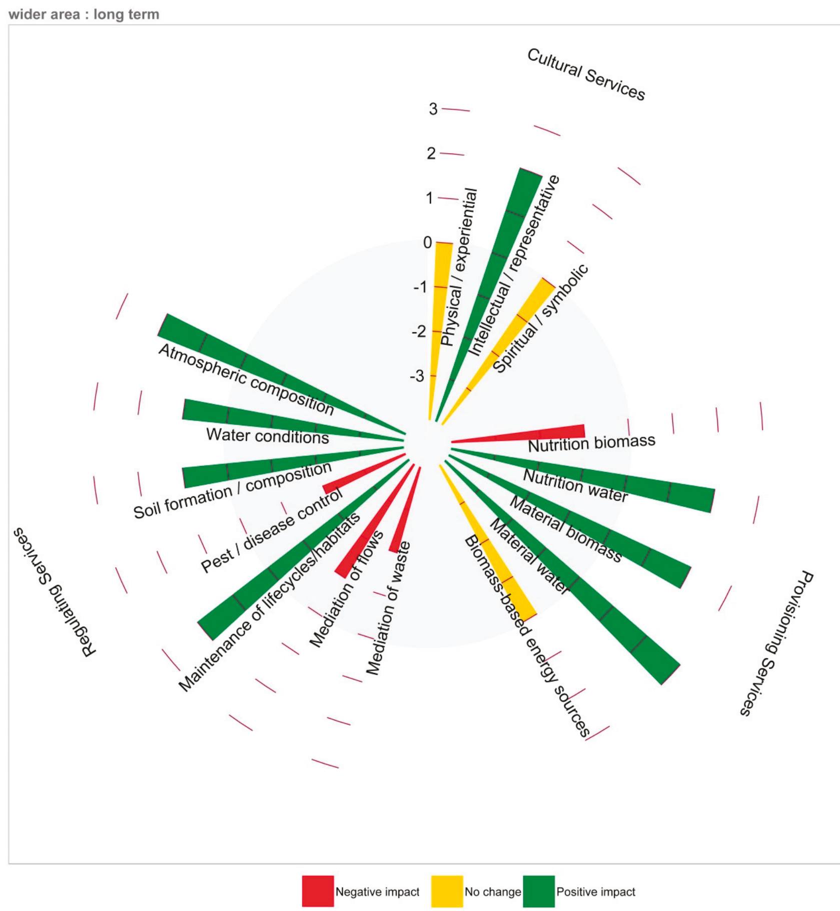


**Figure 4.** Example of graph presenting the ES change for a 10-year scenario on a wider area from the conservation agriculture trials in Veneto, Italy.

## 3. Results

The application of the ES assessment methodology to 26 trialled measures (Table 1), provided information for the case study partners on changes in ES brought about by the trialled measures. It also enabled cross-site comparisons and analysis, presented in the following sections along the single methodology steps.

### *3.1. Changes in Properties and their Impact on ES*

#### 3.1.1. Measured and Estimated Properties of Natural Capital

Figure 5 shows that vegetation cover, soil organic matter, and soil moisture were assessed (i.e., measured or estimated) in about two-thirds of all trialled measures (red bars). The properties that were most frequently measured (blue bars) are vegetation cover, soil organic matter, pH, and soil moisture. Changes in properties that were estimated (green bars) rather than measured include surface water/runoff, soil fauna/microorganisms, water holding capacity, humidity, surface structure/roughness, infiltration, vegetation species composition, soil flora, and air temperature. The only listed property that was apparently not relevant in the case studies is the number of animals (grazing pressure), as this was not selected by any case study. Other properties of very little significance (only mentioned by one case study) included many of the inherent soil properties, the vertical and horizontal structure of vegetation, and the composition of animal type. This relates to the trialled measures in the case studies, which are mostly applied on cropland, with only few on forests and grazing land. However, the result of this analysis may provide a clue as to which properties are key to understanding and measuring land management-induced changes in the natural capital.

| Natural capital | Properties of the natural capital | | Total count | Measured | Estimated |
|---|---|---|---|---|---|
| Soil | Inherent | Slope | 2 | 2 | 0 |
| | | Orientation | 2 | 2 | 0 |
| | | Depth | 7 | 4 | 3 |
| | | Clay types | 1 | 1 | 0 |
| | | Texture | 6 | 5 | 1 |
| | | Temperature | 6 | 3 | 3 |
| | | Size of aggregates (subsoil) | 1 | 0 | 1 |
| | | Strength (subsoil) | 1 | 1 | 0 |
| | | Subsoil pans | 2 | 1 | 1 |
| | Manageable | Available phosphate | 7 | 5 | 2 |
| | | Mineral nitrogen | 8 | 5 | 3 |
| | | Soil organic matter | 18 | 11 | 7 |
| | | Soil moisture (topsoil) | 17 | 9 | 8 |
| | | Subsoil wetness class | 4 | 1 | 3 |
| | | pH | 13 | 11 | 2 |
| | | Chemical quality | 3 | 2 | 1 |
| | | Stoniness | 3 | 2 | 1 |
| | | Soil cover (stones, litter, vegetation, etc.) | 7 | 5 | 2 |
| | | Macroporosity | 3 | 2 | 1 |
| | | Bulk density | 8 | 6 | 2 |
| | | Strength (topsoil) | 2 | 1 | 1 |
| | | Size of aggregates (topsoil) | 2 | 1 | 1 |
| | | Surface structure / roughness | 4 | 0 | 4 |
| | | Infiltration (capacity) | 5 | 1 | 4 |
| | | Aggregate stability | 2 | 0 | 2 |
| | | Root depth | 3 | 3 | 0 |
| | | Penetration resistance | 2 | 2 | 0 |
| | | Hydraulic conductivity | 1 | 1 | 0 |
| | | Trace element availability | 3 | 2 | 1 |
| | | Soil respiration | 6 | 6 | 0 |
| | | water holding capacity | 7 | 1 | 6 |
| Water | Manageable | Irrigation (water scarcity) | 6 | 2 | 4 |
| | | Drainage (water abundance) | 5 | 1 | 4 |
| | | Groundwater depth | 4 | 2 | 2 |
| | | Surface water/runoff | 10 | 2 | 8 |
| | | Chemical quality | 6 | 3 | 3 |
| Vegetation | Manageable | Vegetation cover (%) | 18 | 12 | 6 |
| | | Vertical structure (e.g. multi-story) | 1 | 0 | 1 |
| | | Horizontal structure (e.g. patchiness, strips) | 1 | 0 | 1 |
| | | Species composition | 6 | 2 | 4 |
| | | Soil flora | 3 | 0 | 3 |
| | | Weeds amount / species | 5 | 2 | 3 |
| | | Root density | 2 | 0 | 2 |
| | | Pathogens | 2 | 0 | 2 |
| | | Type composition | 1 | 0 | 1 |
| | | Soil fauna and micro-organisms | 9 | 2 | 7 |
| Air | Inherent | Temperature | 5 | 2 | 3 |
| | | Humidity | 6 | 1 | 5 |
| | Manageable | Chemical quality | 2 | 1 | 1 |
| **Total number of assessed properties** | | | **248** | **128** | **120** |

**Figure 5.** Number of properties assessed by the case studies (red = total count, blue = measured, green = estimated).

### 3.1.2. Comparison of Measured Values and Appraisal of Magnitude for Selected Properties

Figure 6 shows the measured values of three selected properties of the natural capital before and after the trial implementation for the plot scale (affected area) and their appraisal of magnitude of change compared to the local context. The selection of these particular properties was for illustration purposes only.

Soil organic matter: Looking at the estimated magnitude of changes in Figure 6 (right column), many sites report an increase in SOM. Portugal is an exception, as here the topsoil layer that is most rich in SOM was ploughed under and increased SOM decomposition resulted from aeration. Spain-Guadiamar reported an increase of 71% (magnitude 2 = moderate increase) for biosolid compost amendment and 23% for use of tree plantation of Olea europaea var. sylvestris, considered a magnitude of 3 (high increase) because SOM levels in the region are currently very low. In Romania, organic soil amendments from manure and an increased root growth of plants led to an increase in SOM of 32%, considered moderate. Veenweidegebied in the Netherlands reported a decrease in SOM loss for their peat soil from a loss of 11.6 to a loss of 5.6 t/ha/year with the implementation of submerged drains (since the decrease has become smaller this is shown as +3 in Figure 6). For the UK case study, where detailed data were available for over 10 years of measurements, changes in SOM were reported in opposite directions for the two measures. Elemental sulphur treatment led to a slight decrease from initially 4.1% SOM to 4.0%, while the treatment with ferrous sulphate increased SOM from 4.1% to 4.4%. This was rated with magnitude −1 and 1, respectively. These values are not shown in Figure 6 because they reflect a long-term change.

Vegetation cover: This property is reported to have increased considerably for a number of sites, namely Romania, Spain-Guadiamar, Italy, Iceland, and Slovakia. Only Portugal and Spain-Canyoles (mulching) report a decrease; in Portugal this was due to ploughing and in Spain mulching led to an increase in soil cover but a decrease in vegetation cover. For the contaminated site in Spain-Guadiamar, natural colonization of the contaminated area by plants was very slow, while tree plantation accelerated colonization and succession of plant communities. The Spain-Guadiamar trial with biosolid compost amendment managed to increase vegetation cover from 19% to 68% due to reduced metal phytotoxicity and improved soil fertility. In Romania, the second site under threat of contamination, researchers explain the effect as follows: "reducing the metals mobility in soil led to a diminishing of metals toxicity with benefits on plant growth". This resulted in an increase from initially 50% to finally 65% vegetation cover (trial with inorganic soil amendments bentonite, zeolite, and dolomite). Their second trial (organic amendment) even increased vegetation cover from 50% to 75%. Both Italian trials increased vegetation cover by a magnitude of 3 by increasing cover from 50% initially to, respectively, 80% and 90% finally. Conservation agriculture as well as cover crops provide a soil cover by vegetation throughout the year.

Soil moisture (topsoil): Measured changes in soil moisture (mostly seasonal averages) were rather minimal, but on a very different level due to the different pedo-climatic conditions found in the case study areas. While the trialled measures in Sweden (peat soils) and in the UK (organic rich former heathland soils) achieved volumetric soil water content of over 40%, Spain-Canyoles and Cyprus reported only around 10% (semi-arid climate). While most sites reported an increase, there was a decrease in one of the Portuguese trials (ploughing), in the two Norwegian trials, as well as in the UK site with the ferrous sulphate treatment. In Portugal, this is due to increased macroporosity, at least during the initial period following ploughing, while in Norway this is a desired effect due to the threat of flooding.

From Figure 6, we conclude that most of the trialled measures did increase the assessed properties, with only few showing a decrease. The appraised magnitude of change confirms that these changes in properties are in many cases considerable (i.e., magnitude 2 or 3) within their local context.

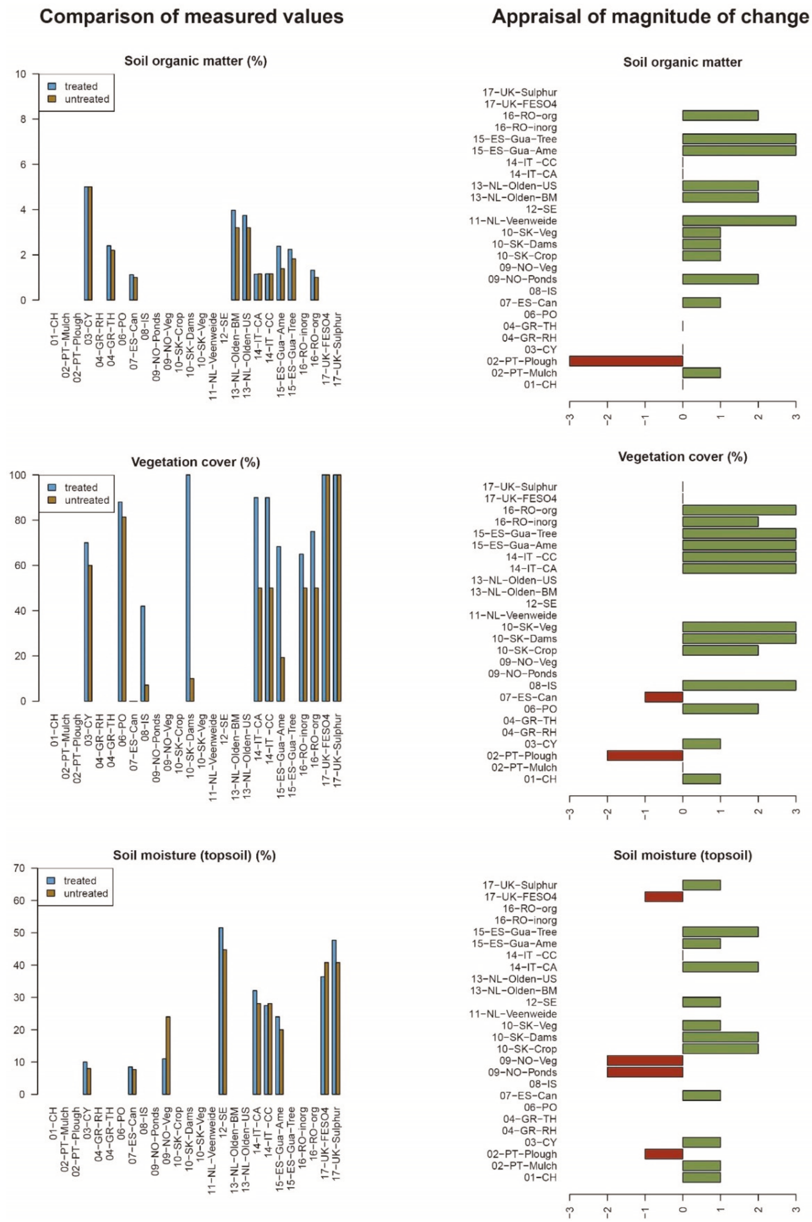


**Figure 6.** Comparison of measured values (**left column**) and the appraisal of magnitude of change (**right column**) of selected properties in the 16 case studies.

### *3.2. Measured Impact on ES*

The results for Step 3 in Figure 2 include the assessed indicators for provisioning, regulating, and cultural services and their magnitude of change, i.e., how the level of ES provision has changed due to the trialled measure. Here we present the data for the affected area/plot level only, as there is more data available for that level due to the local trials and their monitoring.

Provisioning services: Figure 7 shows that among provisioning services, cultivated crops were by far the most assessed (in 16 out of 26 trials, see red bars). Crop yield was measured in 10 of the cases (blue bars) and estimated in the other 6 (green bars). Most other changes in provisioning services were estimated rather than measured.

| Section | Division | Class | Total count | Measured | Estimated |
|---|---|---|---|---|---|
| Provisioning | Nutrition biomass | Cultivated crops | 16 | 10 | 6 |
| | | Reared animals and their outputs | 3 | 0 | 3 |
| | | Wild plants, algae and their outputs | 3 | 0 | 3 |
| | | Wild animals and their outputs | 5 | 0 | 5 |
| | Nutrition water | Surface water for drinking | 7 | 1 | 6 |
| | | Ground water for drinking | 4 | 0 | 4 |
| | Material biomass | Fibres and other materials from plants, algae and animals for direct use or processing | 5 | 0 | 5 |
| | | Materials from plants, algae and animals for agricultural use | 10 | 4 | 6 |
| | Material water | Ground water for non-drinking purposes | 3 | 1 | 2 |
| | Biomass-based energy sources | Plant-based resources | 8 | 0 | 8 |
| | | Animal-based resources | 1 | 0 | 1 |
| Regulation & Maintenance | Mediation of waste, toxics and other nuisances | Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals | 7 | 4 | 3 |
| | | Filtration/sequestration/storage/ accumulation by ecosystems | 15 | 6 | 9 |
| | Mediation of flows (mass, liquid, air) | Mass stabilisation and control of erosion rates | 13 | 4 | 9 |
| | | Buffering and attenuation of mass flows | 3 | 0 | 3 |
| | | Hydrological cycle and water flow maintenance | 10 | 4 | 6 |
| | | Flood protection | 8 | 1 | 7 |
| | | Storm protection | 2 | 0 | 2 |
| | Lifecycle maintenance, habitat and gene pool protection | Pollination and seed dispersal | 9 | 2 | 7 |
| | Pest and disease control | Pest control | 2 | 0 | 2 |
| | | Disease control | 3 | 0 | 3 |
| | Soil formation and composition | Weathering processes | 13 | 6 | 7 |
| | | Decomposition and fixing processes | 15 | 7 | 8 |
| | Water conditions | Chemical condition of freshwaters | 7 | 2 | 5 |
| | Atmospheric composition and climate regulation | Global climate regulation by reduction of greenhouse gas concentrations | 11 | 8 | 3 |
| | | Micro and regional climate regulation | 9 | 2 | 7 |
| Cultural | Physical and experiential interactions | Experiential use of plants, animals and land-/seascapes in different environmental settings | 4 | 0 | 4 |
| | | Physical use of land-/seascapes in different environmental settings | 4 | 0 | 4 |
| | Intellectual and representative interactions | Scientific | 8 | 0 | 8 |
| | | Educational | 14 | 8 | 6 |
| | | Heritage, cultural | 6 | 1 | 5 |
| | | Entertainment | 3 | 1 | 2 |
| | | Aesthetic | 8 | 1 | 7 |
| | Spiritual and symbolic interactions | Sacred and/or religious | 1 | 0 | 1 |
| | | Existence | 4 | 0 | 4 |
| | | Bequest | 8 | 1 | 7 |
| | Total number of assessed indicators | | 60 | 12 | 48 |

**Figure 7.** Number of indicators of the 15 ES services assessed by the case studies (red = total count, blue = measured, green = estimated).

Most trials related to crop production resulted in a measured or estimated yield increase ('cultivated crops' in Figure 8). The only exception is the Italian trial, where conservation agriculture led to a yield decrease of 25% (from 8 to 6 t/ha average from a three-year rotation of maize, wheat, and soybean). Some trials report a considerable increase (magnitude +3), such as Norway (flood retention ponds) and Iceland. In Norway, implementation of a retention pond reduced the incidences and the duration of flooding on crop fields located below the retention; there is less flood damage and thus an improvement in farm productivity. In Iceland, the increase in yield is almost 500% (from 7 to 42 t/ha), as the treatment involves direct reseeding. Other provisioning services are less affected by the trialled measures, or less important. Wild animals and their outputs are important in grazed ecosystems, such as in Spain-Guadiamar, Slovakia, Norway, Iceland, and the UK.

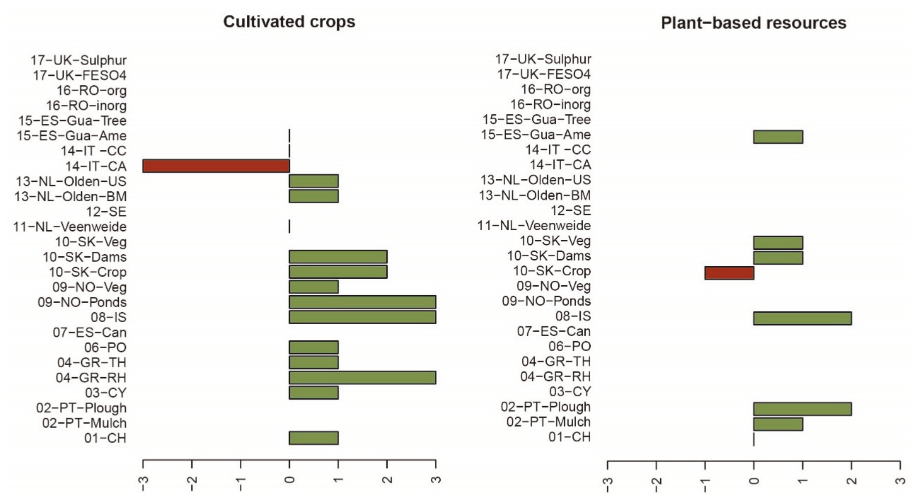


**Figure 8.** Appraisal of magnitude for assessed provisioning services (illustrative selection from those services with more than seven mentions).

In Slovakia, the ES 'plant-based energy resources' include biofuel from rape and maize. A decrease is reported because the trialled measure of 'changes in crop and land use management' intended a reduction in agricultural land used for rape and maize cultivation due to their negative effects on soils. The other two Slovakian trials reported a small increase in 'plant-based energy resources', for example the trial with changes in vegetation that increase wood fuel.

Regulating Services: Figure 7 shows that for many of the regulating services, about half were measured and the other half estimated. Measuring was apparently more possible here than with the provisioning services.

Many of the regulating services show a strong improvement (Figure 9). The sites dealing with flooding and soil erosion report improvements in the ES 'mass stabilization', with as many as six trials reporting a strong improvement of magnitude 3. Streambank vegetation in Norway, for example, increased shear strength of the soil by up to 155%.

'Weathering processes' and 'decomposition and fixing processes', the two ES in the group of soil formation and composition, are important in many sites. Improvements of magnitude 3 are estimated in Norway, Romania, and Spain-Guadiamar. In the Italian Conservation Agriculture trial, a decrease in soil porosity was measured. This was interpreted as potential soil compaction and reported as a slight deterioration of the ES 'weathering processes'.

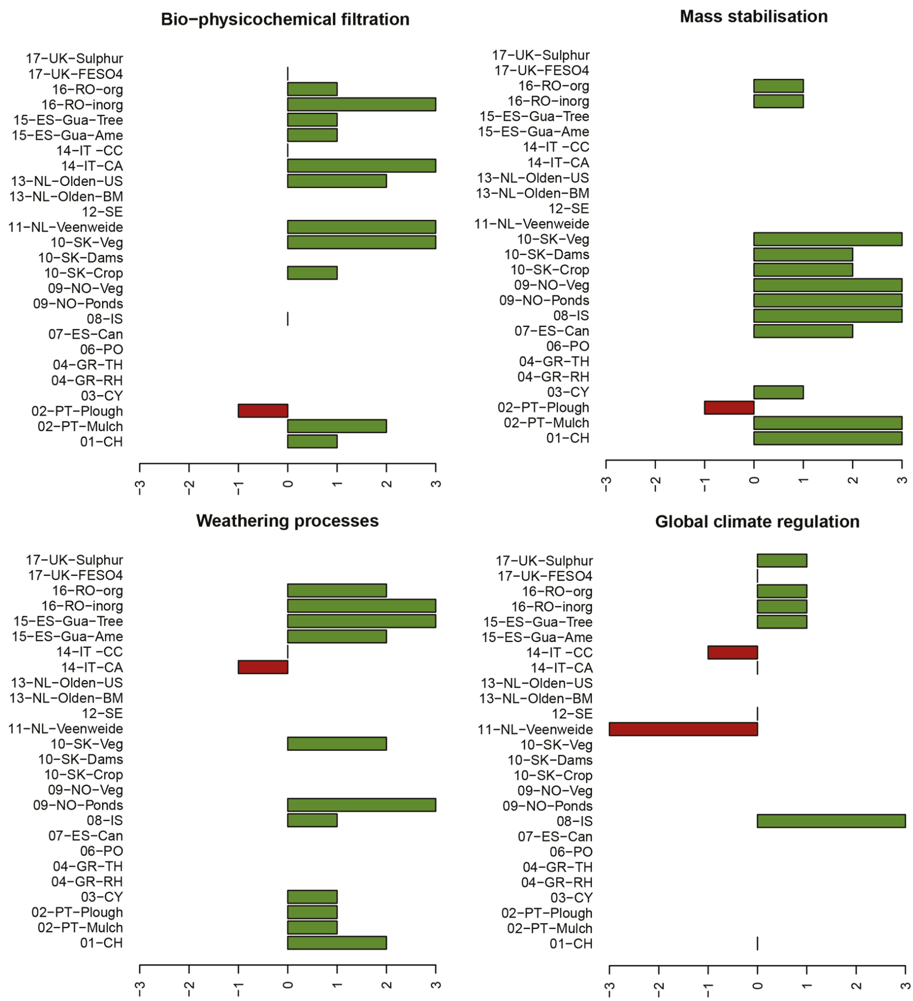


**Figure 9.** Appraisal of magnitude for assessed regulating services (illustrative selection from those services with more than 11 mentions).

The ES of 'mediation of waste, toxics, and other nuisances' is especially important in the two case studies where soil contamination needs to be remediated, namely Romania and Spain-Guadiamar. For both case studies, both trials show an improvement, and in each case study, one of the trials is clearly better than the other. Inorganic soil amendments in Romania increased the soil capacity to bind the metals and reduced the transfer of heavy metals from soil to plants. For the ES class 'bio-physicochemical filtration', the advantage of the inorganic soil amendments is particularly apparent, in that the sorption of contaminants on inorganic amendments has reduced the mobility of metals (e.g., Cd—mobile forms) in the soil by 94% (from 6.34 to 0.38 mg/kg) = magnitude 3. For the organic amendment, this value is 38.5% = magnitude 1. In Spain-Guadiamar, the benefits of the trials occur through a phytostabilization process, which is an immobilization of contaminants by plants and associated microorganisms. Trials with conservation agriculture in Italy showed that the nitrate concentration in percolation water decreased by almost 90% (from 39.7 mg/L to 4.3 mg/L), which is considered a strong improvement of magnitude 3 and benefits groundwater quality.

The ES 'global climate regulation' was of specific interest to the four case studies featuring soils threatened by loss of organic matter in mineral and peat soils. In Italy, carbon sequestration was measured as SOC stock variation (t/ha/y) for both trials. While conservation agriculture had negligible impact on this (15% reduction in GHG emissions from 1 to 0.86 t/ha/y, rated as magnitude 0), the cover crops trial caused a reduction of 41% (from 1 to 0.59 t/ha/y SOC stock variation, rated as magnitude −1). Data was obtained as a yearly average during the 2011–2017 period in the 0–30 cm soil layer.

Cultural Services: For the cultural services, measuring seems most feasible for the indicator of education, measured in eight trials as shown in Figure 7. Most other cultural services can only be estimated.

Many of the trialled measures have an impact on scientific, educational, heritage, and aesthetic interactions (see Figure 10). For example, in Iceland, it provides the opportunity to educate about land degradation processes, land reclamation activities, and the value of the provided ES. Education not only includes training of students, but also of farmers, such as on the issue of contamination in Romania, where the results from the experiments are used for dissemination and improvement of the knowledge about agricultural use of contaminated land with minimum risk for humans. The aesthetic ES of the Norwegian trial 'streambank vegetation' considers the diversification of the vegetation, which was rated magnitude 2, while the 'flood retention pond' did not provide any such service. In the UK, aesthetics is an important factor, as this is what people visit the case study area for and it is the socio-economic fabric of the landscape. Within the group of 'spiritual and symbolic interactions', the class 'sacred and/or religious' was not an issue in most sites, and 'existence' as well as 'bequest' were relevant in some sites. In Romania, a higher value for 'bequest' is due to the preserved agricultural use of contaminated land for traditional farmers without negative impact on human health. In the Slovakian 'changes in crop and land use management', the benefits are that there is an improvement of the landscape character, but with the drawback of a diversion from the past crop production, which was indicated as a small deterioration of magnitude −1. The Greek trial 'rainwater harvesting system installed in greenhouses' was rated with magnitude 2 for the ES 'bequest', because there is a water footprint reduction through the saved groundwater.

### *3.3. Final ES Change*

Figure 11 plots the resulting calculated ES changes for all ES, all sites (sorted according to soil threat), and plot level. Overall, we observed mostly positive changes in ES, with only very few dots below the zero line (25 out of 382). Provisioning and cultural ES hardly reached a value above two, while the regulating ES showed some significant improvements between two and three. Few specific patterns were immediately visible, but a more detailed look revealed some that were not visible at first sight. For example, nutrition biomass (dark green dots in Figure 11) was higher overall in its service provision than nutrition water (dark blue dots), and almost all sites reported either an increase or no change in these services. Notable exceptions are Italy (yield decrease under conservation agriculture) and Poland (drinking water decrease). Overall, nutrition biomass achieved the highest changes within the group of provisioning services.

For the regulating services, pest and disease control were affected the least, the ES changes range between −0.1 and 1.2 for all sites, presumably because this issue was not the focus of the trialled measures targeting soil degradation. High values of increase, i.e., with a magnitude of >2, were achieved for 'mediation of flows' (dark green dots in Figure 11), 'mediation of waste' (purple dots), 'soil formation and composition' (salmon dots; namely NL-Veenweide with a magnitude of 3), and 'water condition' (olive dots). Looking at the overall picture, the ES 'mediation of flows' and 'mediation of waste' showed the most important positive impacts. The first is especially crucial for the soil erosion case studies (Switzerland, Portugal, Cyprus), with only the Portugal plough trial not showing an improvement. It is obviously also important for the flooding sites (Norway and Slovakia). The latter (mediation of waste) is specifically important for the contamination sites (Spain-Guadiamar and Romania), both of which reported an increase for their two trials, but with a distinct difference in favor of one of the trials each. Negative values were very rare. NL-Veenweide reported a moderate decrease (−2) and Portugal (plough) a small decrease (−1) of the ES 'climate regulation' (dark blue dots).

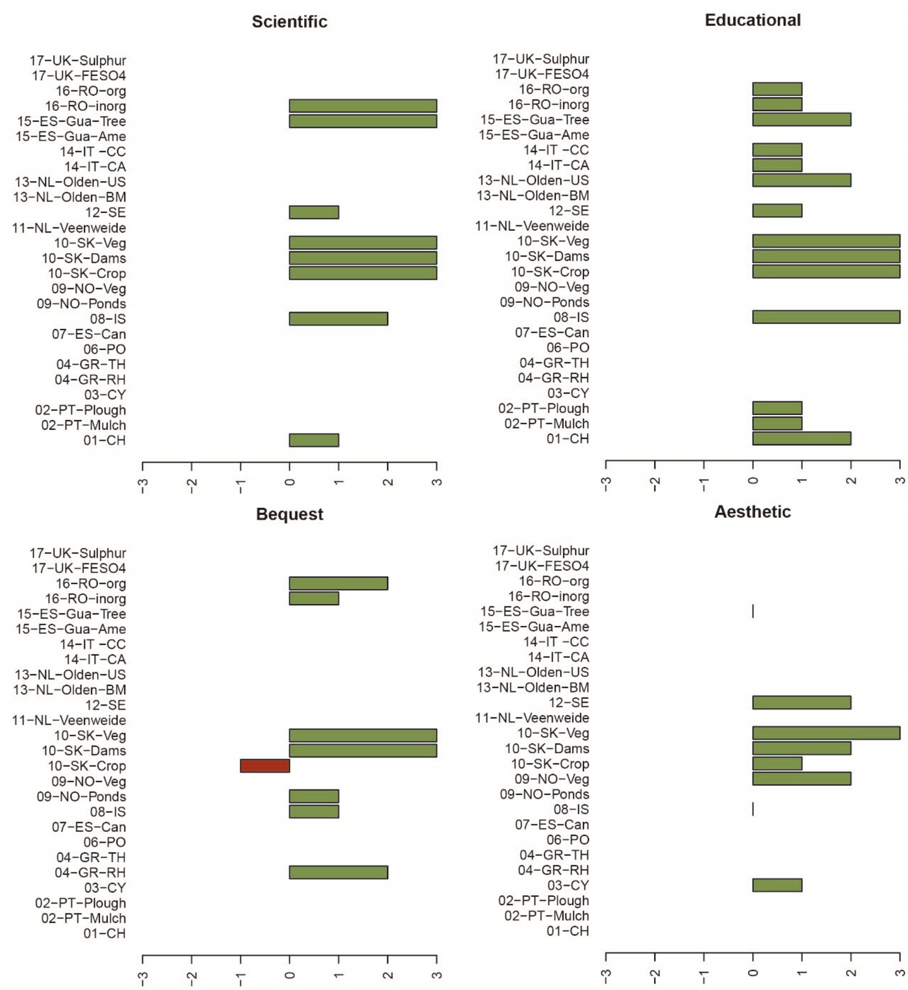


**Figure 10.** Appraisal of magnitude for assessed cultural services (only for services with more than seven mentions).

Out of the cultural services (Figure 11), it was mainly the ES 'intellectual and representative interactions' that increased for most sites and trials. This is probably due to the scientific and educational value of the project being a research project of mostly universities. The ES of 'physical and experiential interactions' seems to be affected positively mostly in the sealing, desertification, and flooding sites. Compared to other sites, these sites deal with larger areas. Interactions like walking, hiking, and sightseeing are thus more important and were positively influenced by the trialled measures.

Assuming a soil management measure that increases the supply of all three categories of ES would be best, Figure 11 indicates that no single trialled measure is clearly better than all others, i.e., there is no management measure which is most promising to improve ES.

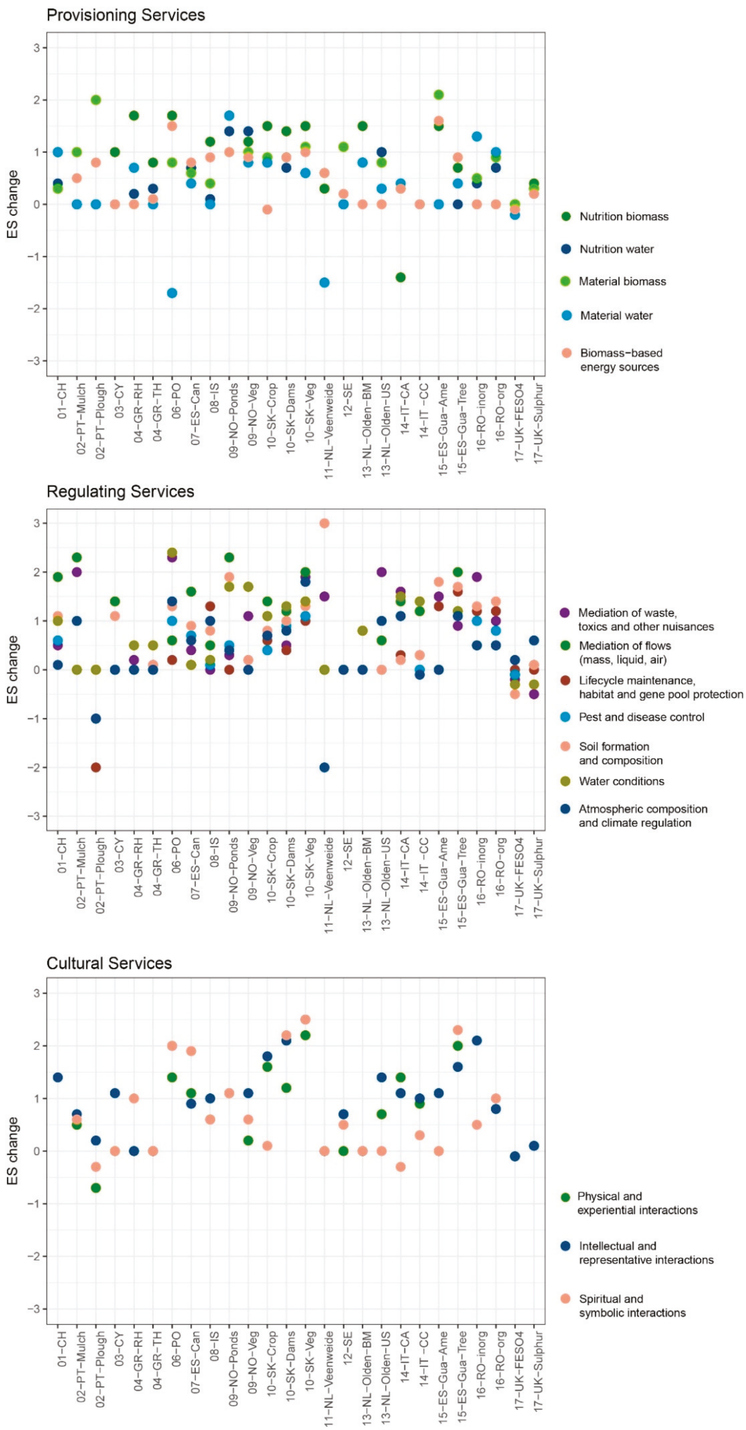


**Figure 11.** Final ES changes at plot level.

### 3.4. 10-Year Scenarios

Figure 12 depicts the changes in selected provisioning, regulating, and cultural services that are expected for a 10-year scenario compared to the assessed changes after the trial implementation period (at plot level). Although this is based on a rough estimate, a slight to medium increase in all appraised ES can be shown. To illustrate the implications this has, we present selected results from three case study sites. In Cyprus, the short-term impacts of participatory terrace rehabilitation can be sustained in the long term with further engagement of the younger generation in mountain terrace farming [14]; more importantly, if applied at the wider area, some considerable future benefits may arise, such as reduced run-off and soil erosion, and flood prevention (ES mediation of flows). The relevance of terrace rehabilitation is also reflected in an increased and maintained cultural service 'preservation of heritage (cultural landscapes)'. For the cover crops measure in Italy, it is expected that most ES will show a slight improvement in the long term. Researchers specifically mentioned improvements in groundwater quality, water cycle regulation, and organic carbon stabilization (C/N ratio), as well as a reduction in GHG emissions. For the conservation agriculture measure, the researchers expect an increase in crop production in the long term as observed in several studies. Mediation of waste, toxics, and other nuisances as well as pest and disease control are expected to show a moderate decrease in the long term because of an increase in the use of pesticides when applying conservation agriculture, especially relevant at the level of the wider area (see also Figure 4). The cultural service 'spiritual and symbolic interaction' is expected to change from a small decrease after the trial to a 'no change' in the long term, because people will recognize the continuous soil cover as a common practice and will not confuse it with land abandonment. For the UK trials, detailed data were available for over 10 years of measurements. The observed reduction in soil pH and nutrient content might be considered detrimental to mesotrophic pasture species and hence overall plant production, but these conditions are beneficial for acid grassland and heathland species. In a restoration ecology project, reverting agricultural land to support a heathland and acid grassland system, a reduction in nutrition biomass is to be expected. The outcome is intended to be a low input, ancestral agricultural grazing system. Such systems are becoming increasingly popular in the region as part of a general move towards traditional farming systems and habitat recreation for rare fauna and flora: a key part of the area's touristic appeal.

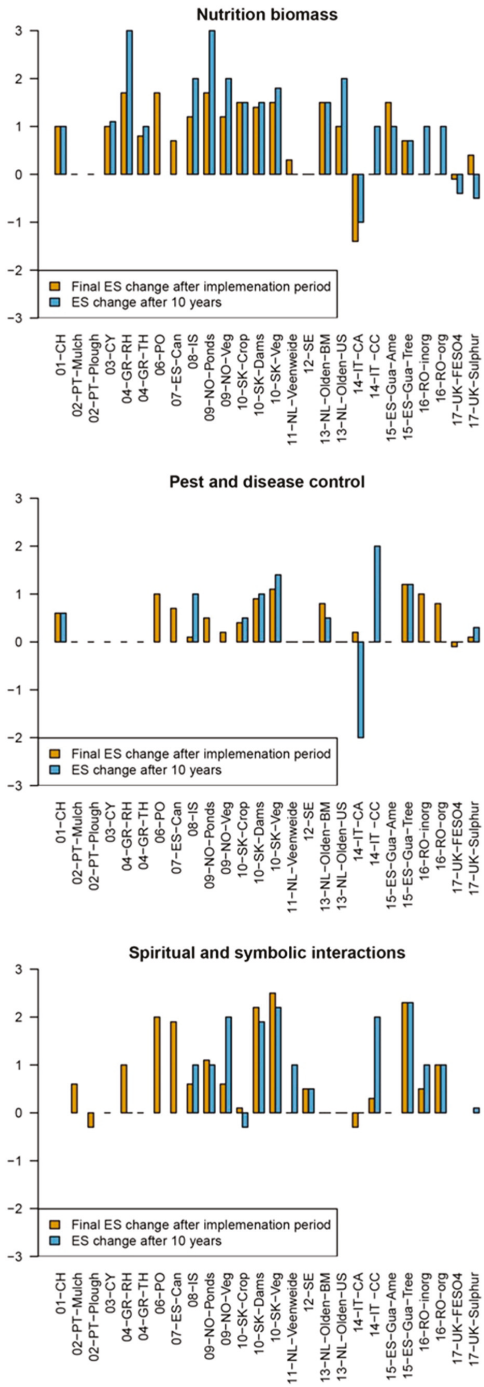


**Figure 12.** Changes in selected ES services after the implementation period and after 10 years.

## 4. Discussion

### 4.1. Soil Management and ES

#### 4.1.1. Changes in ES due to Soil Management

Overall, the results paint a very positive picture in terms of the impacts of the trialled measures on ES, indicating that the trialled measures indeed increase ES. This was hypothesized, as most of these measures were selected for trialing due to their expected positive effects regarding the soil threat at stake (except for some trials being included to compare with conventional practices, such as the ploughing trial in Portugal). However, we were curious to see whether these measures would also show an impact on ES other than those affected by the soil threat. Would, for example, a measure against soil erosion only lead to an improved 'mediation of flows', or would it also provide positive impacts on 'nutrition biomass' (yields), as well as cultural services? Would it thus be possible to provide and improve a multitude of services and not decrease some services or present trade-offs over scale and time? Looking at the results from this perspective confirms that 18 out of 26 trialled measures did not show a decrease in any service at the affected area/plot level. For the wider area/regional level, it was even 20 cases out of 26. In other words, 67% and 74% of the trialled measures had only positive impacts on the ES at the plot level and wider area respectively. However, negative impacts on ecosystem services could have gone undetected in the trials or may not have emerged yet.

Can we now identify those properties of the natural capital that play a decisive role in improving the ES? In other words, which modifications of the natural capital would be required to achieve an effect on ES? This would be a very pertinent result relevant for science and for land management. However, more research is needed to better understand the relationship between the natural capital and ES, in order to derive information on these mechanisms. The critical point is the assignment of relative weights to explain how much the different properties of the natural capital affect ES or affect changes in ES. As mentioned before, we consider this to be one of the most difficult and challenging aspects of this research, although our methodology provides one way of solving the issue.

Nevertheless, as the detailed description of the results showed, some unexpected insights emerged from application of the methodology, in terms of the trialled measures and their direct comparison at case study level as well as across all case study sites. Some patterns became visible, e.g., regarding the soil threat at stake and the effectiveness of the measure in addressing these. The direct comparison of the effectively achieved magnitude of changes in properties as well as in ES sometimes confirmed expected impacts, but also revealed impacts that might have been unnoticed before or were under- or overestimated. Additionally, the results enabled easy detection of synergies and trade-offs among the 15 assessed ES for each trialled measure, and thus provided an evidence base for valuation.

#### 4.1.2. Valuation of ES by Stakeholders

Following the assessment of impacts on ES as described in this paper, a valuation of the benefits of these ES is required, in order to use the results for future soil management decisions and for policymaking (see also [3]). Acknowledging that ES provided and influenced (changed) by soil management measures are valued differently by different stakeholders favours deliberative ways of stakeholder valuation and decision-making over monetary approaches. At the basis of stakeholder valuation is the understanding that a change in land management affects ecological processes, which in turn affect the kinds of benefits that people derive from land. Soil management thus alters ecological processes in such a way as to produce benefits (e.g., yield), but sometimes also drawbacks (e.g., contamination of groundwater with pesticides). However, benefits for some stakeholders might be drawbacks for others (or vice versa)—and for other geographical locations (e.g., downstream) or for future generations. This has to be taken into account for a comprehensive valuation of ES targeting the sustainability of soil management. RECARE has developed a stakeholder workshop methodology with a sequence of exercises enabling stakeholders (at the local as well as the sub-national level) to conduct such a valuation by combining local and scientific knowledge [47].

We noticed that stakeholders sometimes find the concept of ES difficult to understand or work with [48]. While the provisioning services are easy to understand due to their immediate use value or benefit to people, the regulating services are more difficult to perceive, as they frequently involve processes that show their positive or negative effects only in the long term and/or in a bigger context, and which are therefore often overlooked. The same holds true for the cultural services, which are less tangible and often go unnoticed. We found that some of these ES valuation workshops specifically uncovered some of these neglected (by the researchers) cultural services [48]. The valuation process further helped to evaluate whether the trialled measure(s) contributed to the desired benefits of the stakeholders. This also revealed synergies across stakeholders, scale, and time, e.g., if a measure provided distinct benefits for two or more different user groups (e.g., less on-site soil erosion for farmers and less off-site sedimentation damaging public infrastructure). Additionally, it also enabled an evaluation of which measure contributed most to the benefits and/or least to the drawbacks, in cases where several measures were compared.

### *4.2. Methodological Challenges and Critical Reflections*

#### 4.2.1. Measurements vs. Estimations

Asking for researchers' estimates where no measured data were available (or where it would have been too demanding or costly to measure it) was a delicate issue. Nonetheless, we decided to do so to achieve a more balanced, comprehensive, and holistic assessment than basing the results on the measured data only, which is often limited. Many ES assessment studies base their calculations on selected and available data only [4,49,50], although ES is a holistic concept. In our view, ES assessment only makes sense if the whole system is assessed and any changes in the properties of the natural capital are included, while acknowledging that different expert teams would provide different ES assessment results, even with the same data available, also because some researchers are more hesitant to estimate than others. Additionally, some of the estimations and assigned magnitudes may reflect expectations or even 'wishful thinking' of the researchers involved, rather than reality [51]. For a holistic approach as used here, it is nearly impossible to measure every single property, and we thus consider expert elicitation indispensable and justified (see also the Best Professional Judgement approach used by Rutgers et al. [4]). Especially in ES mapping and modelling, this is a frequently used approach, because expert estimation "is based on the assumption that through experience, education or profession, certain people have sufficient knowledge on the research subject, to officially rely upon their opinion" [52] (p. 22), [53].

#### 4.2.2. Assignment of Magnitudes and Impact Dependence

Contextual factors matter in the importance of changes in soil properties for changes in ES, such as the purpose of the soil management measure and regional differences. An example is the positive appraisal of low soil moisture values in Norway regarding flood reduction, compared to the negative appraisal of the same property in Slovakia, where water availability is important for vegetation growth, which positively influences flood risk reduction. The assignments of magnitude to interpret the changes in properties of the natural capital was thus an important step in understanding them in the local context, making them dimensionless, and comparing data across sites. However, this was also a difficult and tricky step, as the assignment of the impact dependence with 'the more the better' or 'the less the better' implies implicit values. For example, the low-resilience character of subsoil compaction turns the evaluation into accepting changes in subsoil compaction, while the precautionary principle would call for no change of the subsoil. However, working with the concept of ES is never value-free. The concept as such is anthropocentric and implies that there are 'services for the benefits of humans'. However, the real valuation of the ES, whether they are increased or decreased by the trialled measure, is done during the stakeholder workshop following the ES assessment, where the researchers' assignments can also be questioned and reversed again. This is in line with the doubts and criticism on valuation of soil ES formulated by many (soil) scientists and recently reviewed by Baveye et al. [2].

#### 4.2.3. Assignment of Weights to Explain ES

It appeared to be difficult to estimate the relative importance of changes in soil properties in influencing the delivery of ES. However, assuming that all soil properties carry equal weight, as done in other studies (e.g., [54]), is also an assumption of weights. As described in the methodology section of this article, we could not find in the literature another way to calculate changes in ES based on changed properties of the natural capital, and it was thus impossible to avoid the assignment of relative importance to properties. Other scientists have researched the influence of soil properties on just one ES (e.g., nutrient cycling), and only indicated the ones that matter, without trying to rank the properties or to quantify the effect on the ES [42]. The recent global review on linking soils to ES, by Adhikari and Hartemink [1], also revealed that—although there are many studies defining the linkage of soil properties to ES—there are very few that quantify the contribution of different soil properties to the services.

#### 4.2.4. Working towards a Holistic Appraisal of ES

One of the merits of the methodology lies in allowing all relevant ES to be included, and thus also dealing with ES that cannot easily be measured, such as cultural ES. We understand ecosystems as a holistic concept and therefore tried to avoid reducing the ES assessment to those ES that can easily be measured. We consider it important to identify, quantify, and valuate all changes in ES, as also supported by Braat and de Groot, who stated that "to choose a priori and arbitrarily to exclude some classes of services makes no sense" [55] (p. 12). Baveye [56] confirmed that the "key appeal of the concept of ES (the multiplicity of concurrent services) disappears if, in applications, authors pick and choose which services they include, and some are systematically overlooked" [56] (p. 47).

Nonetheless, how to combine the calculated ES change from the changed properties with the directly measured ES remains challenging. As described in the methodology development section, we decided to combine them using equal weight (50% each), which allowed both components to be represented in the outcome. Baveye et al. [2] (p. 17) state that "in the vast literature on the ES of soils, it is symptomatic that no publication to date has reported explicitly on the *direct* measurement of a single function or service. [ . . . ] there are currently no solid data at all on any function or service of soils." In his recent article, Baveye [56] further confirmed the need for actual measurements of ES of soils at field scale, which is still lacking. The present study provides some of this as well.

## 5. Conclusions

Despite all the limitations and challenges mentioned above, the methodology presented for assessing impacts on ES was highly effective in evaluating the trialled measures. It has allowed us to study the impacts of the trialled measures through the lenses of ES, which was taken even a step further in the stakeholder workshop on the valuation of ES. Although this stakeholder valuation, which is based on this ES assessment, was an integral part of the overall methodology as applied in the RECARE project, it was not possible to present and discuss it in detail in this paper.

Furthermore, our assessment provided the opportunity to compare monitoring results across the case study sites. Through the assignment of magnitudes of change, the monitoring data became directly comparable and independent of the parameter used or the unit of measurement applied. Additionally, the request to estimate changes even if no measured data were available enhanced the comprehensiveness of the assessment, taking into account drawbacks on its accuracy and reliability.

Methodologically, we consider our study to make an important contribution to the contemporary discussion on the role of soils for ES. Although there have been many studies defining the linkages of soil properties to ES, very few studies directly link soil properties to the services [1,53]. This was indeed the biggest methodological challenge, as reported above, and more research is urgently needed here.

Overall, we conclude that, with this method, we were able to successfully collect and compare data regarding the impact of land management on 15 different ES from 26 different trialled measures from 16 different case study sites across Europe. Without claiming that this would reflect reality in detail, we believe that this has not been done before in such a comprehensive and holistic way.

**Supplementary Materials:** The RECARE ES Assessment Tool is available online at http://www.mdpi.com/2071-1050/10/12/4416/s1, File S1: RECARE_Tool_ES_Assessment.zip. S2 presents the CICES 4.3 table adapted for RECARE, File S2: RECARE_CICES_adapted.doc.

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# Soil Fertility Management by Transition Matrices and Crop Rotation: On Spatial and Dynamic Aspects in Programming of Ecosystem Services

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**Abstract:** This paper deals with crop rotation as a method to improve soil fertility and control pests from an economic point of view. It outlines a new framework for modelling of more sustainable decision-making of farmers under the auspices of ecosystem services. It is intended for practical application in extension and farmer communication to show values of rotations referring to natural capital. In the past farmers created complex rotations to benefit from ecological processes which enabled them to control natural pests (at least partly), to build soil fertility on recycling of organics (humus formation), and to promote pollination (including wild bees and other insects) and water retention (diverse water requests of different crops). Farmers which were accommodating cropping orders in small parcels of fields used long lists of crop sequences and offered mixed farming systems: this was a major feature of agriculture. Cropping orders evolved from necessity and were followed as rules. Today we are faced with large fields and monoculture, instead, and ecosystem services are diminished. Usually, attempts to recognize economic pay-offs from rotation through modelling are meagre because of complexity. We address the issue of complexity by suggesting a new flexible type of modelling crop rotations (dynamic optimization) which condenses ecological information into matrices. A newly-hosted transfer matrix shall delineate the impacts of cropping patterns in period t to fertility of land in t + 1. Categorizing different states of nature (which have to be brought in line with farmers' knowledge of externalities), it can be implemented in models on rotation decision.

**Keywords:** crop rotation modelling; spatially explicit; dynamic programming

## 1. Introduction

Modern agriculture has given priority to chemical inputs in pest control and soil fertility management. However, particularly in monocultures and in landscapes with limited shares of natural vegetation, farmers still have problems with pest control and frequently report/observe declining soil fertility, as well as increasing pest problems. Since pests and declining fertility (i.e., annihilation of soil structures and micro-biological activities) can strongly decrease yields, nature-based methods have regained some attraction (at least in academics: Sandu et al. [1]). For practical farming, increasing unit costs of production will most likely prevail in the future (see the danger of myopic behaviour: Pemsl, et al. [2]) if ecosystem services diminish. Many public players, as sustainability advocates, request the implementation of ecologically-sound land use practices [3]. Problems with sustainable agriculture haven been discussed thoroughly in the past [4] and crop rotation is one important element. In fact, problems have emerged in agriculture in the context of soil fertility going beyond minerals or chemical pest control and resistance of species to pesticides, for example, black grass. Additionally, the concern for decreasing biodiversity and conservation is now a request for measures directed at the reduction of negative externalities. However, these problems are not solely limited to farming; ecologically-oriented researchers and the society, itself, see major problems of biodiversity loss from converting traditional cultural landscapes into production steppes [5,6]. Some authors (Fiedler et al. [7] and Lindborg et al. [8]) think that if the demand for nature conservation in cultural landscapes is not given priority (which is actually an environmental service, ecosystem service, of multi-functional agriculture for the society) problems of sustainability in the landscape will persist. This seems to be exogenous to the farming sector. However, again, the sector itself faces frequent problems of fertility [9,10]. Thus, we have an endogeneity problem. To a growing extent, farmers face problems with diminishing ecosystem services (fertility) even as a private good (natural resources and input) which reduces individual revenues, (i.e., yields, outputs, etc.) increases costs (inputs, labour, etc.), and reduces income [11].

In this context two strains of thought emerge: (1) What are the real costs of alternatives (natural pest control, rotation, mixed farming, etc.), i.e., vs. chemical control (more external input, more labour and machinery, etc.)? For example, what is the scope of fertility control by rotation and, hence, caring for nature? This issue is exaggerated by increasing prices for chemicals. In Germany, for instance, for 30 years (until 2009) the costs of combating pests and maintaining soil fertility with chemical substances were relatively stable, but then (since 2010) it seems that costs are picking up [12]. This is a trend and, as part of global energy price increases in the last decade (peaking in 2008 and, again, in 2018), we will most likely foresee a new situation of high input costs again. Then, (2) due to processes like the appearance of resistance against chemicals, the effectiveness of chemical substances seems to decline [13] and costs increase, as more substances are needed. This trend will change the competitiveness of chemical vs. natural methods. Real costs are changing absolutely and relatively and ecosystem services and their returns may even become a vision for farmers. A crucial thing is also labour cost. Since external costs are important, a question is to what extend do ecosystem services change labour requirements? For such questions we need to address rotations.

However, directed towards monocultures and uniform landscapes, those appearances are driven by economies of scale and concerns for large farms. At least currently, specialization drive and use of chemicals (as strategy) are pertinent. This is grounded in the farmers' knowledge system (as an example see typical reports like those of USDA: [14]); farmers seemed to work with a perfect chemical system. As a majority, they are no longer willing to maintain land productivity through "natural" measures, such as rotations. They, rather, applied more and more pesticides, artificial fertilizer, and other technical measures to keep their land "fertile". Though some scientists (Regev et al. [15]) spoke very early of problems, including the public good character of pest problems, as well as the consequences of myopic behaviour, not much work is done concerning the long-term cost comparison between traditional and modern modes of farming. Additionally, is there really an alternative? As suggested by Schönhard et al. [16] one way to maintain fertility and combat pests is to deal with crop rotation extensively from the point of view of agronomy and economy. They showed how representative farms can make choices on existing and recommended patterns for different rotations. Note that choices on rotation types were normally embedded in cultural traditions and not real choices, as there was an understanding in agronomy of typical (standardized) locally-confined rotations, though these rotations followed well-explained procedures [17–19]. Rotation choices were part of farm routines followed as collective knowledge and action. They were even partly enforced by local authorities. However, due to modern inputs, complex rotations seem to become obsolete because rationality changed. In particular, as a result of needs to economize on profitable crops, less profitable crops were dropped in rotations and fields increased in size because of limited recognition of essentials in rotations (ecosystem services from a mosaic of small fields; see below). Nowadays large machinery drives choices, farms are maximizing gross margins with a preference for high-yielding crops, well-priced crops, etc. In contrast, from an ecological point, it seems necessary and sound to integrate as many crops in rotations as feasible and follow a landscape-oriented analysis [20] for the benefits from rotation (see below).

However, today farmers will tell ecologists they make less money with ecologically-sound rotations. There is a tendency to reduce the complexity of rotations and even to introduce mono-cropping from a very narrow economic point of view of survival. Though it is argued by simulations that farmers could do better by including diversity through rotations and mixed cropping, they refuse. This clash of "culture" has strong implications on ecology and also the appearance of landscapes which could provide ecosystem services. Landscapes become uniform and there is a vicious cycle. In fertile areas, for example, pasture/meadow land has been strongly reduced, though it was part of traditional rotations. As a consequence, some organisms (including. micro-organisms in the soils) are no longer present/abundant and farmers voice that they cannot rely on ecosystem services. In summary, modern farms are composed of large fields and use few, highly profitable crops (wheat, rape seed, etc.) and seemingly do not care for rotation, unless it is incentivised externally (for example, payments for "greening", like in the EU).

Currently, for most farmers it does not seem to pay off to care for long-lasting soil fertility and natural pest control through crop rotation and landscape management. Thus, why do they act in the current way? Knowing that crop rotation and conservation have a considerable impact on soil and yields [21], there might be a ("wrong") reasoning for saying that planning and simulation have not yet reached farmers. Rather, due to the overwhelming pressure of economies of scale and short-term thinking, they prefer to strongly discount benefits of rotation. The (ir)-rationality of such behaviour seems to be evident, perhaps from the perspective of ecologists. However, farmers also expect that the pesticide industry offers new substances to deal with pests occurring as a consequence of mono-cropping. They also seem to have lost experiences and knowledge on the positive impacts of diversified crop rotations. At the same time farmers face growing problems with resistances, new pests, and declining ecosystem services, like reduced pollination, ground water formation, natural soil fertility, etc. Note that these services are traditionally based on landscape functions (foremost, diversity). A major problem in this respect is that the modelling and programming of rotations is quite complex and the seemingly very profound academic programming tools are not adapted. It is here where we suggest endeavouring into new approaches.

We will start by showing the potential for the application of the state-and-transition concept and corresponding transition matrix to rotation modelling at the farm level and then make some remarks for landscape inclusion and extension. It is the objective of this paper to show how it may be possible to increase the appreciation of advantages of long-term rotations through changed modelling and programming tools. By suggesting advanced modelling concepts of rotations which are in line with the capacity to handle them at the farm level, we think one can increase awareness of long-term effects of declining natural fertility and conduct better cost-benefit analyses for long-term commitments to rotations. These have to be locally appropriate and adapted and should not reduce income significantly. An essential question is how a potential drop in fertility can be linked to economic planning of crops, space, and rotation? For a researcher in agronomy the interesting issue is: how do deficits in farm planning methods (programming) determine behaviour? Then, how can things change? Is there scope for counselling on methods and recommendations, etc? We will show that there are deficits in the current planning methods and suggest a new concept (method) for temporal optimization of land use at the farm and landscape levels. This concept includes a transition matrix depicting degradation (or upgrading) of land. It is based on pre-fabricated rotations as references, but offers deliberate choices at the individual and landscape level.

In this context our paper will address the question of how modelling as an instrument can be used in the assessment of long-term effects of rotations (soil fertility and ecosystem services). The aim is that concepts become more appropriate for programming and portraying short- and long-term effects of crop use. However, it is not the aim to solve the "fundamental" conflict between the goals of ecology and economy; rather, a conceptual framework within the farming sphere is presented which could make farming more ecologically oriented. A mathematical tool is presented which helps to include thresholds, dynamics, and spatial aspects fundamental for rotation design. Assessments should work in a time frame of dynamic programming which is pre-defined. Hereby we want to address sustainability, spatial appearance, and ecosystem services from the farmers' perspective, but also the landscape view. A further aim is to present a dynamic optimization approach, including rotation and spatial design of landscapes which is specifically oriented towards field sizes, field edges, and needs to accommodate low-yielding crops. The paper is organized along a problem statement, a review on the state of the art, methodological problems and solutions, and it gives an outline of work to be done.

## 2. State of the Art

The issue of programming optimal land use as an instrument for crop rotation modelling, specifically designed for farmers or, by extension, working with farmers, has not been very intensively studied over the last decades. Yet El-Nazer and McCarl [22] worked with yield regressions which were implemented in linear programming LPs. Detlefsen [23] suggests working with network analysis and Klein et al. [24] studied crop successions as constraints. However, their approach is already very complex. They used an algorithm which, due to its complexity, its data requirement, and software problems, will most likely not be used by farmers. Recently, other complex models have been developed in operation research by Alfandari [25], but rotations are only shallowly tackled.

For example, rotation options are given in decision trees (on the one hand) which looks simple, but becomes very complex (on the other hand) because we deal with many years of foresight. Additionally, in contrast to theoretical insight, empirical research seems to confirm that narrow rotations suit current aims of maximizing profits best; even though no long-term concerns exist. Mostly, guided by the programming of activities with purchased inputs, farmers believe that new pesticide types will help to combat pests in the future. By chemical inputs, zero tillage, etc., benefits of rotations are qualified as marginal and should be simply based on empirical findings [26]. Thus, it is plausible that, in practice, farmers have departed from complex rotations.

As another method, threshold analysis was used by Lundkvist [27] as a rule of thumb. Weed control should no longer be based on successions of crops, but on the observation of thresholds. In line with this thinking, some decision support models are based on the economics of weed depression [28] through short-term reaction and not rotation. No wonder that rotation is outdated; yet, in this research, ecosystem service functions may not be really reflected, appreciated, and integrated. However, the economics of a full integration of weed depression is limited. It has created a need to model long-term effects using bio-economic approaches.

Another integration of crop models and economic models in a bio-economic approach for practical applications has recently been worked out by Cong et al. [29]. It works on soil organic matter as natural capital. In a further recent article an agricultural economist used programming [30] as a tool for dynamic optimization of crop mixes by indexed soil fertility. Again, in a simplified dynamic on the basis of the dynamics of a single variable to describe ecological effects [31], we get a future positive response to diverse rotations. Ecological (soil fertility) effects are mostly working on carbon in soil. However, there is more behind rotation: ecosystem health. The issue is: is this farm or landscape related?

In order to address the higher degree of complexity in dynamic optimization models in a frame of landscape and ecosystem services, the many needed aspects have been included by Cong et al. [32]. The bottleneck is again that “too” many differential equations are needed. Further note that researchers who have worked on an overview and review of existing models [33] showed deficits in capacity and practical reasoning to apply rotation. However, this has increased the esteem for methodological requests and farmers (as applicants) rarely will be capable of understanding and using the complex models. There is a need for compromise in modelling which enables more practical application and which, by providing a comprehensive outline on ecological processes, is capable to valuing the long-term benefits of rotation.

## 3. Framers' Objective for Individual Optimality and Society in the Case of Landscape Involvement

Within the following (below) frame of explaining how crop rotation can be better embedded in dynamic optimization (as a problem of farm optimization) we firstly suggest to maximize the long-term discounted income of individual farms. In that regard it is a traditional model typically applied in agricultural economics [33]. The aim is to implement soil fertility and pest regulation primarily through controlling crop mixes. Soil fertility and pest control are not aims, per se, they are intermediary paying-off in the long-term as reduced costs or improved yields. Though, as the advocated modelling frame is working in the programming modus (of linear programming), it will also contain standard activities such as spraying pesticides, applying fertilizers, etc., Rotation practices have to compete with conventional farming. Yet the model will contain some temporary constraints which can be interpreted as secondary objectives and which is typical procedure in dynamic programming and models of demand and supply that work with partial objectives [33]. Finally, these partial, intermediary objectives are evaluated economically and contribute to the long-term aims for farmers.

Secondly, at the landscape level a simple version would be to add (sum up) the individual objectives. However, since there might be a further benefit from the public good character of ecosystem services provided at the landscape level, one could work additionally within a principle-agent framework. This says that farmers individually calculate achievable income gains from benefits which are accrued by individual rotations. Then they take them as a reference in a participation constraint. The management of the landscape itself optimizes the collective gains independent of the distribution of individual gains. Collective gains are monetized and are contributions of the rotation choices with respect to cost minimization for food production of a society. For the monetization we can use shadow prices, as well as prices of inputs saved, such as pesticides, fertilizer and, perhaps, fuels. In the case of less mechanical control for pests even special investments for machinery might be avoided.

## 4. Transition Matrices in Eco-System Dynamics and Links to Farm Productivity

We suggest a new measure to detect a potential decline in soil fertility due to "too" narrow crop rotations (in extreme mono-cropping) based on a transition matrix approach [34]. The aim of this paper is to show how the transition matrix (approach) can be used in a modelling of rotation choice. Achievable results shall then fit into a dialogue with practical applications. Yet it is not the intention to substitute crop science-based decisions; rather, the emphasis is on modelling and the depiction of economic consequences of different rotations with regards to long-term effects. The transition matrix approach can be embedded in a conceptual framework which has been worked out by ecologists under the topic "state-and-transition" (for recent applications: Van Dyke [35,36]). A transition matrix enables research to include processes and thresholds. For example, an agronomist can set up a temporal link between yield potentials of today and yields in the future (it is an extension of forecasting bringing in ecological knowledge: see Christensen et al. [37]). It should be extended towards many potential crops (crop mix and rotation, as ordered mix over time) and can be based on a joint ecological and agronomical assessment of the fertility of land. It applies discrete states on the quality of the ecosystem (see below) and the process of transgression is at the level of probability. The potential cropping pattern of each period (and as an anticipated process for future yields) is dependent on an endogenous cropping pattern decision (built on an algorithm) that is implemented as a recursive planning tool. States are not used as in an aggregate single variable version but, rather, a Markov type of approach [38] is postulated. Then, using a transition matrix, we can establish a dynamic programming approach in bio-economic modelling being closely linked to ecological arguing and modelling of system change. It is a type of recursive modelling and planning [39] which uses forecasting and decisions in models simultaneously.

Note that Markov chains are categorical; for instance we can take the states. Then, by using probabilities to switch the states in the model between categories, the Markov chain provides a structural change outline or filter. Here, for example, the ecosystem states and fertility are discrete.

States are frequently used, for instance, in sector analysis; they are dynamic units. Recently, the analysis has been extended to filtering methods which enable learning while time passes (see by Dean et al. [40]).

To explain further why "Markov" is suggested, why this needs attention, and why it fits into a conceptual framework of transition-and-state which gives more room to ecologically-oriented thinking in agricultural economics, we refer to work on state-and-transition modelling, for example, in pasture management [41]. For instance, if the rotation choice puts too much emphasis on single crops, there is a problem already in the depiction of the potential decline in yields of other crops for the next years. Rooted in the interaction of crops, soil, micro-organism, etc., soil and ecosystems, in general, are entities which can best be explained by thresholds, multiple interactions, etc. (see also the chapter on empirical foundations below).

Thus, what is the response in agricultural economics? We think "degradation" has an overall effect for many other crops which can be depicted by a system approach referring to a transition matrix. In ecological economics this is the "capture by a state" description. In our case we refer to a measurement of degradation vs. fertility as a share of land in different states. Then, for practical reasons, the inclusion of the matrix enables the delineation of negative externalities (degradation) in programming techniques using software like GAMS (General Algrebraic Modelling System, GAMS Corporation, Washington, USA; for detail see Domptail et al. [41].) GAMS enables dynamic modelling by taking discrete, annual steps and transferring results from one period to the next as an element of endogenous optimization.

In Figure 1 the main principle is outlined. The modelling works with "planned" areas for crops at time t which are given as a percentage of farm area (spatial aspects will be tackled soon) and the impact on states at t + 1. Hereby categories of land quality are distinguished and they deliver constraints to farming in future periods. This means that land for farming is split into different fertility categories appreciable jointly by farmers and ecologists. Farmers face quality "states" of their land (as a mix) being the consequence of farming in the past and future relies on the past. They can "plan" the future of their land through programming within the computer model. "States" are characterized by discrete fertility categories, for instance "very fertile, . . . , fertile, poor, . . . , very poor". In each category yields are different and the assumption is that farmers' knowledge is based on assigning quality categories by referring to potential yields. These yields should reflect the natural fertility and not that which is coming from artificial fertilizer. By assigning the land quality categories one can simplify matters. Then, the focus is on land-related activities changing land composition and quality. In Figure 1 we depict a situation in which past land use activities, given as a percentage of land use, can create improved or degraded options in the future. Planned areas in period t + 1 must fit into the inheritance categories of land quality.

$$\begin{bmatrix} land - quality - category - 1_{t+1} \\ land - quality - category - 2_{t+1} \\ land - quality - category - 3_{t+1} \\ \dots \end{bmatrix} = \begin{bmatrix} \pi_{11} & \dots & \dots \\ & \dots & \\ & & \pi_{33} \\ \dots & & \end{bmatrix} \begin{bmatrix} wheat - area_{t} \\ barley - area_{t} \\ grassland_{t} \\ \dots \end{bmatrix}$$

Legend:
Land …: land in state quality categories
$\pi$: probability
Source: Own design

**Figure 1.** Scheme for the transition matrix.

On the left-hand side we have land in different quality categories which are the result of cropping patterns in the previous period. Yields and gross margins of land quality categories are varying systematically. This does not mean that the observed yields are declining if monocultures prevail, only natural fertility (yields) diminishes. The analysis is on the potential natural fertility (yields);

this means that, eventually, more fertilizer is used and the underlying natural fertility declines. Alternative management options can be assigned through programming; in this case as discrete choices with separate gross margins (such as wheat, for example with 30, 40, or 50 dt/ha, etc.). If, for example, more and more land is in a low-quality category, farmers face limited choices in the natural fertility of land for the future and have to use more chemicals to maintain yields. Consequently, increasing unit costs prevail, or yields may even decline, reducing revenue, which finally results in a decrease of gross margins.

A corresponding choice for production alternatives is given in Figure 2 for clarification. In this structure the highest yields are only reached from land in category 1. In category 2 we see lower "natural" yields (meaning more inputs are needed) and choices for crops within this category are limited. Technically, in GAMS the choices in period t are converted into constraints in t + 1. Note, on the right side, choice potentials are collected from different crops and represent the fertility composition at farm and landscape level. A necessity is to change practices (conceptually, rotations), eventually also for advancements of better quality in the future. For farmers, if they want less land in poor categories and are willing to transfer land in the category "best", this is only feasible if "good" rotation choice is practiced. Rotation choice is part of a set assignment in GAMS. It makes "good" land available. Apparently, the analysis can be made more complex if we include a possibility to substitute natural fertility and the use of chemicals. Hence, rotation choices are imbedded in farm practice and activities (see programming in computers of linear systems: LP). Farmers are offered alternatives which fit into their management, also including, for example, the use of pesticides.

The matrix depiction in Figures 1 and 2 is a substitute for differential equations in dynamic resource economics. It works with land classification (discrete one) which is perceivable by farmers and enables communication on states. The matrix anticipates local knowledge on transitions or, alternatively, it can be derived from ecological-economic modelling [41]. In a similar context of pasture management [41] work showed that, applying an ecological modelling to derive a transition matrix, is a step to formulate a holistic rangeland transition dependent on farming intensity, choice of activities, and response to degradation. In fact a similarity is given of arable farming and finding the matrix is also feasible. Using minimal maths and simple calculi, or working with tables, the matrix approach for management of degradation can be transferred to mixed farming on arable land and inclusion of pasture land.

As a follow up, states can be differentiated along productivity, and productivity of states give options for different cropping activities, apparently with different yields in the future! We must formulate land use in different categories being suitable for different crops. For example, if a farm is almost completely degraded, i.e., land is in the worst category (perhaps V), on this land a farmer could only produce rye, yet at a reasonable gross margin. Imagine, rye will still offer a reasonable yield, even if land is "exhausted"; i.e., wheat will yield comparatively poorly (soil fertility and pest pressure can be linked if yields are given in a category to measure discrete states of natural yields). Then the farmer has the choice of rotation to upgrade. Usually it is fallowing, or clover, grassland, etc., which may contribute to an upgrading and reaching of yield goals in grade IV. Apparently it can last several years to get back to good yields, so probabilities are consecutive. Vice versa, if there is a threat of dropping down in yields (actual yield category), for example, after several years of wheat mono-cropping, only the adoption of a "better" rotation helps. The information on the switches is displayed in the transition matrix linking states and land occupation. The information comes from agro-ecology and experts, or also from models [41]. However, that would merely be a description of an eventual causal (though quantifiable) process of degradation. To use the state-and transition concept and the look at the scope for improvements, as well as to see programming of rotation as an aim, the causal analysis has to be transferred into a normative approach. Figure 2 expresses the second feature of a transition matrix in terms of specifying the land classification categories, as well as formulating when a "constraint" is to be met. In terms of an endogenous, recursive optimization for period t + 1 the land shares in the given categories form the scope of using different crops most productively.

The tool is the transition matrix T with probabilities π and the request of the vector q for land quality; q is then the result of a combination of activities c and quality achievements are built at the level of probabilities: T c ≤ q. Now, in Figure 2, as compared to Figure 1, we differentiated the land categories along the potential to grow crops with different yields.

$$\begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} & 0 & 0 & 0 \\ & & & \pi_{24} & \pi_{25} & \cdots \\ & & & & & \cdots\cdot \\ & & & & & \\ & & & & & \end{bmatrix} \begin{bmatrix} wheat-yield-1_t \\ barley-yield-1_t \\ grass-yield-1_t \\ wheat-yield-2_t \\ barley-yield-2_t \\ grass-yield-2_t \\ \cdots \end{bmatrix} \leq \begin{bmatrix} land-quality-category-1_{t+1} \\ land-quality-category-2_{t+1} \\ land-quality-category-3_{t+1} \\ \cdots \end{bmatrix}$$

Legend:
Crops …: land for crops with different yields in state quality categories
π: probability
Source: Own design

**Figure 2.** Qualified scheme for transition.

Crops with different yields, as suggested in Figure 2 are the basic categories in land use and, hence, also for programming production activities we can use these categories. Though, now T is a tool to achieve a combination of crops which is conducive for maintaining the quality of land, in the context of consecutive and recursive modelling it makes the choice of one endogenous period to the next. Imagine that programming starts from the end and runs backward. This apparently implies that the final state (perhaps after 60 years of simulation) has to be given. Again this is normative and there must be reasoning for a mix of states.

## 5. Field Location and Allocation in Dynamic Programming of Rotations

As a next step in modelling a cluster of fields with different states of fertility must be outlined. In Figure 3 the computerized choice for land use is depicted. Fields are farm and landscape structures conducive to rotations. Farm land is always spatial. For modelling we have to stylize/simplify the reality. In modelling a crucial aspect is to initialize the current fields, but also to give flexibility. A compromise is stylization (example: a polder). We assume a rectangular form of fields and size: $a_i \cdot b_j$ (Figure 3). Under such conditions land area and size are portrayed by $b_j$ (fields and note: $a_i$ is fixed). Fields are programmed by the distance of $b_j$ as stretch ($a_i$ is constant).

The figure depicts two time periods, t = 1 and t = 2, of optimized land use out of a range of several periods (dynamic optimization. The interim period 1–2 is artificial and the computer uses it for a calculation of a consolidated plan in t = 2. It is composed of several options in quality categories (for illustration: I, II, and III) which give the final status after the weighted average calculation. Weights are given by the size of I, II, and III, which is the forwarded "prediction" in the computer program. A farm is composed of fields and their size or can be expressed as a cluster of fields. A field has a certain total length $\Sigma\, b_j = B$. In this distance we have to fit parcels (plots, fields) as activities in rotation, which means a constraint in programming prevails for land. The consecutive step is assigning activities in land use (cropping pattern) for the future. A way of doing so is introducing different categories of crops, yields, and types of crop-yield combinations as part of a rotation (see above). In Figure 3 we illustrate three different quality categories (I, II, III), but it can be more.


Legend:
a : farm size as vertical stretch in a rectangular landscape design
b : field size by number as horizontal stretch in a rectangular landscape design
I : categories of land quality
t : time
Source: Own design

**Figure 3.** Field size and allocation at the farm level.

Additionally, in the figure we illustrate that the allocation can change from period t to t + 1. As preferred crops, like wheat, generally require "best" land, the program would sequentially allocate land to, for example, wheat (land in "I": best) first. The program will do this through the optimization of gross margins. Here, on paper, it is for demonstration purposes only. However, area is numerically given by the size of the field. After the transition between periods, then, programming will reproduce a distribution of land quality as a constraint. In the program, model activities (as the allocation of land to crops) for each year are chosen according to long-term profits (discounted profits). We work with dynamic programming and discounted flows of gross margins are the objective. Additionally investments in machines and economies of scale can be tested. Prevailing, for instance, over a horizon of 30 years or more, the land allocation in each year is optimized recursively.

In the just-given conceptual outline to formulate a programming model, we have to categorize $b_j$ further as $b_{j,q,t}$ (crop, quality, and time). As an augmented choice on crops, quality categories, "q", become involved, which represent different classes of "natural" productivity of the land in time t and t + 1; hence, natural yield effects are captured. Note: high natural yields being ecosystem services save costs. For example, wheat yields can be as said: "best, good, medium, poor, and low". In terms of activities wheat production is categorized in fixed yields and the underlying practices are discretely formulated. The advantage is that farm planning can be associated with categories and gross margins simultaneously, requiring minimal knowledge on system development and degradation. Furthermore, categories which require different technologies to answer degradation must be separated, which is regularly done in programming. With deteriorated yields farmers have to use more inputs (combatting pests and recovering soil nutrients).

The above type of modelling can now be combined with different technology coefficients in programming to depict the quality category change in terms of new options. Quality categories become temporal constraints (see above). Categories are plannable and foreseeable for farmers; at least in the computerized forecast future categorical states of fertility provide information on scopes to conserve fertility. As a consequence the availability of land in different quality categories changes (as planned) over time. Vice versa, by actions in the past, farmers can improve land through rotation choice. Temporal constraints show the availability of good land in t+ . . . and in different productivity categories as subject to the choice of a specific rotation (see below). Nevertheless, in between the whole period there is an option to also change the "pre-fabricated" rotation. The model is flexible in regards to strategies. Note, categories (sizes in b) indicate different declines in productivity, need of inputs, and come up with different gross margins. For instance, eventually in category III wheat will require a great deal of inputs. Without inputs it would perform worse than rye. As mentioned above, being in category V, wheat would not perform in terms of yields at all and rye would be the "only" choice if previous degradation has resulted in poor land quality. Thus, it was a matter of "choice" (see below for the "choice of rotation" and depiction of alternatives at the meta-level).

## 6. Anticipation of Results in Rotation as a Design Problem for Agronomists

To be able to introduce knowledge on potential rotations into the previously-explained modelling concept of applying a transition matrix (soil quality, spatial, time, etc.; i.e., to specify alternatives in rotation) a foundation of alternatives as discrete choices is required. Two aspects prevail: (1) agronomists' concepts on "designing" rotation alternatives; and (2) the programming techniques (modes). As (1) crops can be distinguished according to their stand in a rotation (in Figure 4 a complex rotation is given first, a simplex, second, and, finally, a complex rotation of, eventually, 12 years). A rotation might start with wheat after wheat "WW" or wheat after rape "RW". Technically, it would mean adding a fourth dimension "r" in $b_{c,j,q,r,t}$, to land use activities which characterizes the type of rotation that is an upper layer choice beyond the crop. Sequences in rotations are fixed by experts (knowledge of scientists). Theoretically, the production for crop c, at a plot j ("size of b"), with the quality of land q and rotation r can now be identified by the five dimensions: crop, location (field), quality, rotation and time (eventually as the farm number may add, see below for landscape). Normally, linear programming has no spatially-oriented algorithm to assign crops to fields, but by numbering fields we can construct a substitute for field j. As a ranking, like in time and in space, in GAMS, a ranked numbering of fields is possible. In programming by a selection process for the most profitable alternatives we use all the dimensions (technically in GAMS). We will find numerical solutions and this means that many b's become zeros, though they are possible (note: unused alternatives are automatically set to zero by the computer and program choices are limited). A selection of b means that only one quality, rotation, and location opportunity becomes selected, for instance, by an if-else statement. This is possible through deliberate programming and reflects actual choices of farms.

Our compromise is that information from crop science is further used to specify typical rotation choices (alternatives for pre-selection) and the computer looks at the sequential cost-benefits for the "package". A package requests a full run of years at maximum given by the longest rotation. For short rotations they are a repeated set; thus, choices on rotation have a long-term commitment. However, it does not exclude if the farmer switching after the maximal year (for example, 12 consecutive years of fulfilling a rotation) is transgressed. At least, by the length of the dynamic modelling (the number of years and investigations), several full runs can be depicted. In general, we make some suggestions and clarifications on how issues arising from the modelling of fixed rotation and choices on switches can be put into programming.

a: complex

Field/ 1 2 3 4 5 6 7 8 9 10 … 30

Period

1 W S L A S

2 B W S L

3 P B W S

R P B W

C W

O W

M W

A W

L W

S W

b: simple

Field/ 1 2

W S

W W

R W

…

Legend:

W: wheat, B: barley, P: Potatoes, R: rye, cow peas, O: oats, M: Maize, A: alfa alfa, L: legumes, S: rape seed

seed

Source: Own design

**Figure 4.** Rotation and its periodicity.

In Figure 4 the second line after the first line (the sequence of crops in field 1) is lacking, i.e., field 2 lacks one period behind field 1. Further, as can be seen from the diagonal from wheat, for instance, wheat moves from field i in t to field I + 1 in t + 1, yet it is a "normed crop rotation". At the rights side in the figure, a simple version of three crops and two years of wheat is presented for comparison. Wheat dominates and rye and rape are paying off; secondly, apparently some rotation, though minor, is practiced; yet economically pre-stated, the farm has a preference for high gross margins. For a reference of a similar approach in the whole area (admittedly, an easier case of pasture management [41]) we refer to the programming techniques which are optional given in GAMS, for example as "if-else" statements. What follows is an outline of adapting rotation to programming techniques. For the programming as given in Figure 4, sequences are to be conducted at fields.

The practicability of farm management may impose additional constraints, such as labour constraints for certain crops and machinery. A first step is that information on practical crop rotations is depicted as crop sequencing. For example, in Figure 5 such an "ideal rotation" is given by 12 years. This implies that, for example, plot "1" has to follow a sequence: wheat, barley, potato, rye, cow peas, maize, oats, alfalfa, livestock with legumes, rape seed, fallow, and carrots (w-b-p-r-c-m-o-a-l-s-f-a); i.e., if this rotation is chosen it binds the farmer to finish the rotation. After finishing, however, he has a choice. For the digital modelling, such conditionality can be programmed. Indeed this applies only to plot 1. Then plot "2" follows with one year lacking and plot "3" with two years, etc., (i.e., steps of rotation are spatially transferred: see Figure 4). Under this condition the spatiality of the farm is recognized and designed rotations are implemented along a necessary number of plots. As indicated by the number of steps in a rotation, plots are potentially given for the choice algorithm. Thus, we most likely get small fields. For the GAMS program outline potential numbers, and not actual fulfilments, count. Further, technically, by summation of the rotation options we guarantee that no other system or sequence is selected. Flexibility lies in the size of the plots.

However, other sequences (rotations with lower consecutive numbers: for example, w-p-r) are potentially possible. Rotations, which are eventually prescribed by a consortium of experts, are optional and the programming shall select the "best" rotation. However, the rotation systems can be changed if it is opportune, as said after the years to complete. Simulations must be longer than just one sequence (we suggest four times; then, with 12 years, 48 years are optimized). The rotation systems depend on the recommendation of agronomists and are given for one run or sequence; for example, for 12 years at a maximum it is reasonable to say that back-and-forth is feasible for "neighbouring" rotations. Nevertheless, they can be swapped more frequently if we extend the time frame and look for several episodes of replications (even more than 60 years, which means five sequences). Note that usually in dynamic programming the lifespan of a decision can be extended, which is a technicality of programming. Then, in Figure 5, we see alternatives on plot "1" (1a–h). The flexibility, built in, comes with the choice of alternatives at the plot level; though choices are discretionary, they can be anticipative.

The needed different modes in rotation for soil fertility management can increase the complexity of rotations and can open the way for longer rotations. Pest pressure, seasonality, increased labour at smaller plots, etc., are elements constituting the different options and choices on rotation. Additionally, special crops in the particular rotation system, as well as eventual modern technologies to offset disadvantages from narrow rotation, can be explicitly recognized and modelled. However, the alternatives must be discrete. For instance, pesticides and mineral fertilizer are complementary inputs in narrow rotations and they substitute natural fertility accomplished through commitments to ecologically-sound rotations. Though, in the activity spectrum, more chemical inputs may appear for narrow rotations, which may not pay off. The programs' logic (being similar to the farmers' goal of maximizing long-term gains) will decide rotation A B C; which means we name them and they are "sets" in GAMS. Even maize in a mono-culture can be an alternative (1h).

It is exactly here where the dispute between proponents of modernization and proponents of sustainable agriculture lay, and people clash in grey zones of not testing alternatives. The modelling can do the testing and give answers. Again, for our purpose of obtaining a spatial representation it is sufficient to have benchmark rotations. To get simple and treatable structures we propose using a "block" combined of 12 years as the "offer" and elements of the "most suitable" crop rotation. Within this framework of potential rotations and plot outlets the "design" of the field composition must include a type of "supply" flexibility between rotations, i.e., superficial activities in programming activities are to be created equally. What suits the special type of rotations in a discrete order is endogenous.

Next, as optimization is based on five distinct dimensions, for practicability reasons the results must be aggregated to given fields. This is done at the level of priority. As an example, in period 3, plot (field) 2 shall be mainly under livestock in rotation 1; for logical reasons it must take over all corresponding activities given at this time.Additionally the dominant land quality category obtained in the area under livestock is of category 5. The dominant category is the one that is conducted. Different results are summarized in crop categories for a given slot following the choice of the relevant rotation as a priority. The consequence is a reasonable flexibility, though still the choices of the "rotation system" are along the dominant category and, temporarily, the dominant one is the fixed one. For the moment it looks that such a practical procedure and the flexibility in dimensions are enough and they can open an outline in which they fit with farmers' choices. Apparently this is based on knowledge of alternatives. Making things sufficiently flexible requires a relaxation in the fixed rotation sequence. A compromise would be allowing a split into a restrictive and a less restrictive treatment of combinations, or traditional versus modern rotations.

| Field/ | 1a | 1b | … | 1g | 1h | 2a | 2b | … | 2h | 3a .. | 4a.. 5a.. 6a.. 7a.. 8a.. 9a … (alternatives) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Period | W | W | … | S | M | S | S | | M | W | L |
| 2 | B | W | … | W | M | W | W | | M | B | W S |
| 3 | P | R | … | W | M | B | W | | M | P | W |
| 4 | R | M | … | S | M | P | | | M | R | W |
| 5 | C | M | … | R | M | R | | | M | C | W |
| 6 | O | W | … | W | M | C | | | M | O | W |
| 7 | M | W | … | W | M | O | | | M | M | W |
| 8 | A | R | … | S | M | M | | | M | A | W |
| 9 | L | M | … | A | M | A | | | M | L | W |
| 10 | S | S | … | L | M | L | | | M | S | W |

Legend:

W: wheat, B: barley, P: Potatoes, R: rye, cow peas, O: oats, M: Maize, A: alfa alfa, L: legumes, S: rape seed

Field/ 1a 1b …1g 1h 2a 2b … 2h 3a .. 4a.. 5a.. 6a.. 7a.. 8a.. 9a … (alternatives)

Source: Own design

**Figure 5.** Alternatives in rotation.

For an explanation of Figure 5: In field 1 (see first two columns of Figure 5) we contrast the options 1a and 1b (but we can go up to 1h of the pre-designed rotations). The computer chooses the best sequence "a, b . . . or h" and crops "i" for $b_{ki}$. For example, 2h means that the monoculture M (maize) rotation has been chosen on plot 2. 1g would have meant that two years of wheat are followed by two years of barley, etc.; however, after choice 2h the combinations are exclusively M in that field. This means that in programming, firstly, a choice between types of rotations (a–h) has to be made, and then field sizes are determined secondarily. Determining the size of the plot is the actual optimization program, but choice and optimization can be programmed simultaneously, because one can use if-else statements in GAMS.

(1) The consecutive choice in time is a mixture of rotations. For instance, after 12 years as the threshold period, a new rotation is chosen because yields are good. This is projected using the transition matrix running parallel to the issue of land quality. The alternative is a split in the plot size between rotations. In practical terms this is normally impossible. It would imply a fragmentation of fields. Since a split (fragmentation) is unattractive due to economies of scale, we aggregate and the dominant crop wins the field occupation. To solve this problem with the logic applied in programming, the application of an "if-else" function is a possibility, i.e., if field 1a is larger than 1b, the computer takes the option (1a) for the whole plot size. (i.e., the if-else in the GAMS code assures that the winner takes all). This is relevant because, in our modelling approach, an inter-temporal implication is envisaged based on the land use in period t which is transferred in period t + 1 via transition-and-state via the transition matrix changes occurring in land quality from this year to next year's crop based on the probabilities modelled in the transition-and-state concept. Note the predecessor crop in the rotation mode determines yield potentials and crop choices for the next period (see above). The transfer between periods matters for future choices (crop choices, i.e., understanding soil mining crops vs. soil recovering crops).

(2) However, we have to not only restrict choices and let conservation prevail. A further issue in programming is that a switch between rotations (towards higher-yielding crops) shall be possible in a more episodically-specified manner. Yet it inherits the risk of being inhibited due to maturing rehabilitation costs in the next periods. Rehabilitation costs reflect rehabilitation activities as shadow

prices. However, the objective within the algorithm (discounted future profits) assures that only profitable regimes are presented as regards to the total profitability (discounted), and such activities are only chosen, as if no final capital restrictions exist.

(3) The implementation of the outlined procedure in software programs is of major relevance. For example, in programming, as mentioned above, the exclusion of an activity by the disposal of another can be achieved through assignments. In GAMS we can specify it as an "if-else" statement on the basis of "greater (less) equal", and then let the model solve the problem of which rotation is optimal. This can be extended to several transition matrices and their dynamic constraints. Specifically, in GAMS there is the option to create "if-else" statements for choice sets in which dynamic equations and constraints (matrices) prevail. In terms of the transition matrix, itself, we configure them dependent of activities. This means we can use thresholds and can then switch the relevant transition matrices and corresponding rotation on or off. Rotation choices are represented by transition matrices. This refers to modelling farmers' decisions, investments in soil fertility, pesticides, or modern technology change constraints, etc., as if choice sets are used. Passing thresholds opens options for less restrictive rotations in the future, and vice versa. Investments are separate activities. To adapt a new constraint function (for instance, a narrow rotation instead of an old complex), investments are to be made to climb over an edge (threshold). The effects can be tested in computer simulations. The consequence will be an outcompeting of old by new rotation systems; done potentially, but not necessarily, the farmer will come back to which rotation suits him, i.e., if investments are cheap, farmers prefer narrow rotations; if not, they opt for complex ones. Since we model a dynamic (constraint) system, a switch in the strategy of farmers should be possible, but it has temporal effects. The matter of an underlying strategy can help to understand the importance of rotation choices three-fold: (1) what matters is the state of soil fertility and ecosystem health; (2) as rotation planning, it is embedded in dynamic programming (i.e., conditions to obtain good yields or gross margins) to minimize costs of pesticide matters. Then applications of the model control land use pattern. The pattern, however, can change in time; and (3) investments through spraying or decontamination are decision variables which could make a modern rotation (i.e., a simple one) still preferable.

For dynamic optimization, the start and end conditions further play a major role. Hence, we may start with a situation of depleted stocks of soil fertility. The consequence is a need to restore fertility by crop rotation. In this context we can use an index of soil fertility "I". It can be used to specify conditions under which a switch in rotations is relevant. Apparently, the size of the criteria index $I > s$ (threshold) is a matter of open debate and subject to agronomist knowledge. In programming, at least for the final period, the threshold is exogenous. i.e., before the threshold is transgressed we may suggest a fixing of the index as a sustainability criterion. Technically, the criterion of the threshold or the index that needs to be passed in order to pursue a simple rotation instead of a complex one is normally given exogenously. Why do we have to do so? Simple rotations give higher gross margins, because low-yielding crops, pertinent for traditional crop rotations, are excluded. This should only be possible if the state of nature is good and no threat of future decline appears.

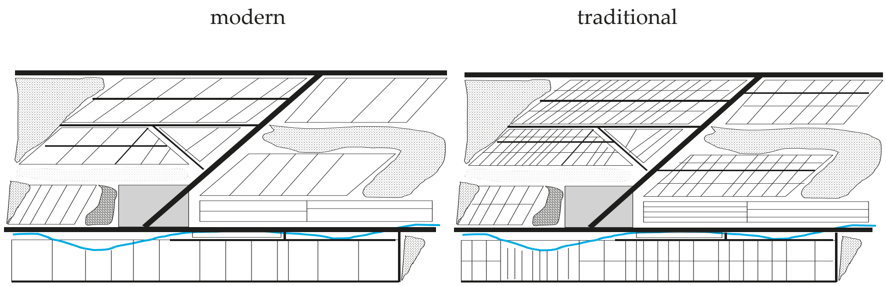
On the other hand the threshold constitutes the ecosystem behaviour as a response to mono-cropping. Thus, the threshold is a critical value and it serves as an interface between the ecological and economic aspects of a farming system. We need joint knowledge. The issue is that, today, farmers should already anticipate deteriorations in crop rotations according to the transition matrix, knowing the ecology of the system [42]. This means, in the given framework, according to a threshold, either the traditional or modern rotation is applicable. This is the output of the software/program. Yes, this is normative, but it is given by a farmer's ecosystem service request. In principle, for decision support and sensitivity analyses communications with farmers are necessary. The question is whether the threshold is exogenous or endogenous to knowledge, i.e., are we facing the problem of whether the norm or threshold is up to decision-making? From the point of view of endogenous decision-making, exogeneity is questionable if the health of ecosystems does not matter. Vice versa, ecologist will say ecosystem health is a norm which cannot be compromised. Accordingly, periodic decisions which follow should be known. At the moment envisaged decision-making rests on the periodicity of rotations and norms; thus, sizes of land chosen for crops will change.

## 7. Empirical Foundation, Eco-System Services, and Landscape

In the case of small farms, the issue of crop rotation must be extended to landscapes, if ecosystem services are to be more prominently addressed. Yet landscapes are a public good. To address landscape issues, we need a deeper thought on ecosystem health and landscape design [43]. For the ranking of land quality categories we could employ states of the ecosystem at the hamlet or parish level, which are jointly farmed. We suggest a modelling of yields grounded in an ecological framework or modelling functions and species [44]. Categorizing productivity of land-based ecosystem states in landscapes, yet by expert opinion, modelling, forecast, etc., can be a method that is highly successful if it works in the same framework and with the categories outlined above. However, reducing complexity in ecosystem analysis remains an issue [45]. Farmers and researchers can build assessments of rotation problems on the landscape analysis level only if there is cooperation. The assessments should include a common understanding of classes, or "states", of nature, which are associated with soil fertility, resistance decline, prevalent pests, etc., and threats of further pest problems, etc., For this we need a common box of relevance: ecosystem conservation. The use of the service is not a goal, per se, but secondary and a mean. It could also include diminishing water and moisture problems, which go beyond the farm level and is watershed-oriented. If performed decently and anticipated correctly, states contain quantitative and qualitative information on system health at the larger scale. Underlying service provisions, for instance, of pollination and water retention, are always beyond the farm level. The transition matrix must be extended to the landscape level. Hereby it changes its character from farm to system knowledge.

From the farmers' point of view, reckoning the ecosystem service (system) underlying farming systems, the decision on rotations contains a double hurdle: a control of negative effects on the farm (1) and on the landscape (2) levels. At the landscape level dynamics and equilibria between prey and predatory species in nature through designing rotations and landscapes must be understood. This seems to be a high aspiration. However, to support agronomists and farmers in designing rotations landscape analysis can help to employ ecological modelling, in particular by finding transition matrices with a ubiquity claim. Though ecological modelling is frequently detailed and very complex, the advantage is that it can integrate landscape interactions and elements at a larger scale. Another advantage is that it can establish classifications for states characterising ecosystem health (also for farming purposes) at the system level. Traditional and local knowledge helps in conceptualizing states. This hopefully enables projections of ecosystem trajectories in order to fully explore rotation effects. A technique of receiving information might be a straightforward ecological modelling of rotation systems based on events and triggers which are containing stochastic elements and fuzziness. This can help to accommodate disturbances created by farming and the effects can be demonstrated by simulating ecological consequences by spatial ecological models [46]. Rotations and their consequences for ecosystems can stabilize farming systems.

However, what landscape and what farming style are we heading for? Figure 4 gives a comparison between traditional and modern landscapes. We can mediate between these two systems by creating a "surrogate" of diversity over time by rotations and deliver services. Rotation also has an impact on field sizes; not necessarily, but the logic tells us more crops need more fields and fields become smaller. An ecosystem is more than rotation at the farm level. Rotation experiments at the farm level have to be embedded into landscape designs. Then we can really observe what happens, if (neighbourhood) effects between farms exist. Research shows that ecosystem services depend on landscape diversity. We have to extend farm analysis to simulations with several farms also at the spatial level to fully explore rotation benefits. In Figure 6 the landscape effects of rotations are depicted. It shows, in a stylized version, the effects of modern vs. traditional choices of rotation and field size combinations on landscape appearance.




Source: Own design

**Figure 6.** Farm and landscape level.

In principle we should become capable of transferring cropping patterns of a current period given a number of farms at a collective level into an availability of land fertility classes in the following period. Note that this implies a new matrix outline of cross effects and we should necessarily implement productivity improvements at the farming system level dependent on landscape elements, such as hedges, buffer strips, etc., Rotations become interconnected to landscape elements. Further improvements, for instance, by fallowing, clover, and legume inclusion, etc., in the rotation can be implemented as an augmenting function of good land quality for the community. The management is land allocation at different quality levels and beyond farms.

## 8. Discussion on Management Units

As a deduction, we have to think about decision-making on soil fertility and thresholds in a broader sense. Hereby appears the question about the unit of decision-making: who makes decisions on rotation? If we proceed with methodological individualism, representative farmers optimize their discounted income flow, but does it also work at the community level? It is possible to minimize the costs of food production at the community level and farmers are modelled as participating in actions (rotation). However, deliberations on rotation choice may be a joint exercise between landscape ecologist, agronomists, and farmers. Deliberations may start with results of individual rotation optimization, assuming an average farm in terms of size, labour, etc., Adjustments can be expected in the case of labour input and machinery, as the size of the operation is concerned. As there is flexibility in the input choice, a pre-determined product mix must be anticipated with different technologies. The input choice is given based on average results from the rotation optimization. This choice should be expressed in an "economies of scale" section of the model, because this will especially determine the size of the farm.

However, we then have to expand beyond the farm level to obtain "rotation" as a prescription. The farm size is correlated with technology choice, rotation, and landscape needs for ecosystem services: is this a dilemma? If the approach stops at the farm level, we would not correctly address the farm and landscape connectivity and potentials. Thus, we have to extend the approach to the landscape level and calculate the implication from rotation decisions of several individual farmers on landscape appearance. For this, a planner is necessary. The task is manifold grouped in three steps: (1) it has to be explained how individual and collective decisions are compatible; (2) the issue of retrieving a quality index for the landscape must be discussed at the landscape level; (3) a recursive implementation of the quality index as a measure to guide rotation decisions must be outlined; and (4) to address questions of landscape organization and ecology, an explicit spatial programming of fields, farm size, and rotation strategies (that goes beyond individual farms) is necessary. It aims at synthesising several farms in one larger approach. This, again, is complex; it normally goes beyond a simple programming model. A compromise is to stylize the spatial organization of farming at the landscape level (Figure 6) and iterates farm behaviour with more complex rotation interactions. To emphasize: at the centre of this analysis stands the newly-suggested transformation matrix for the landscape which shall translate a certain choice of cropping patterns in period t into ecological effects of a consecutive period t + 1 in a landscape. The ecological effects are decoded as a certain value of on-farm productivity change. The empirical foundation of the analysis can be provided by a productivity ranking, as well as by the determination of the pest danger in the predominant farming system of the landscape. The ranking is implemented by different states of the ecosystem that are jointly elaborated.

Farmers and researchers can then base their management propositions jointly on a modelled assessment of the crop rotation problem as a landscape problem. This is depicted by eventual planning of a "central unit". Assessment is based on common (community) understanding of classes, or "states", of the ecology in the whole landscape. We must assume that farmers, agronomists, and scientists have a reasonable understanding of the outlined problem (i.e., traditional and local knowledge, conceptualized capacities to project ecosystem trajectories, information on mechanisms in ecology, etc.). To achieve such understanding "states" can be used and the aim should be that community plans reflect the "state" achievements in the future. For instance, if soil fertility in the landscape declines, the model must be capable to project different states at the landscape level (note, it must not be equal to the farms' assessments), as well as show diminishing moisture and pest problems (from very good to very poor). From a point of view of the landscape, a custodian for farmers has to be installed as an agent. However, as a consequence, stylized rotation plans at the community level should follow underlying simple ecosystem detections. We hope that farmers' views of possible alternatives (in farming and categories at the farm level) change practice. For this intention a characterization and valuation of a defined "best" rotation in a participatory way is important. Yet it goes beyond rotation as a technical concept; rotation can become a bit ecologically-oriented; however, we cannot solve the conflict by modelling, but give hints. The reason is that some beneficial organisms eventually only occur (and with them positive externalities) if we introduce community-oriented landscape elements (notability as elements of rotation: meadows). Finally, ecological equilibria can be regulated by designing landscapes and rotations simultaneously based on fields, farm size, fallow, etc., Notice, though, the intention can be to recognize the scope for interaction of ecological and economic knowledge in rotation design; admittedly, rotation remains a farming tool. Not to raise too great an aspiration, rotation is a tool in the farmers' rationale of long-term profit.

## 9. Discussion, Limitations, and Conclusions

We pointed out that the reduced capacity of ecosystems to assimilate disturbances created by current farming systems is a reason for reduced ecosystem services and this requests better rotation choice. A reduced recognition of ecosystem services by farmers is also amplified by the lack of appropriate planning methods. We suggested using a transition matrix and a concept of states and transition to alleviate these deficits, as well as to conduct spatial planning. Apparently, the transition matrix is a substitute for differential equations in dynamic resource economics. We acknowledge that programming based on a transition matrix and qualitative states has its limitations in the capability to identify states and to obtain the matrixes. In programming the major choice to be made concerns decision variables of farmers in spatial land use. Since land use and rotation are the focus, farmers would never understand why they should program pest populations. Our approach is a compromise which accommodates farmers' and ecologists' knowledge, and seeks to develop a farmer-oriented approach to rotation design.

Another issue is the consideration of the spatial connectivity of fields, crops, and ecosystem. We constructed a stylized landscape. The spatial problem is to be solved simultaneously as a choice of crops and land quality. A discretionary variable has to be constructed that has the capacity to depict land use and quality variations simultaneously. A method to combine qualitative and quantitative information is used to categorize choices and to introduce variations in yields along farms. The farms are given in a rectangular plot system, i.e., in a polder landscape as a reference for modelling choices of farmers. Only then can rotations be introduced as discrete problems, requiring the interaction of farmers, agronomists, and landscape ecologists. The future benefit of the model depends crucially on whether it is possible to properly develop the ecologically-oriented rules needed besides the programming, itself, and incorporate them properly. This has already been achieved in a simpler version of pasture management [41].

## 10. Summary

A traditional answer of farmers to address problems of soil fertility, pest control, and ecosystem services had been the use of crop rotations. Additionally labour-intensive rotations were normally linked to diverse and species-rich cultural landscapes. We discussed the background why this has changed and what the ecological, especially ecosystem service issues which are linked to rotation oriented behaviour, are. Instead, in modern agriculture, few crops, heavy machinery, and economies of scale dominate farming and landscape systems. However, farmers also face the loss of positive externalities of ecosystem services; though short-term orientation and use of chemicals have created myopic behaviour. We addressed the issues by making suggestions for modelling crop rotations (through dynamic optimization models) and landscape analysis, including ecosystem services which are depicted by a transition matrix. A newly-introduced transfer matrix, which is based on the transition-and-state concept in ecology, shall delineate impacts of crop compositions in period t to natural fertility of farm land in t + 1. Further thoughts are given concerning the spatial organization, landscape and agronomic aspects for modelling rotations. A joint modelling of these components is proposed, and it is indicated how programming software can be used to model rotations.

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# Exploratory Analysis of the Productivity of Carob Tree (*Ceratonia siliqua*) Orchards Conducted under Dry-Farming Conditions

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**Abstract:** In Southern Portugal (Algarve), the occurrence of extreme climatic events has become more limiting to agriculture and forestry productivity. Severe or moderate drought during spring, summer, and autumn is common, with major implications on yield, farmers income, and on a long-term basis, land use. Facing this scenario, farmers rely on certain crops in order to obtain a complementary revenue, as an alternative to more intensive and high-demanding farming. One of these crops is carob tree, a multipurpose and industrial fruit tree species very well adapted to dry-farming conditions and very important to the sustainability of these fragile agroecosystems. The aim of this study is to analyse the fruit productivity during 30 years in two mature carob tree orchards grown in two contrasting soils: a fertile, calcareous soil and in a non-fertile soil. Based on this exploratory analysis, the gross income of farmers obtained from fruit selling in the regional market is discussed. Moreover, the possibility of using tree carbon sequestration as an ecosystem service shall be considered as a novel alternative in these depreciated agroecosystems.

**Keywords:** gross income; carob; yield; soils; desertification

## 1. Introduction

Carob tree (*Ceratonia siliqua* L.) is a woody tree species cultivated all over the Mediterranean region, which presents a great ability to grow under different edaphic conditions [1]. It is tolerant to water and soil nutrient stress (e.g., low N and P) due to a marked ecological plasticity, possessing several types of physiological and morphological resistance and tolerance mechanisms [1,2]. Currently, it is an industrial crop and Portugal is the third top producer, globally, of carob, a dry pod that is used for animal feed and human food [2]. Several interesting compounds may be extracted from the pulp (sugars, polyphenols) or seeds (proteins, vitamins, and amino acids) and used in the pharmaceutical and nutraceutical industry [3,4].

One of the greatest concerns of the carob industry at the transnational level is the regional availability of pods, which must be consistent and regular year round. The problem arises when fruit production in the region decreases. In general, there is a positive effect of summer irrigation and N fertilization on tree performance [1], but the majority of carob tree orchards are not irrigated and do not receive mineral fertilizers, thus relying mostly on favourable pedo-climatic conditions during the crop cycle. Carob tree is well adapted to different soil types, providing that excessive soil water accumulation in the root zone can be avoided. Calcareous soils with medium to high soil organic matter are the best soils to grow carob tree, but less fertile soils (low organic matter) with no calcium carbonate may also be used, revealing the high ecological plasticity of this crop [1,2]. Economic return and long-term variation of gross income in these two contrasting ecosystems—calcareous soil ("Barrocal" region) and non-calcareous soil ("Serra" region)—have never been studied and compared.

The objective of this exploratory analysis is to provide basic information regarding the long-term variation of fruit production in two orchards, grown in two different soils in Southern Portugal. This information may support future measures of supporting agricultural policies in marginal regions chronically affected by desertification and rural abandonment.

## 2. Materials and Methods

The study was conducted in two different orchards. The orchard in the Barrocal region with a total area of 4.3 ha was located in Castro Marim (37°20′ N, 7°44′ W). Trees of the cultivar "Mulata", particularly suited to industrial purposes, are more than 50 years old and are established at a density of 51 trees per ha. The soil is a clay-loam soil comprised of 16% active lime. At 30–40 cm depth, the pH($H_2O$) is 8, with low values of extractable P and medium values of extractable K. Organic matter (OM) is 4.1%. No irrigation and no mineral fertilization is applied, although some OM is occasionally incorporated in the soil surface. Soil is tilled once or twice per year. Overall, the cultural practices of this orchard are minimal, thus, we may consider this a low input farming system, where tree productivity mostly relies on favourable seasonal environmental variations. The soil of the orchard is suitable for carob tree development, and based on soil chemical analysis, no major nutritional limitations are expected to occur at the site.

The orchard in the Serra region, located in Junqueira (37°26′ N, 7°46′ W), is established in a sandy-loam soil, with no active lime (0%), with low values of extractable P and medium to low values of extractable K, and with 1.6% of OM. The pH($H_2O$) is 5.8. Applications of OM in this site are rare and sparse. The density is 68 trees per ha, and the total area of the orchard is 43.8 ha. The cultivar is also Mulata, and the orchard age is similar in this second site. Although it is not possible to indicate with accuracy the exact age of the trees, both orchards reach their maturity in terms of yield potential. Both orchards belong to the same farmer, thus, the cultural practices and soil management are quite similar. The climate of both locations is a typical Mediterranean with hot summer and mild winter (*Cs* according to Köppen classification) similar since they are located only 7 km apart. Mean annual air temperature is 16.5 °C and precipitation is around 500 mm per year.

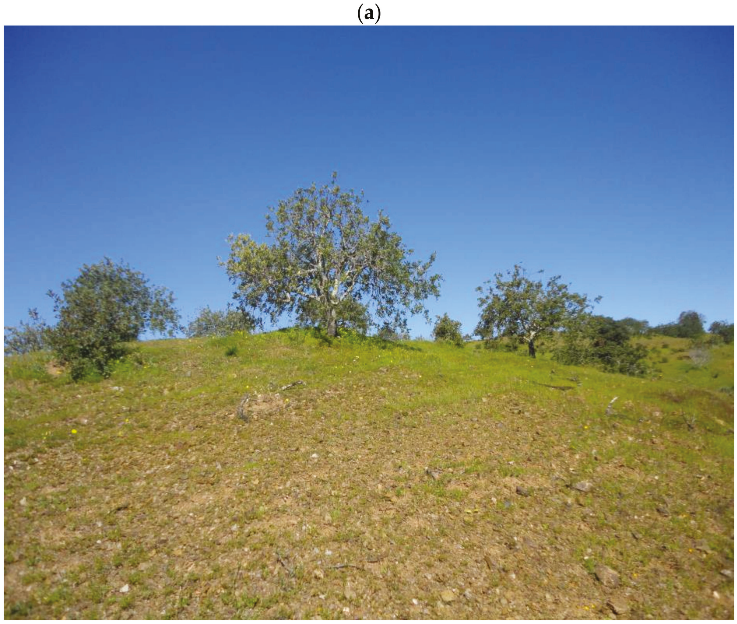
Yield data (fruit production) was collected from the farmer's inventory and reported to the period 1985–2015. The price per kg of pods was also obtained from farmer. Yield data used in this exploratory study is in kg of pods per tree, collected at harvest (late summer). The values per tree were calculated based on the total yield per ha and dividing this value by the total number of trees. No male trees were found within the selected areas, but male trees were found in adjacent areas. Two response models (to each soil type) were proposed to predict gross income as a function of increasing tree density. Multiplying 0.50 euros per kg and assuming the average of fruit production for each site, a total gross income per tree was obtained. Subsequently, the gross income per ha according to projected tree density, was calculated and plotted.

One-way analysis of variance was used to compare yield per tree in the two sites, by using SPSS software (IBM, SPSS Statistics for Windows, version 23.0, Armonk, NY, USA).

## 3. Results

In Figure 1a, mature carob trees in a traditional low-density orchard in the calcareous soil of the Barrocal region are shown. Trees with similar ages, but grown in a non-calcareous and less fertile soil of the Serra are much less developed, as can be seen in Figure 1b.

(**a**)



(**b**)

**Figure 1.** Traditional carob tree orchards in the southern Portugal (Algarve). Calcareous and fertile soils at Castro Marim (Barrocal region) (**a**) and less fertile soils in the Serra region (**b**). Soils are tilled once or twice per year and no mineral fertilization is done. Occasionally, organic matter (OM) is applied.

The variation of fruit production per tree in both locations is observed in Figure 2.

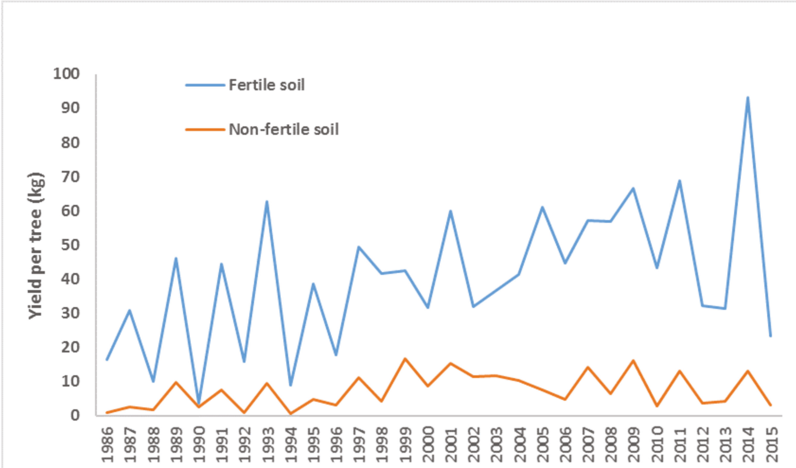



**Figure 2.** Long-term variation of yield, expressed by kg of pods per tree in both soils (farmer's inventory). Difference between the two sites is statistically significant, $p < 0.01$ (one-way ANOVA).

The differences between the two locations were clear, and mostly reflects the effect of soil (Table 1). The pattern of yield is also variable for each situation. In the fertile soil of Barrocal, there was an "on-off" yield pattern between 1986 and 1996, which was not observed in the following decade. Between 2011 and 2015 that "on-off" outcome seemed to occur again. On the contrary, the fruit production of trees in the low-fertility soil, wass extremely low, although the same yield variation pattern between years may be seen.

**Table 1.** Descriptive statistics of fruit production per tree (in kg) in the two locations: non-fertile soil (Serra) and fertile soil (Barrocal); N = 30 years.

| Statistics | Non-Fertile Soil | Fertile Soil |
|---|---|---|
| Average | 7.4 | 40.3 |
| Variance | 24.8 | 410.5 |
| Standard deviation | 5.0 | 20.0 |
| Maximum | 16.6 | 93.0 |
| Minimum | 0.6 | 3.7 |

In Figure 3, the variation of the fruit's price from 1986 to 2015 is shown. The value of kg of carob pods was low compared to the value used as reference in the region. Accordingly, only in 2004 and 2005 was the value above that threshold level. If we consider the production per hectare for each region and take into account the densities of 51 and 68 trees per ha, respectively, for fertile and non-fertile soil, the variation of gross income per ha and per year is presented in Figure 4. In the first case (fertile soil) the average of fruit production income was 652 Euros per ha (±392 Euros, s.d.), whereas in non-fertile soil it decreased to 158 ± 113 Euros (75% less). To reach the values obtained in the fertile soil (mean = 652 Euros), at least 4 ha of non-fertile soil in the Serra region would be needed, despite the high variation between years.

Figure 5 shows the variation of gross income in relation to the increase of tree density.

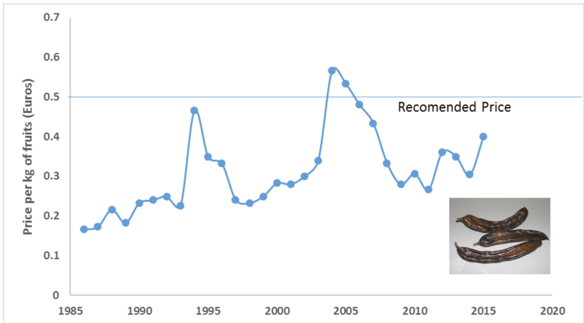



**Figure 3.** Price of the kg of carob pods (inside picture) in the regional market. The recommended price (0.50 euros per kg) is a reference value, which is considered a good price by farmers' organizations and regional associations.

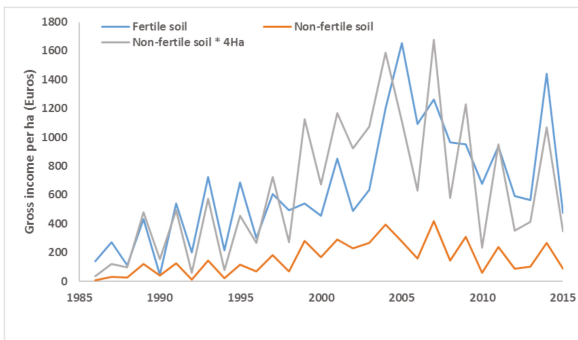



**Figure 4.** Gross income (Euros per ha and per year) obtained in "Barrocal" region (fertile soil) and in the "Serra" region (non-fertile soil). To reach the values obtained in fertile soils (average = 652 Euros), an area of four ha of in the non-fertile soil would be requested to trigger similar income (average = 632 Euros).

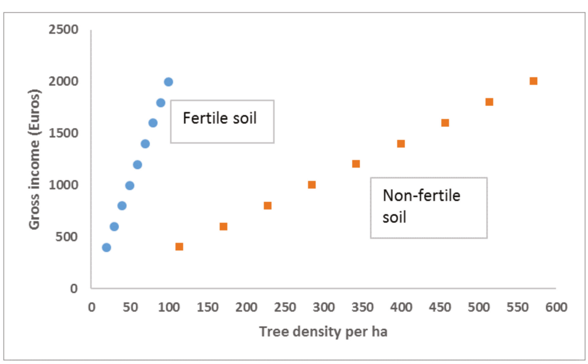



**Figure 5.** Two hypothetical models of gross income per ha (Euros) and per year in the two regions (Barrocal—fertile soil; Serra—non fertile soil), in relation to projected tree density. A value of 0.50 Euros per kg of pods was assumed; the mean of fruit production per tree obtained from the data in Figure 2 was also considered for calculations.

The models considered the recommended price of 0.50 Euros per kg and an average of 40 kg and 7 kg of fruit per tree, respectively, for fertile and non-fertile soil. To obtain the maximum gross income in the Serra region, and considering a low tree productivity (7 kg per tree), 571 trees per ha would be required.

## 4. Discussion

Portugal is the third top carob producer in the world [2], and the cultivation of carob tree is practically restricted to the southern province (Algarve). Carob tree is an industrial crop since the fruits (all of its components: pulp, seeds, and embryos) and leaves, are processed by local industry. Carob byproducts are then exported worldwide, representing a positive economic return of 11.4 million Euros (the average of 2010–2015, [5]). The seed and pulp industry (mainly kibblers), therefore, acquire all the available production after harvest (late summer) ensuring a consistent and regular demand throughout the season. The cultivated area with mature and productive orchards is currently around 9000 ha, but if we also consider other agrosystems, such as carob mixed orchards (with almond, fig, and olive trees), semi-abandoned orchards, urban areas, and gardens, a rough estimate indicates around 80,000 ha.

The most productive orchards grow in the calcareous soils of the Barrocal region. These soils have a higher water holding capacity and normally shows higher K, Ca, and Mg content. These chemical characteristics may explain the higher yields reported in this study for the Castro Marim site, despite the large variation between years (an average of $40 \pm 20$ kg, s.d.). Contrastingly, the soils of “Serra”, which represents more than 50% of the total area of the province, are much less fertile, with very low levels of OM (0–1%), and low levels of P [6]. These conditions are similar to those found in the non-fertile soil of this study (Junqueira site), where extremely low yield was observed (an average of $7 \pm 5$ kg). In this marginal soil, at least four ha of non-fertile soil are needed to meet the gross income obtained in the fertile soil. This is not unrealistic, since the average of the land area per farmer operating in the Serra region is greater than 10 ha. This is a reasonable option for land-use in marginal soils since it allows a continuous mosaic of carob tree orchards, providing a complementary annual income. However, the very low price payed to farmers associated to the high yield irregularity still constitutes two major constraints. This irregularity, sometimes a marked “on-off” pattern, is apparently not related to climatic conditions, but rather due to endogenous metabolic factors, as found by Haselberg [7] in this region, turning into a very difficult, and complex to describe and predict tree productivity, which is a crucial issue to the carob industry.

Taking into consideration the results described above, how can we maintain the sustainability of the system for carob tree/land use? Increasing tree density may be an option, but in non-fertile soils this option is not realistic since the demand for water and soil nutrients increases [1,2]. Higher tree densities (>200 trees per ha) imply external inputs, such as drip irrigation during spring and summer, and mineral fertilization (N, P, and K), representing additional costs to the farmer. We believe that if the price is consistently low, most of them will not be willing to invest in those external resources. Moreover, and in the case where water is available to irrigate agricultural crops, the options easily fall to *Citrus* trees or horticultural crops.

Taking into account the climatic change scenario in the Iberian Peninsula [8], the sustainability of the carob tree agroecosystems conducted under dry-farming conditions requires novel perspectives. Several new compounds have been identified in carob pulp [9], and some of them are related to soil properties [10], but a regular demanding market for these products should be implemented. Finally, tree carbon sequestration potential should be clearly assumed [11] as a new source of income, otherwise we might assist in the long-term depreciation of this traditional crop in Southern Europe.

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# Assessment of Benefits of Conservation Agriculture on Soil Functions in Arable Production Systems in Europe

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**Abstract:** Conventional farming (CONV) is the norm in European farming, causing adverse effects on some of the five major soil functions, viz. primary productivity, carbon sequestration and regulation, nutrient cycling and provision, water regulation and purification, and habitat for functional and intrinsic biodiversity. Conservation agriculture (CA) is an alternative to enhance soil functions. However, there is no analysis of CA benefits on the five soil functions as most studies addressed individual soil functions. The objective was to compare effects of CA and CONV practices on the five soil functions in four major environmental zones (Atlantic North, Pannonian, Continental and Mediterranean North) in Europe by applying expert scoring based on synthesis of existing literature. In each environmental zone, a team of experts scored the five soil functions due to CA and CONV treatments and median scores indicated the overall effects on five soil functions. Across the environmental zones, CONV had overall negative effects on soil functions with a median score of 0.50 whereas CA had overall positive effects with median score ranging from 0.80 to 0.83. The study proposes the need for field-based investigations, policies and subsidy support to benefit from CA adoption to enhance the five soil functions.

**Keywords:** soil functions; conservation agriculture; conventional farming; zero tillage; environmental zones

## 1. Introduction

Soil is vital for the provision of soil-based ecosystem services that are essential for human wellbeing. These soil-based ecosystem services are the outcomes of the complex interplay of soil properties, environment, land use management and their interactions [1–3] of which five key soil functions are identified; (a) primary productivity; (b) water regulation and purification; (c) carbon sequestration and regulation; (d) habitat for functional and intrinsic biodiversity; and (e) nutrient cycling and provision [4]. These five soil functions contribute to agricultural productivity, as well as the provision of other regulating and supporting ecosystem services. Soil management is a key driver that will determine whether soils are capable of supplying these multiple functions, which underscores the significance of soil custodianship [5]. As soils provide a suite of soil functions, optimization of one function can have trade-offs with other soil functions. The objective of enhancing individual soil function viz. primary productivity function in the agriculture sector at the cost of other soil functions will depend on the local demands for the other soil function (e.g., clean drinking water) or national or regional demands (e.g., national carbon sequestration targets) [6]. Due to the competing demands for different soil functions, there is a need for an integrated, or holistic assessment, of the suite of five soil functions in order to mitigate trade-offs and to optimize supply which contrasts with efforts that focus only on individual soil functions. This study builds upon earlier reviews [7,8] and assesses the five soil functions concurrently and the optimization of same, so that one soil function is not maximized at the cost of other soil functions.

Conventional farming (CONV) refers to mono-cropping, inversion tillage and residue removal, which is often, although not always, associated with contributing to adverse effects on soil functions. Conservation Agriculture (CA) practice constitutes no-till combined with residue retention and crop rotation [9–11], as an alternative to optimize the provision of soil functions. In a framework of soil custodianship, CA is practiced to optimize available resources (soil, water and biological) whilst minimizing external inputs [12] and soil degradation [13]. Despite reported benefits, such as improved soil fertility, crop growth, better water infiltration, increased biological activity, decreased soil erosion and reduced labour, machinery use and fuel costs, CA is practiced only in 25.8% of European agricultural lands, well below the land areas of similar continental farming landscapes [12,14,15]. Hence, there is a need to assess the effects of CA and CONV practices on soil functions in order to better understand their potentials to optimize soil functions and to provide evidence to support more sustainable outcomes.

Due to the knowledge gaps on outcomes of CA adoption [15], there is a need to assess the impacts of CA and CONV practices on the five soil functions to guide recommendations for sustainable land uses and policy making [16,17]. As the effects of CA and CONV practices are dependent upon environmental zones [18], out of the 13 environmental zones in Europe [19], four environmental zones viz. Atlantic North, Continental, Pannonian and Mediterranean North were identified to represent the major environmental zones in Europe. Hence, the objective was to assess the effects of CA and CONV practices on the five soil functions in four major environmental zones in Europe.

## 2. Materials and Methods

### *2.1. Identification of Environmental Zones and Treatments*

Based on climate, soil and vegetation and land cover, Europe is classified into 13 environmental zones [19] and a representative population of studies from identified environmental zones, representing major production systems in LANDMARK project [20], were used to extrapolate results for the zones investigated. Of the 13 environmental zones, four environmental zones were identified viz. Atlantic North, Continental, Pannonian and Mediterranean North (Figure 1). Atlantic North includes mountains and uplands in Western Scandinavia and narrow coastal plains [21]. It is characterised by glacial deposits and oceanic climate with tundra vegetation in the north and grasslands in the high mountains and arable agriculture in the areas near the coastlines. Continental zone covers a large area including lowlands from Central and Eastern Europe and Balkan countries. The zone has variable land cover due to inherent geology and soil types with a huge annual temperature range and high precipitation during the summer. The Pannonian Zone covers the lowlands, valleys and mountain in the middle and the lower Danube basin and the Black Sea lowlands. The zone experiences a warm continental climate with early summer precipitation and it is a dominant arable agriculture zone converted from grasslands. The Mediterranean North Zone covers lowlands of the northern and central Mediterranean, but also hills and low mountains in the south. The zone is characterised with warm dry summers and precipitation in the winter months and water availability is the main constraint for agriculture in this zone [21]. Hence, these four environmental zones were selected with the aim of assessing the dominant environmental zones in Europe.

In each environmental zone, the effects of CA and CONV practices on five soil functions were assessed in annual cereal crop production systems. Six treatments were identified as common treatments across the environmental zones to compare the effects of CA and CONV over five soil functions. The six treatments compared were (i) conventional farming (CONV) (ii) No-tillage (iii) reduced tillage (iv) crop rotation (v) residue retention and (vi) conservation agriculture (CA). The six treatments were defined as:

1. Conventional farming (CONV) practice constitutes mono-cropping, ploughing to 20–30 cm depth to prepare the land for sowing and crop residue removal
2. No-tillage is a practice of directly sowing in the stubble, by cutting narrow slots for seeding
3. Reduced tillage, whereby near-surface soil (5–10 cm) is physically disturbed with discs, chisels or field cultivar, resulting in loose topsoil. A significant proportion of crop residues are retained on the soil surface equivalent to 30–60% soil coverage by residue.
4. Crop rotation which involves growing different crops in sequence in a field in 4–5 year crop rotation including cover/catch crops depending upon the environmental zone
5. Residue retention is a practice, where crop stubble, straw or other crop debris is left on the field, and is then incorporated when the field is tilled or left on the soil surface
6. CA is a combination of (i) no-tillage, (ii) crop rotation and (iii) residue retention

CONV is the control practice of intensively managed winter wheat (*Triticum aestivum* L.) monoculture with mineral fertilizer and pest and disease control with chemicals and residue removal. The treatment effects were evaluated on five soil functions and soil functions were defined as below [1,4,22]:

i. Primary Productivity: The productive capacity of a soil to produce plant biomass for human use, providing food, feed, fibre and fuel within natural or managed ecosystem boundaries
ii. Carbon sequestration and regulation: The capacity of a soil to store carbon in a non-labile form with the aim to mitigate increases in atmospheric $CO_2$ concentrations
iii. Water regulation and purification: The capacity of a soil to receive, store and conduct water for subsequent use and the prevention of both prolonged droughts, flooding and erosion. Water purification is the capacity of a soil to remove harmful compounds (e.g., volatile organic compounds and heavy metals) from the water that it holds
iv. Nutrient cycling and provision: The capacity of the soil to receive and retain nutrients, to make and to keep nutrients available for crop uptake and to facilitate recovery of plant-available nutrients over these nutrients into harvested crops

v. Habitat for functional and intrinsic biodiversity: The multitude of soil organisms and processes, interacting in an ecosystem, making up a significant part of the soil's natural capital, providing society with a wide range of cultural services and unknown services.

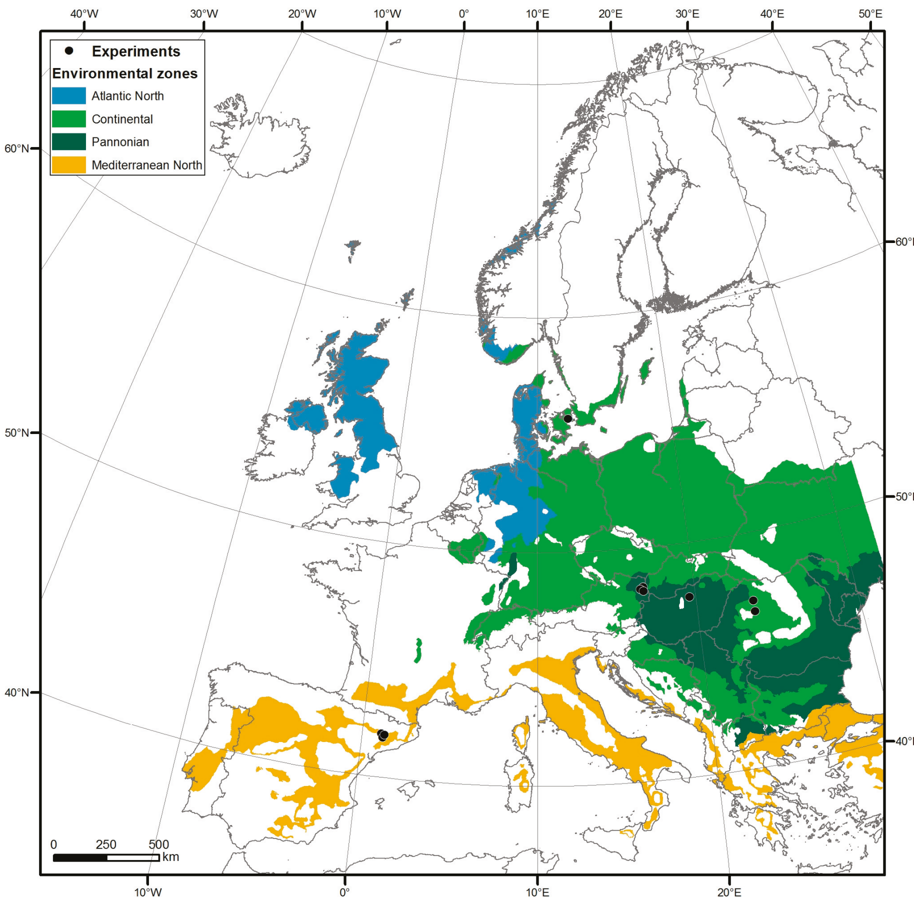


**Figure 1.** Map of the four major environmental zones with locations of the on-site long term experiments, in LANDMARK consortium countries viz. Ireland, Denmark, Netherlands, Hungary, United Kingdom, Belgium, France, Germany, Austria, China, Brazil, Switzerland, Romania, Sweden, Slovenia, Italy and Spain.

For the literature search, key search strings were tillage, minimum tillage, soil functions, conventional tillage, conservation agriculture, soil properties, crop rotations, residue retention, Atlantic, Continent, Pannonian and Mediterranean. The resulting papers were subjected to the following criteria for inclusion in the study:

i. Experiment period was a minimum of 2 years prior to the date of response variable (e.g., grain yield) measurement
ii. At least two treatment levels were included in the trial design (e.g., minimum tillage vs. conventional tillage or residue retention vs removal)
iii. Experiments were conducted in any of the selected environmental zones in Europe [19]

iv. Only annual cereal crops (wheat, barley, oat etc.) production systems were taken into account.
v. Other field crops were only considered within the crop rotation such as associated companion undersown grass, maize, rapeseed, legumes, root crops (potato and beets) and catch/cover crops
vi. A minimum of three replicates per treatments were required.

### *2.2. Soil Function Scoring by the Subject Matter Experts*

The five soil functions were scored at a coarse scale of environmental zones and the four environmental zones identified, representing the major environmental zones in Europe. The identified environmental zones are justified to represent wide differences in climate, land uses, management practices and soils [19]. For each of the four environmental zones, a team of 2–4 subject matter experts were assigned to the respective environmental zones, to provide one consolidated scoring of the effects of six treatments of CA and CONV practices on five soil functions in annual cereal production systems. The team of subject matter experts from each environmental zone used a common list of 10–22 references (Table 3) to agree on a common scoring by each team. The consolidated scoring of each soil function was based on the mix of three methods consisting of a minimum of 2–3 papers per treatment, expert knowledge and on-site long-term experiments. The on-site long term experiments, were the combined food and energy production system in Denmark, Fuchsenbigl tillage trial and the Rutzendorf crop residue incorporation trial in Austria, a soil tillage field experiment in Romania, a cultivation experiment in Hungary, and the tillage management effects on soil water conservation, organic matter and crop productivity sites in Agramunt, Selvanera and El Canós in Spain. The on-site long-term experiments were very useful data sources for scoring soil functions, especially in cases, where data was scarce. Although the treatment effects may vary within a single farm due to interactions between management, climate and soil variables, the consolidated scoring provided general direction of treatment effects for comparison across the four major environmental zones in Europe. The information available on the five soil functions varied significantly across the zones and hence the scoring of some commonly quantified soil functions (e.g., primary productivity, soil carbon sequestration etc.) may be based on more extensive number of studies compared to the other soil functions, the information of which can be scarce to non-existent.

In this study, the soil function scoring may be biased, to a certain extent, based on the particular studies the experts were aware of, depending on the field experiments available at the local experimental farm or research environments. We have mitigated this bias by taking account of the soil function scoring from at least 2–4 subject matter specialists from each environmental zones. As our aim was to assess the general effects of the CA and CONV practices on soil functions, our analysis provided a broad acceptance of views on effects rather than context-specific treatment effects. The study is an attempt to provide a framework on the direction of change in soil functions due to management practices for the land managers to adjust land use and management practices in order to meet the demand for soil functions.

The scoring of the soil functions were carried out in the following three steps. Firstly, a set of three indicators were identified for each of the five soil functions (see Table 1) and the team of subject matter experts provided the scorings on indicators. Secondly, indicator scorings were aggregated over soil functions and hence the performance of a single soil function was considered as the median score of three indicators and this methodology was followed for all the five soil functions (Table 3). Thirdly, soil function median scores were aggregated over each of the six treatments, which provided the performance of each treatment over five soil functions (Table 3). Median, a measure of central tendency, is used to describe the data spread in ordinal dataset (scoring dataset).

The scorings were carried out using a Likert-type scale ranking [23] and arranged in an incremental order; viz. high negative effect ($-2$), low negative effect ($-1$), no effect (0), low positive effect (+1) and high positive effects (+2). These scorings were carried out at indicator level for each of the soil functions, which were subjected to positive reassignment between 1–5 scale as shown in Table 2.

The positive reassignment is required to rank the scoring as a precondition for data normalization. Following positive reassignment, scores were normalized to between 0–1 (Table 2) by dividing each score with five, assigning equal weights to each score [24]. For example, for the primary productivity function, the three parameters under primary productivity were scored between −2 to +2 followed by conversion of the scoring to 1–5 scale, which was subsequently normalized by dividing by 5 to arrive at scores between 0–1 [24]. The median scores aggregated over soil functions and treatments were interpreted as negative effect (0 < 0.60), no effect (0.60) and positive effect (>0.60) corresponding to −2 to −1, 0 and +1 to +2 scoring values respectively.

**Table 1.** Three indicators identified for each of the five soil functions.

| Soil Function Indicators | Primary Productivity | Carbon Sequestration and Climate Regulation | Water Regulation and Purification | Nutrient Cycling and Provision | Habitat for Functional and Intrinsic Biodiversity |
|---|---|---|---|---|---|
| 1. | Increase in grain yield | Increase in stable soil organic matter (humus) | Increase in the water holding capacity of soil | Reduction of soil erosion | Increase of above ground biodiversity |
| 2. | Improvement in grain quality (e.g., protein content) | Increase in reactive soil organic matter | Enhance water infiltration into soil matrix | Reduction of $NO_3$ leaching | Increase of soil biodiversity |
| 3. | Increase in biomass yield (grain + aboveground biomass) | Incorporation of plant residues | Reduce groundwater contaimination | Reduction of phosphorus leaching | Increase earthworm count |

**Table 2.** Soil function scoring rules [24].

| Directional Change | Value Range | Positive Re-Assignment | Normalized Scores |
|---|---|---|---|
| High positive effect | 2 | 5 | 1 |
| Low positive effect | 1 | 4 | 0.8 |
| No effect | 0 | 3 | 0.6 |
| Low negative effect | −1 | 2 | 0.4 |
| High negative effect | −2 | 1 | 0.2 |

### *2.3. Statistical Analysis*

The aggregated median values of the five soil functions for each of the six treatments were subjected to Kruskal-Wallis non-parametric test [25] to determine the differences between the six treatments on the five soil functions. Kruskal-Wallis non-parametric test is used to test if the samples originate from the same distribution to compare two or more independent samples of equal or unequal size [25]. Test Statistic H [26] was calculated on the median score and H critical value at 95% significance was the basis for significant differences across the treatments. Statistic H was found to be higher than H critical indicating that the treatment median scores were significantly different ($p \leq 0.05$) between the treatments. Median scores were assigned with alphabet letters (a, b, c, d and e) and scores with no common letters are significantly different.

## 3. Results

### *3.1. Effects of CA and CONV Practices on Five Soil Functions in Atlantic North Environmental Zone*

In the Atlantic North environmental zone, soil functions were affected in both directions viz. positively and negatively by application of CONV practices whereas only positive effects were recorded due to CA (Table 3). The differential treatment effects of CONV on the five soil functions indicated that there were trade-offs where one soil function was enhanced at the risk of decreasing another soil function. The CONV scored significantly lower median values (0.33; Table 3) indicating that the practice had overall negative effects (<0.60) on soil functions. In contrast, the CA and its component practices scored significantly higher median values (0.87–1.0) indicating positive effects on soil functions.

Across the treatments, CONV had negative effects on four out of the five soil functions except for a positive effect on primary productivity function (0.87) (Table 3). CA and its component practices had varying positive effects (>0.60) on all five soil functions except primary productivity in no-tillage and residue retention treatments (0.47). Crop rotation had the highest positive effect on primary productivity (0.93), whereas CA and no-tillage had the highest positive effect on carbon sequestration (1.0). No-tillage and residue retention had the highest positive effect on water retention and regulation (1.0) whereas the no-tillage and crop rotation had the highest positive effect on nutrient retention and cycling. No-tillage had the highest positive effect on habitat for functional and intrinsic biodiversity (Table 3). Hence, no-tillage had the highest positive effects on four soil functions followed by crop rotation with highest positive effects on two soil functions (Table 3).

### *3.2. Effects of CA and CONV Practices on Five Soil Functions in Pannonian Environmental Zone*

In the Pannonian zone, the median scores were significantly lower (0.53; Table 3) in CONV indicating overall negative effects on soil functions. In contrast, CA and its component practices had significantly higher median score (0.67–0.80) indicating positive effects on soil functions (>0.60) compared to the CONV practice.

Across the treatments, CONV had a positive effect on the water regulation and provision function, with no effect on primary productivity function and with negative effects on the other three soil functions (<0.60) (Table 3). CA and its component practices had varying positive (>0.60) and neutral effects on each of the five soil functions except negative effects on primary productivity (0.47). Crop rotation had the highest positive effects on primary productivity whereas CA had the highest positive effect on carbon sequestration (Table 3). Residue retention had highest positive effects on water regulation and provision whereas crop rotation, residue retention and CA had highest positive effects on nutrient regulation and cycling. No-tillage had the highest positive effect on habitat for functional and intrinsic biodiversity function. Some treatments had positive effects on a greater number of soil functions than other treatments. For example, crop rotation, residue retention and CA had highest positive effects on at least two soil functions (Table 3), whereas no-tillage had highest positive effect on only one soil function.

### *3.3. Effects of CA and CONV Practices on Five Soil Functions in Mediterranean North Environmental Zone*

In Mediterranean North, the impacts of CA and CONV treatments differed widely from negative effects (<0.60) to highly positive effects (>0.60–1) (Table 3). Among the treatments, CONV had significantly lower median score (0.53) indicating overall negative effects on soil functions. In contrast, CA and its component tillage practices had significantly higher median scores (0.80–0.93) indicating overall positive effects on soil functions.

Of the treatments, CONV had negative effects on three soil functions viz. carbon sequestration, water regulation and cycling and habitat for functional and intrinsic biodiversity whereas, of the CA and its component tillage practices, only residue retention had a negative effect on primary productivity. No-tillage had the highest positive effect on primary productivity followed by crop rotation, whereas, CA had highest positive effects on carbon sequestration followed by residue retention (Table 3). Residue retention had the highest positive effects on water regulation and cycling function followed by no-tillage whereas, residue retention had the highest positive effects on nutrient cycling and regulation. No-tillage and CA had the highest positive effects on habitat for functional and intrinsic biodiversity compared to other CA and CONV practices. Hence, CONV contributed to negative effects on three of the five soil functions whereas, the CA and its component practices, had a negative effect only in primary productivity due to residue retention.

**Table 3.** Scorings of CA and CONV practices (1–6 as described above) on five soil functions in Atlantic North, Pannonian, Mediterranean North and Continental environmental zone. Studies (no) is the number of studies per soil function in each environmental zone.

| Soil Functions/Treatments | Primary Productivity | Carbon Sequestration and Climate Regulation | Water Regulation and Purification | Nutrient Cycling and Provision | Habitat for Functional and Intrinsic Biodiversity | Median | References |
|---|---|---|---|---|---|---|---|
| **Atlantic North—Studies (no)** | (6) | (4) | (3) | (5) | (2) | | |
| Conventionl farming | 0.87 | **0.33** | **0.20** | **0.20** | **0.35** | [a] **0.33** (0.20,0.87) | [27–30] |
| No-tillage | **0.47** | 1.00 | 1.00 | 1.00 | 0.95 | [b] 1.00 (0,47,1.0) | [7,28,31–33] (expert opinion) |
| Reduced tillage | 0.73 | 0.80 | 0.80 | 0.80 | 0.80 | [c] 0.80 (0.73,0.80) | [31,34,35] |
| Crop rotation | 0.93 | 0.73 | 0.87 | 1.00 | 0.90 | [d] 0.90 (0.73,1.0) | [36–38] (expert opinion) |
| Residue retention | **0.47** | 0.73 | 1.00 | 0.87 | 0.80 | [c] 0.80 (0.47,1.0) | [24,39,40] (expert opinion) |
| Conservation agriculture | 0.73 | 1.00 | 0.93 | 0.87 | 0.85 | [d] 0.87 (0.73,1.0) | [6,7,33,41] (expert opinion) |
| **Pannonian** | (8) | (13) | (4) | (8) | (3) | | |
| Conventional farming | 0.60 | **0.53** | 0.67 | **0.53** | **0.40** | [a] **0.53** (0.40,0.67) | [42–53] (expert opinion) |
| No-tillage | 0.60 | 0.87 | 0.67 | 0.73 | 0.93 | [b] 0.73 (0.60,0.93) | [43,44,46–52] (expert opinion) |
| Reduced tillage | 0.60 | 0.67 | 0.67 | 0.60 | 0.80 | [c] 0.67 (0.60,0.80) | [42,47–49] (expert opinion) |
| Crop rotation | 0.80 | 0.80 | 0.73 | 0.80 | 0.80 | [e] 0.80 (0.73,0.80) | [48,53–55] (expert opinion) |
| Residue retention | 0.67 | 0.80 | 0.80 | 0.80 | 0.80 | [bde] 0.80 (0.67,0.80) | [46,56–58] (expert opinion) |
| Conservation agriculture | **0.47** | 1.00 | 0.73 | 0.80 | 0.80 | [bd] 0.80 (0.47,1.0) | (expert opinion) |

**Table 3.** *Cont.*

| Soil Functions/Treatments | Primary Productivity | Carbon Sequestration and Climate Regulation | Water Regulation and Purification | Nutrient Cycling and Provision | Habitat for Functional and Intrinsic Biodiversity | Median | References |
|---|---|---|---|---|---|---|---|
| **Mediterranean North** | (3) | (9) | (3) | (8) | (5) | | |
| Conventional farming | 0.73 | **0.53** | **0.33** | 0.67 | **0.20** | $^{a}$ **0.53** (0.20,0.73) | [59–69] (expert opinion) |
| No-tillage | 0.87 | 0.87 | 0.93 | 0.87 | 1.00 | $^{b}$ 0.87 (0.87,1.0) | [59–64,66–70] (expert opinion) |
| Reduced tillage | 0.73 | 0.80 | 0.80 | 0.80 | 0.80 | $^{c}$ 0.80 (0.73,0.80) | [60,63,66] |
| Crop rotation | 0.80 | 0.80 | 0.73 | 0.80 | 0.80 | $^{c}$ 0.80 (0.73,0.80) | [59,67,71] |
| Residue retention | **0.47** | 0.93 | 1.00 | 0.93 | 0.93 | $^{bd}$ 0.93 (0.47,1.0) | [62,65] (expert opinion) |
| Conservation agriculture | 0.73 | 1.00 | 0.73 | 0.87 | 1.00 | $^{d}$ 0.87 (0.73,1.0) | [60,63,66] |
| **Continental** | (5) | (5) | (4) | (5) | (1) | | |
| Conventional farming | **0.40** | 0.60 | **0.40** | 0.60 | **0.47** | $^{a}$ **0.47** (0.40,0.60) | [50,72–74] |
| No-tillage | 0.80 | 0.87 | 0.93 | 0.80 | 0.73 | $^{bd}$ 0.80 (0.73,0.93) | [72,75–78] |
| Reduced tillage | 0.80 | 0.80 | 0.93 | 0.80 | 0.73 | $^{b}$ 0.80 (0.73,0.93) | [78–81] (expert opinion) |
| Crop rotation | 0.93 | 0.87 | 0.80 | 0.87 | 0.87 | $^{e}$ 0.87 (0.80,0.93) | [78,82] (expert opinion) |
| Residue retention | 0.80 | 0.87 | 0.93 | 0.80 | 0.73 | $^{bd}$ 0.80 (0.73,0.93) | [83] (expert opinion) |
| Conservation agriculture | 0.93 | 0.87 | 0.80 | 0.80 | 0.80 | $^{cd}$ 0.80 (0.80,0.93) | [83–86] (expert opinion) |

Bold numbers indicate the negative effects (<0.6) on soil functions. Median scores are presented as Median (minimum, maximum) and median scores with no common superscript letters are significantly different at $p = 0.05$.

### *3.4. Effects of CA and CONV Practices on Five Soil Functions in Continental Zone*

In the Continental zone, the median scores of CA was significantly higher (0.80–0.87; Table 3) indicating positive effects on soil functions compared to CONV with significantly lower median value of 0.47 indicating negative effects (Table 3). Across treatments, CONV had no positive effects (<0.60) on soil functions at all, with only negative (<0.60) to no effect (0.60) on five soil functions (Table 3). In contrast, CA and its component practices had only positive (>0.60) effects on the five soil functions. Crop rotation and CA had the highest positive effects on primary productivity whereas CA, no-tillage, crop rotation and residue retention had the highest positive effect on carbon sequestration (Table 3). Residue retention, reduced tillage and no-tillage had highest positive effects on water regulation and provision whereas crop rotation had highest positive effects on nutrient regulation and cycling. Crop rotation had the highest positive effect on habitat for functional and intrinsic biodiversity function. Hence, CA and its component tillage practices had particularly positive effects on the soil functions compared to CONV with neutral to negative effects on soil functions.

### *3.5. Comparison of CA and CONV Practices on Five Soil Functions in Atlantic North, Pannonian, Mediterranean North and Continental Environmental Zones*

Comparing the CA and CONV across environmental zones, there were consistent differences between the CONV and CA and its component practices. CONV had overall negative effects on soil functions across the environmental zones with median score value of 0.50 (Table 3). In comparison, CA and its component tillage practices had overall positive effects on soil functions across the environmental zones with median score values ranging from 0.80 to 0.83 (Table 3).

Comparing the differences in effects due to application of the six treatments, the magnitude of positive effects over soil functions differed between environmental zones. In Atlantic North, Continental and Pannonian zone, crop rotation had the highest positive effects on soil functions compared to CA and its component practices whereas in Mediterranean North, no-tillage had the highest positive effects on soil functions (Table 3). The data clearly indicated that the same practice can have varying consequences in terms of positive and negative effects on the suite of soil functions and hence the suitability of enhancing one particular soil functions or bundle of soil functions is context-specific.

## **4. Discussion**

### *4.1. Integration of Soil Function Scoring Data*

The study is an attempt to deliver a framework to indicate the direction of changes in soil functions due to different land management so that land managers can adjust land use and management practices in order to meet the demand for soil functions. The impacts of CA and CONV on soil functions are important to resolve, as there is conflicting evidence of management effects on soil functions. The difference in effects are attributed to multiple factors as soil functions are the outcomes of interactions of climate, land use, management practice and soils [1,4,87]. Due to multiplicity of factors above, it is a challenging task to quantify soil functions and be precise for a given land use, management practice, climate and soils.

CA and CONV are contrasting practices in terms of crop rotation, crop residue management and soil disturbance from no-till and/or reduced tillage to conventional moldboard ploughing to 20–30 cm. The management practices had differential effects on soil physical, biological and chemical attributes affecting the soil functions. Overall, in our study, CONV had consistent negative effects on soil functions with a median score of 0.50 across environmental zones, in concurrence with Stavi et al. [24], where conventional production system scored 0.52 compared to 0.69 and 0.72 in integrated production system and CA respectively. The negative effects of CONV are attributed to undue emphasis on primary productivity neglecting the provision of other soil functions, explicit from the scorings [28,60]. The positive effects of CA and its component practices were attributed to, in general, synergistic provision of the five soil functions [7,48] although primary productivity declined in some environmental zones [39,70]. For example, in Mediterranean zone, positive effects of CA on primary productivity varied depending on rainfall when compared with CONV and CA performed better than CONV in dry years [59].

### *4.2. CA and CONV Treatment Effects on Soil Functions*

CA practice consists of three core measures viz. no-till, crop rotation and residue retention [8]. However, all the three core measures are applied with different modifications in different socio-economic contexts based on the relevance of different soil functions in a particular environmental zone, which makes the comparison of performance of CA across the environments difficult [33]. Furthermore, the main effects of the three core measures, applied in isolation or in different combinations are difficult to separate and there is a wide variation in effects of management and the associated impacts on the suite of soil functions depending on the environmental context [41]. For example, in Mediterranean environments, the overall effects of CA is positive in combination with crop residue. However, when only crop residue effect is accounted for, it may lead to transitory nitrogen immobilization, decreasing nitrogen supply at the initial grow stages, particularly in nitrogen vulnerable zones with restriction in nitrogen fertilization [60]. Similarly, CONV is also practiced in different forms in terms of timing, depth and intensity of tillage, the combinations of which can have differential effects on soil functions in diverse environments [6].

A recent global meta-analysis of no-till compared to CONV assessed 5463 paired observations in 610 studies in 48 crops and 63 countries and reported that no/minimum tillage, in general, reduced crop yields while in some areas, produced yields equivalent to CONV [88]. This compares well with our study where, no-tillage reduced yields in Atlantic North [29], increased yields in Mediterranean North [60] and Continental whereas equivalent yields were produced with reduced tillage compared to CONV in Pannonian [51]. More importantly, positive crop yield responses were recorded only when combined with crop rotation and residue cover [88] and this was true in the Pannonian and Continental zone [83]. Except Pannonian zone, CA provided positive yield responses in other zones, particularly in Mediterranean climate due to higher moisture retention and minimized soil erosion [89,90]. In general, the CA yield penalty is found for the first 1–2 years after conversion to CA methods, but is subsequently similar to conventional practice yields over the next 3–9 years, while declining after 10+ years, probably due to weed pressure, pests and disease build-up [91]. A recent meta-analysis of 100 study comparisons reported increase in carbon sequestration in 54 cases due to no-tillage/zero tillage compared to CONV [41]. In another recent meta-analysis, comparison of 184 comparisons, shallow non-inversion tillage increased the carbon stock by 143 g C $m^{-2}$ compared to deep inversion tillage [28]. This is in line with our findings that no-tillage increased the carbon sequestration in the four environmental zones. However, some recent studies have argued that the effects of no-tillage are highly complex, involving many factors and should not be generalized [18,92]. Apart from the aforementioned benefits, the main drivers of CA adoption are economic benefits due to cost reduction of tillage, machinery and labour inputs [7].

The impact of agricultural practices on habitat for functional and intrinsic biodiversity is explicit but, poorly addressed in CA that combine tillage, soil cover and crop rotation. There is no consensus on how to assess this soil function and most of the studies are still segmented with a specific approach on microorganisms, mesofauna or macrofauna. The increase in habitat and biodiversity with no-till or reduced tillage, crop rotation, residue retention and CA is mainly linked to changes in soil carbon and soil physicochemical properties. Similarly, water regulation and purification, and nutrient cycling and provision functions are not addressed well and hence, there is a need to include the effects on the five soil functions to realistically assess the impacts of a measure.

*4.3. Research Gaps on CONV and CA Practices*

The studies on soil functions due to CA are incomplete within the European soil research landscape with some environmental zones having more exhaustive data compared to other zones with sparse data [30]. For example, in Atlantic North, the scoring of the five soil functions due to CA was based on four studies whereas in Pannonian zone, the same was scored only with expert opinion (Table 3). The literature search revealed that majority of the studies collect data on crop yields (22 studies) and carbon sequestration (31 studies) whereas other soil functions are less prioritized lacking information on those soil functions (Table 3). The main gaps are emphasis on one or two soil functions, trade-offs with other soil functions, modified practices or measures in field, lack of stakeholder information and a need for a soil function assessment at farm scale. For example, primary productivity has been the main goal of land use by farmers and emphasis on this individual soil function has compromised the balance of provision of other soil functions that the soils provide. The reason is that the farmers' main goals are grain and biomass yields for income but do not get rewarded for the non-marketable soil functions viz. nutrient cycling and provision, water regulation and purification and habitat for functional and intrinsic biodiversity, which are the core supporting and regulating functions backstopping primary productivity. Hence, there is no incentive to enhance non-marketable soil functions. Another important factor is the temporal factor (e.g., years of CA practice) on soil functions that needs to be taken into account as it has significant implications on the five soil functions [93]. Hence, there is a need to take account of the five soil functions rather than individual soil functions, by policy support at national to European scale to enhance provision of the five soil functions. For example, in Norway and Germany, CA practice is eligible for subsidy support [39], which has encouraged adoption of CA and such policy support will contribute, indirectly, to enhanced provision of the five soil functions. CA adoption does pose challenges due to increased weeds and competition for the use of crop residues for other purposes, such as fodder and energy production and hence loss of income to the farmers. Indeed, one of the main criticisms of conservation agriculture is the increase in herbicide use. Developing research on alternatives for weed management would facilitate the development of conservation agriculture (especially in increasingly constrained pesticide regulation environment) and limit its potential effects on the quality of water resources. However, there are other compelling reasons for CA adoption viz. reduced machinery and labor use, reduced erosion, which needs to be taken into account for realistic cost-benefit assessment. The information on the economics of CA adoption on and the underlying benefits on the five soil functions, need to be made available to the farmers, land managers, advisory services and policy makers to influence their decision based on evidence-based examples from the locally relevant applied CA field practices.

## 5. Conclusions

The current study has revealed that the existing field studies on CA and CONV practices assessed only individual soil functions and there is a growing need to determine the management effects on the suite of five soil functions. The study shed light on the current weakness of skewed research with emphasis on individual soil functions and there is need to incorporate the five vital soil functions, when assessing the effects of a management practice. Given that the research environment is highly compartmentalized in the research centers and universities, the study provided insight into need for transdisciplinary approaches to determine the five soil functions in field investigations so that objective assessment of a particular measure can be provided to the farmers, land managers and policy makers for informed decision-making.

Our study found significant differences of CA and CONV management effects on five soil functions across the four major environmental zones in Europe. Across environmental zones, overall CONV had consistent negative effects on soil functions whereas CA and its component practices had overall positive effects on soil functions. The study identified a need for more field-based investigations in Europe to provide further evidence of benefits of CA adoption. There is need for concerted efforts from researchers to provide the evidence of CA benefits on five soil functions and the policy-making bodies to encourage CA adoption through policies and subsidy support.

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# Potential for Conservation Agriculture in the Dry Marginal Zone of Central Syria: A Preliminary Assessment

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**Abstract:** This paper reports on early soil related outcomes from conservation agriculture (CA) benchmark sites located within the marginal rainfed environment of agro-ecological zone 4 (annual rainfall: 200–250 mm) in pre-conflict central Syria. The outcomes reported are specifically those that relate to beneficial soil quality and water retention attributes relative to conventional tillage-based soil management practices applied to the fodder barley–livestock system, the dominant system in the zone. On-farm operational research was established to examine the impact of a barley (*Hordeum vulgare)* and vetch (*Vicia sativa*) rotation intercropped with atriplex (*Atriplex halimus*) and salsola (*Salsola collina*), under CA and conventional tillage agriculture, on the soil quality parameters and crop productivity. Preliminary results showed that CA had a positive effect on the soil quality parameters and crop performance. The soil moisture and hydraulic conductivity were higher under CA ($p < 0.05$), combined with improved productivity (grain and above-ground biomass) under specific crop mixes. The results suggest that despite the marginal nature of the zone, the use of CA is a viable option for the future of farmers' livelihoods within similar localities and agro-climates, given the benefits for soil moisture and grain and straw productivity. In addition, it is likely to positively impact those in marginal environments where both pastoralism and agro-pastoralism production systems co-exist and compete for crop biomass as a main source of livestock feed. The increase in grain and straw yields vis-à-vis improvements in biophysical parameters in the CA system relative to tillage agriculture does suggest, however, that the competition with livestock for biomass is likely to reduce over time, and farmers would be able to return increased levels of straw (as stubble and residue) as mulch, given improved biomass yields.

**Keywords:** conservation agriculture; crop–livestock interactions; Syria; soil health; agricultural innovation

## 1. Introduction

Conservation agriculture (CA) has been promoted as a land use management practice that is better able to achieve a desired objective of sustainable production intensification [1]. CA systems comprise the implementation of three interlinked principles: (i) no or minimum mechanical soil disturbance through no-till seeding and weeding; (ii) the maintenance of soil mulch cover with crop residues, stubbles and cover crops; (iii) cropping system diversification through rotations and/or associations involving annuals and perennials, including legume crops [1]. A ground cover of 30% or more is a requirement, because this reduces soil erosion substantially and provides a substrate to soil biota to build and sustain soil health and functions, as well as increases the soil organic matter content, which improves the structure, infiltration and moisture retention capacity. Provided that the C/N ratio in the substrate is conducive, microbes will not bother with biomass with high C and very low N, as is the case with barley (*Hordeum vulgare)* straw.

Transitioning from a conventional tillage-based production system to a CA system requires time for the transformation to occur, in which the three core CA practices are promoted along with other good agricultural practices, including those of integrated crop, soil, nutrient, water, pest and energy management. It is thus clear that the feasibility of adopting CA or implementing CA practices will depend on a range of biophysical, economic, socio-cultural, management and developmental issues related to the prevailing agricultural environment. Consequently, while CA comprises three principles, at the practical level of the CA adoption process, there cannot be a "one-size-fits-all" approach when it comes to how CA is introduced, practiced and evolved in a particular biophysical environment and socio-economic rural setting. This equally applies to how CA adoption can be scaled and organized to harness territorial level benefits for rural communities and the society at large. CA principles apply to production systems in all land-based agro-ecologies, including sown fodder crop–livestock systems or sown pasture–livestock systems of various kinds. In some respects, these are relatively simpler systems to transition to—from a conventional tillage-based production system to a CA system—because they lend themselves to no-till seeding using a diverse mixture of species. However, what is required in transforming such systems from their conventional versions to CA systems is the need to manage livestock differently, such that grazing management is based on a rotational system and thus the minimum necessary ground cover is maintained to build soil health, control erosion and increase biomass production.

Research findings from marginal areas with Mediterranean environments in a number of countries indicate that grain and biomass yields and factor productivities have improved through the adoption of CA, in addition to improvements in soil quality [2–5]. Additionally, and of particular relevance to dryland areas, a number of other likely benefits have been reported. These include, even within dryer months of the year, improved rates of water infiltration, appreciable reduction in run-off losses and increased replenishment of groundwater [3,4,6]. The spread of CA cropland systems worldwide has been occurring at a rate of some 10 million hectares per year since 2009, with some 50% of the area located in low-income countries, including in the Mediterranean environments [3,7]. The broad adoption of CA has been less than desired within the West and Central Asia region, particularly so within the dryland Mediterranean environments. However, the situation has begun to change in recent years in countries such as Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, Armenia, Azerbaijan, Iran, Turkey, Lebanon, Jordan, Iraq, Syria and Pakistan, where CA adoption has been reported [3,7–10].

Within dryland environments, as in many other parts of the world, intensive tillage, bare and exposed soils and mono-cropping continues to contribute to land degradation and to low crop (including fodder and pasture) and total land productivity, thereby inhibiting the prospects for enhanced sustainable agricultural production within these regions (within the CGIAR research system (www.cgiar.org) , drylands are defined on the basis of an aridity index. Consistent with that employed by the United Nations Convention to Combat Desertification (UNCCD) as well as the United Nations Food and Agriculture Organization (FAO), drylands are defined as regions having an aridity index of 0.65 or less (http://www.eatlasdcl.cgiar.org/Docs/WorkingDefinitionOfDrylands.pdf). Estimates suggest that close to 2.1 billion people call drylands their home) [11,12]. Options for uncovering contextually relevant shifts in land use management paradigms with improved environmental, social and economic underpinnings have therefore been of key concern to institutions of agricultural research—both national and international. In Syria, the benefits of CA for soil moisture and grain and biomass yields have recently been uncovered [13], but in a number of cases, these have been in a piecemeal fashion in terms of testing the application of the three interlinked core components of

CA. More generally, meta-analyses and reviews, such as those by [14–18], while highlighting some of the challenges related to CA adoption, show clear moisture-related benefits to crop growth and productivity in CA systems, particularly in semi-arid areas.

Two aspects are important in a persistent argument for not favoring the maintenance of minimum ground mulch cover through the utilization of crop stubbles and straw residues in marginal environments exhibiting strong crop–livestock interactions. The first relates to conventional wisdom, which frowns on direct grazing, given concerns over the retention of animal droppings, which has implications for weed growth (on the basis of discussions with staff at the International Center for Agricultural Research in the Dry Areas (ICARDA) and author discussions in the field). While the concept of managed rotational grazing is now well recognized for its potential to retain stubble and crop residue and, if undertaken with efficacy, a certain amount of residue retention as ground cover, it is argued that animal droppings are likely to contain weed seeds, which would lead to competition with the main cereal crop. This argument is not as important when the crop concerned (i.e., barley) is for fodder, as is the case in zone 4 in Syria.

The district is divided into four standard agro-ecological zones, which span the entire republic. Instituted more than half a century ago, these zones have been (for reasons not entirely known) immutable to change, despite significant variation in annual and seasonal rainfall patterns and a general downward trend in rainfall, the latter resulting in sustained periods of drought and increasing instances of winter frost. Zone 2, located to the east, is relatively the wettest area, with an average annual rainfall of more than 300 mm. In contrast, zone 3 is slightly drier, with a typical average of 250 to 300 mm of rainfall per year. Zone 4 is a marginal area receiving on average between 200 and 250 mm of annual rainfall and bordering zone 5—the Badia (reasonably suitable for nomadic herding) and steppe zone, which on average receives less than 200 mm of rainfall annually. Zones 2 and 3 are characterized by mixed crop–livestock production systems, and zone 4 exhibits the heaviest crop–livestock interaction. The incentive to produce barley, the primary cereal crop grown within the district, varies by zone. Grain production is a primary economic incentive within the relatively wetter zones 2 and 3, while fodder is of primary interest and incentive in zone 4. Prior to 2004, government support in the form of input subsidies, together with a guaranteed buy-back scheme (price and quantity), provided significant economic incentives in the production of grain barley as well as a number of other key national strategic crops such as wheat, tobacco and certain food legumes in particular. Since this time, and after the removal of regulatory support, the production of grain and fodder barley has largely been driven by an economic need to support a fairly significant stock of small ruminants, specifically sheep—and particularly within zone 4 and the vast rangelands of zone 5 where a large portion of national small ruminant livestock holdings are located.

Thus, a second and more compelling argument is a concern over competition for fodder biomass (including straw during the dry season) for feeding livestock—in lieu of retaining a portion for maintaining minimum ground cover, given that little straw is left as ground cover as a result of the low production potential of the barley production zone. Contesting this argument, recent research work in Syria [8] has shown favorable impacts of a no-till system with respect to the potential for biomass retention for ground cover as well as for soil properties and moisture retention.

Other studies have further highlighted the beneficial aspects of straw biomass retention for the surface during the dry season when the biomass is not needed for feeding livestock [19]. Additionally, fodder yield improvements have been demonstrated [20] from barley and vetch (*Vicia sativa)* intercrops in dryland Syria, with reduced tillage and barley straw used as surface ground cover. More recently, significantly higher grain and biomass yields and gross margins have been documented [21] for a variety of crops, including barley under a no-till system, when compared to the conventional tillage-based system in Syria in zone 2. Despite the fact that zone 2 has a relatively higher production potential compared to zone 4, implicitly included is an understanding that above-ground crop biomass (stubble base with root tops, and cut straws and leaves) yields are also likely to increase under a no-till system, relative to the conventional tillage-based system.

Taken together, there is an argument that, in the early phase of transforming from the tillage-based production system to the adoption of CA system practices, a constraint for crop biomass in the use as soil cover is a limiting factor. However, it is argued this this constraint is released over time with the adoption of CA practices, leading to an increase in the biomass yield in the case of zone 4 and in grain and biomass in the case of zones 2 and 3, with the introduction of cover crops in the cropping system contributing additional biomass. Further, with no-till, plant-base or stubble with attached roots, this will also contribute to ground cover and soil health.

The developmental question, therefore, is how to reduce this biomass constraint and overcome it over time in zone 4, where the crop–livestock farming system relies on growing fodder crops of barley, vetch, fodder shrubs and natural rangeland vegetation as the main source of livestock feed.

## 2. Study Objectives and Region

### *2.1. Study Objectives*

We believe this to be the first CA-based applied research study carried out, albeit preliminarily, within the marginal rainfed environment of the agro-ecological zone 4 in Syria (Figure 1), which borders the vast rangelands within the republic, with an aim to investigate the potential benefits of a CA production system relative to the conventional tillage-base production system (for this manuscript, conventional tillage and traditional agriculture is used interchangeably to denote the treatment that utilizes ploughing).

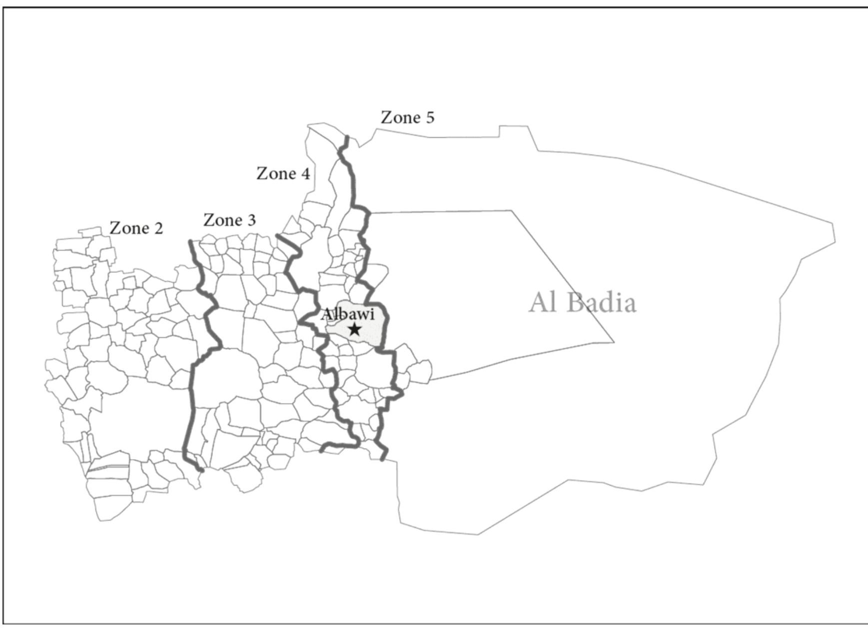


**Figure 1.** Agro-ecological zones in Salamieh District, Syria.

The study comprises an on-farm demonstration of CA and aims to assess its validity within this marginal environment with strong crop–livestock interactions and through an analysis of barley and vetch and ervilia (*Vicia ervilia*) and barley rotations intercropped with the fodder shrubs atriplex (*Atriplex halimus*) and salsola (*Salsola collina*), under both a CA system and the conventional tillage system. Previous research conducted in Ghrerife, Syria (mean annual rainfall of 267 mm, i.e., in zone 2) has highlighted the benefits (under conventional tillage) of barley intercropped with atriplex in providing sources of additional feed as well as in reducing the likelihood of soil erosion from wind [22]. This form of alley cropping was found to be particularly useful as a method to buffer the total feed output against seasonal fluctuations brought about by variability in rainfall.

In addition to an assessment of the early impact on soil quality parameters and crop productivity, the study also examines the impact of each treatment on net farm incomes. It must be mentioned at the outset that the purpose of this study was not to carry out an on-station-type trial, but rather to engage in on-farm operational research, which actively engaged farmers within the surrounding areas through demonstration, consultation, dialogue, and training. On-farm operational research reflects a two-way dialogue in which farmers in the field are active partners in the investigation and are able to assess the impact of different options in the "field" [23,24]. It has also been argued [2] that without farmer engagement and appropriate commitment from farmers to test CA system practices, the integration of such practices into production systems and the rapid adoption of CA by farmers, including the required transformational changes for CA system development, are unlikely to occur. This sentiment is very much in line with recent attention paid to the efficacy in innovation systems, away from a historical concentration on linear models for technology transfer and dissemination and into more participatory multi-stakeholder processes for agricultural innovation [25,26].

In keeping with this notion of participatory innovation, we further argue that in addition to sustainable production intensification, the role of CA in supporting resilience (productivity—environmental, social and economic) within fragile production systems is equally relevant, but is not (generally) promoted in dissemination and demonstration strategies by either developmental agencies or national centers of agricultural research. This is particularly true in terms of the potential ability for CA in production areas, where there are interactions between pastoral and agro-pastoral livelihood systems, to reduce conflict in periods of sustained drought and fluctuations in production volumes of cereal and fodder crops.

### *2.2. Study Region*

The district of Salamieh is situated in central Syria and covers approximately 5000 km$^2$, with an estimated population of 241,000 (civil statistics in Syria are guarded with much sensitivity, and particularly so with respect *to* the registration of individuals.). A significant portion of cultivable land is rainfed (100,174 ha), with only a small portion (9225 ha or 9%) under irrigation [27]. Conventional wisdom, supported by anecdotal evidence, suggests that over years of sustained drought, farmers (particularly mobile and semi-settled farmers) will often liquidate their livestock holdings, and sometimes even abandon them in times of severe market depression, as they are unable to meet necessary feed requirements. Reducing the feed gap through sustainable improvements in fodder biomass production is therefore of significant importance to livelihoods and security in marginal zones, and particularly so when poverty is prevalent and linkages to markets are either weak or not inclusive. While farmers in marginal areas may be concerned with good soil health, higher levels of soil organic matter and all of the beneficial environmental outcomes that accrue from shifting land use paradigms, these outcomes in Syria at least for now are largely situated within the ambit of some research scientists.

In general, it is now well accepted that the initial appeal for farmers to engage in the CA adoption and transformation process is in the form of reduced costs due to no-till seeding [21]. However, predictability in providing a stand of fodder barley for direct grazing may be more of an incentive to farmers in marginal zones, where strong crop–livestock interactions exist, where crop-mix choices are limited by the extent of the access to groundwater and are exacerbated by regulatory restrictions on cropping. The implications of residing within "static" agro-ecological cropping zones are that historic edicts on cropping patterns are fixed, and, when desired, deviating farmers can be punished under the extent of the law. Within zone 4, cropping is restricted to the rainfed production of fodder crops, and the planting of trees, particularly olives, is prohibited by the regulatory code. National statistics would suggest that regulations are being adhered to with respect to prohibitions on the planting of trees, yet anyone familiar with the landscape of central Syria is cognizant of what is stated in official statistics and what exists on the ground. While not as dense or lucrative as in other, wetter zones with relatively well-endowed access to groundwater resources, olive production provides a valuable source of revenue to supplement income streams from the production of dairy products and in support of investments in livestock holdings, which are a form of capital asset and security.

The production of cereal-based fodder cropping, therefore, provides an anchoring of financial input, which supports the livelihood systems for both resident farmers and nomadic farmers, who rent out land for grazing in order to support livestock holding. Supporting resilience and improving the productivity of cereal- and fodder-based crops and shrubs through a shift away from tillage-based production systems is, therefore, a priority area of focus within the broader strategy of research for development. This is not simply an agenda for cost savings and productivity enhancement but is equally important for reversing agricultural land degradation, rehabilitating abandoned agricultural land, and for social and environmental stability, particularly so since the armed uprisings within Syria, and the region more generally, in 2011.

## 3. Materials and Methods

### *3.1. Trial Demonstration Plots*

On-farm trial demonstration plots, initiated in October 2010 (Figure 2), were managed by the Aga Khan Foundation (http://www.akdn.org/our-agencies/aga-khan-foundation), an international development organization, in collaboration with the farmer, a private landowner. The plots were located in the Al-Bawi village within zone 4 but were on the edge of the rangelands within zone 5.

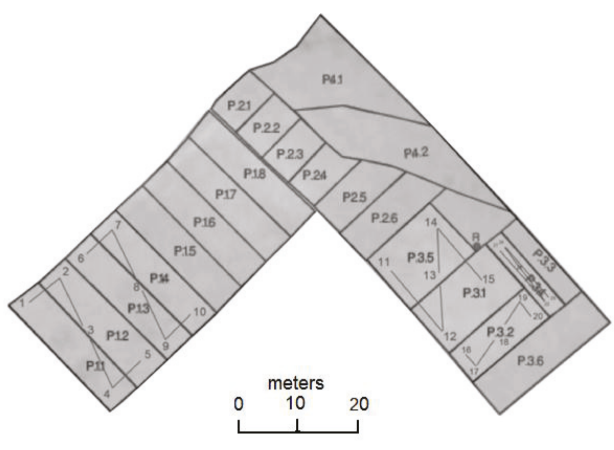


**Figure 2.** Schematic of trial plots initiated in October 2010 by Aga Khan Foundation. Depicts all of the conservation agriculture (CA) benchmark sites (for different crops/treatments, etc.) set up by the Aga Khan Foundation in Al-Bawi. For the purpose of this study, we only report on outcomes from plots P.11–P.14.

The on-farm trial demonstration of two treatments (CA vs TA—tillage agriculture) were unreplicated and aimed to assess the impact of different seeding options incorporating barley and ervilia vetch intercropped with atriplex and salsola on plots under CA and TA (we denote TA as a short form of "traditional" or conventional agricultural land use practices, which utilize motorized tillage-based practices). Plots P.11 (CA) and P.14 (TA) were seeded with barley (intercropped with artriplex and salsola) in 2010/2011 followed by a mixture (30% barley and 70% ervilia) in the subsequent season, 2011/2012. Plots P.12 (CA) and P.13 (TA) were seeded with ervilia (intercropped with fodder shrubs atriplex and salsola) in the 2010/2011 season, followed by barley in 2011/2012 (see Table 1 for the description of treatments).

Applications of fertilizer and seeding rates were kept constant between the two treatments. The seeding rates were 100 kg ha$^{-1}$ for barley and 150 kg ha$^{-1}$ for ervilia vetch. All plots received phosphorus and nitrogen triple superphosphate (TSP) at seeding time (50 kg ha$^{-1}$) and urea (50 kg ha$^{-1}$) after germination. No herbicides were applied. Atriplex and salsola shrubs were also intercropped in all plots, but showed little growth in the 2 years under study; therefore it was not possible to record their biomass yields. For the CA plots, a minimum of 30% ground cover with crop residue (barley straw and leaf biomass) was maintained. All plots within the on-farm benchmark site were sown with a no-till tine seeder developed by ICARDA at its research station in Aleppo.

**Table 1.** Treatment description for on-farm trial demonstration.

| Plot ID | Main Treatment | Year | Sub-Treatment |
|---|---|---|---|
| P.12 | Conservation agriculture (CA) | 2010/2011 | Ervilia intercropped with atriplex and salsola |
| P.12 | CA | 2011/2012 | Barley intercropped with atriplex and salsola |
| P.13 | Traditional/conventional agriculture (TA) | 2010/2011 | Ervilia intercropped with atriplex and salsola |
| P.13 | TA | 2011/2012 | Barley intercropped with atriplex and salsola |
| P.11 | CA | 2010/2011 | Barley intercropped with artriplex and salsola |
| P 11 | CA | 2011/2012 | Barley (30%) and ervilia (70%) |
| P.14 | TA | 2010/2011 | Barley intercropped with artriplex and salsola |
| P.14 | TA | 2011/2012 | Barley (30%) and ervilia (70%) |

### 3.2. Soil Sampling

Undisturbed and disturbed soil samples were taken from both CA (P.11 and P.13) and TA (P.12 and P.14) plots at 0–20 cm depths in February 2011. Five cores per plot were taken in a zig-zag pattern from each plot (see Figure 2) were and analyzed at the ICARDA laboratory based in pre-conflict Aleppo. Watermark sensors (Gypsum block) were placed on both plots (P.12 and P.13) for the 2011–2012 growing season. In order to convert pressure head data into moisture equivalents, the soil moisture-pressure head curve was used; established with the van Genuchten equation [28] through employment of the Rosetta neural network calculation (1999; U.S. Soil Salinity Laboratory) using values for bulk density and texture. Similarly, Hydraulic conductivity (cm/day) was predicted using the values for bulk density and soil texture using the neural network format (Rosetta Software).

### 3.3. Rainfall

Rainfall (precipitation) data from MAAR (Agricultural Statistics, Ministry of Agriculture and Agrarian Reform) were used to give an idea of the recent trends in rainfall during the growing seasons. Where comparisons of soil moisture between CA and TA during peak rainfall periods are presented, these are based on data from a digital solar weather station (Davis Instruments, Vantage Pro2 Weather Station, UK) that has a digital rainfall gauge included to measure precipitation. Hourly readings were taken and the analysis for both soil moisture and hydraulic conductivity are based on a total of 6713 readings per observation.

### 3.4. Grain Yield and Biomass

All plots sizes were 2.5 dunums (1 dunum = 0.1 ha). To estimate the yield and biomass, five replicate samples of 1 m by 1 m square quadrants were harvested from each plot at the end of the crop growing period. After drying, the samples were weighed and recorded and the mean weight of the five replicates was used to calculate the grain yield and biomass yield (above-ground biomass).

### *3.5. Financial Returns*

Partial farm budgets were used to calculate the financial returns of the various treatments. These did not include labor or harvesting and transport costs and only relate to the treatments used, that is, the cost of fertilizer and the tractor service for ploughing and seeding for conventional seeding and for no-till seeding. From the perspective of the discipline of economics, a lack of inclusion of these costs would raise questions. Two reasons support our argument for excluding these costs. The first is that the trial demonstrations were undertaken in a period of initial civil unrest and markets for all inputs had been significantly affected, particularly for labor and material inputs (fuel, machinery, etc.). Secondly, as we were looking primarily at improvements in productivity and returns for farmer demonstration together with beneficial environmental outcomes for research and public good interest, the collection of these data was not directly relevant for the immediate purpose at hand.

Providing information to farmers on the saving of material inputs was in line with conventional wisdom that out of pocket savings in expenses is an initial motive for engaging in the process of CA adoption and establishment. Labor within these marginal areas is predominantly household-based, and farmers would have likely made quick calculations on the impact of a shift in land use management practices in terms of their household labor utilization. For ease of comparison, input and commodity prices are based on 2011 prices prior to the civil unrest in Syria. The currency conversion used was 50 Syrian pounds per US dollar (USD). Those wishing to undertake a comparative analysis of returns with work conducted in zone 2 [21] would find similarity in this respect. For the CA plots in the study, all of the crop biomass (residue) was retained as surface mulch and was valued at the going market rates for biomass (straw) in feeding livestock.

### *3.6. Statistical Analysis*

Statistical analysis was conducted using the Statistical Package for Social Scientists (SPSS). Means were compared using the Student's *t*-test. The results were considered statistically significant at $p < 0.05$.

## 4. Results and Discussion

### *4.1. Rainfall*

The rainfalls over the 2010/2011 and 2011/2012 cropping seasons were 159.0 and 197.5 mm, respectively (Figure 3). While the rainfall in 2010/2011 was close to the average, the rainfall during 2011/2012 was higher than the average cropping season rainfall of 154.6 mm between 2005 and 2013 (Figure 3). While beneficial in terms of trial demonstrations to farmers, this higher-than-average rate of rainfall during 2011/2012 should be factored into an analysis of early results obtained.

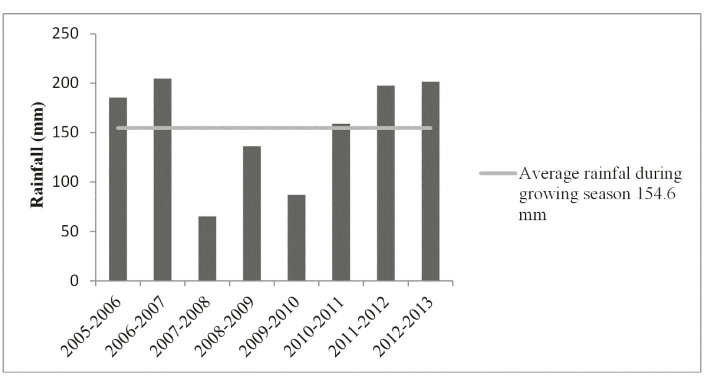


**Figure 3.** Total rainfall during each growing season and overall average rainfall in Al-Bawi.

### *4.2. Soil Characteristics*

Soil characteristics measured through soil sampling are presented in Table 2 and provide a baseline of textures, which were largely sandy clay loam or loam with high proportions of clay and sand and low levels of organic matter and nitrogen (see Table 2). Similarly, low levels of organic matter, nitrogen and plant-available phosphorous within soils in other areas of Syria have been documented [8].

**Table 2.** Soil characteristics on the basis of baseline soil sampling for conservation agriculture (CA; P.11 and P.13) and tillage agriculture (TA; P.12 and P.14) in 2011.

| | pH (1:1) | Olsen P (ppm) * | N Total (ppm) * | K Extractable (ppm) * | $CaCO_3$ (%) | OM ** (%) |
|---|---|---|---|---|---|---|
| CA | 8 (0.06) | 4.7 (1.8) | 1298.8 (158) | 299 (63) | 33.9 (1) | 2.0 (0.3) |
| TA | 8 (0.20) | 4.4 (1.0) | 1342.4 (72) | 267 (54) | 35.6 (2) | 2.0 (0.1) |
| | **Clay (%)** | **Silt (%)** | **Sand (%)** | **Bulk Density ($g\ cm^{-3}$)** | **Soil Water Content % (W/W)** | **C/N Ratio** |
| CA | 29 (2) | 39 (4) | 31 (3) | 1.3 (0.10) | 24.7 (1.1) | 15.0 (0.8) |
| TA | 25 (3) | 38 (3) | 36 (3) | 1.3 (0.14) | 24.0 (1.8) | 15.1 (0.6) |

Notes: On basis of mean of five cores taken; standard deviation in parenthesis; * ppm: measured in parts per million; ** organic matter.

### *4.3. Soil Moisture and Hydraulic Conductivity*

Figure 4 shows that the soil moisture contents for CA (P.12) compared to TA (P.13) at peak rainfall periods during the growing season for 2011/2012 were higher under the CA plot ($p < 0.05$). Figure 5 also highlights that the soil under CA had higher moisture rates at different water potential levels. Water potential represents the energy status of water. At saturation, it is 0 kPa, and at wilting point, the soil matric potential is −1500 kPa (10 cm is equal to 0.98 kPa. We have taken this as roughly a conversion of 10:1; thus kPa values multiplied by 10 give the values in cm (- cm). We know that at wilting point, the soil water potential was −1500 kPa (or −1.5 MPa), and the soil moisture content was about 0.15 cm $cm^{-1}$. After −1500 cm, there was not much change, and the moisture content was around 0.15 cm $cm^{-1}$ (Figure 5). Thus we have excluded this from the graphs, that is, when values were lower than −1500 cm). Moreover, the soil moisture content was significantly higher under CA relative to TA ($p < 0.05$) at different water potential levels observed (see Table 3). The higher soil moisture under CA, measurable immediately in the first 2 years during the period of transition, provides an indication of improved water infiltration and moisture retention capacity under CA conditions, albeit under transition, relative to TA conditions, with an implication for reductions in water runoff and soil erosion [3,4,8]. Given the relative assessment between CA and TA treatments at the same point in time in the growing season, the impact of the higher-than-average rainfall of 197.5 mm on productivity observed during the 2011/2012 season (see Tables 4 and 5) may improve further with time because of the possible further improvements in rainfall infiltration, water retention, and consequently crop growth, which may occur with further improvement in the soil quality over time. During the 2010/2011 growing season, the rainfall of 159 mm was close to the average, yet a yield and biomass advantage was recorded in the CA treatment (Figures 3–5). Thus, we would expect the positive differences between CA and TA in rainfall infiltration and water retention to develop into a buffer against drought over time, even during the years when rainfall during the growing season is below average.

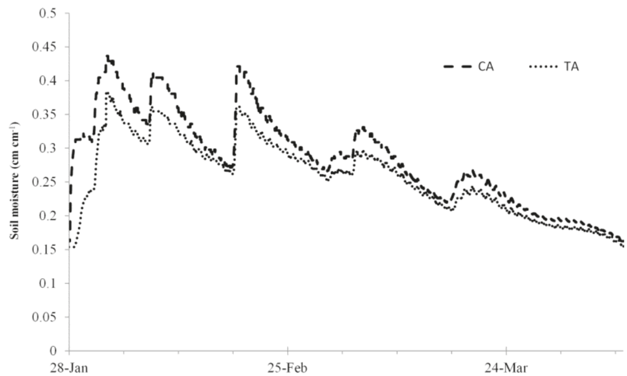


**Figure 4.** Soil moisture levels for conservation agriculture (CA; P.12) and tillage agriculture (TA; P.13) at peak rainfall periods during the growing season for 2011/2012.

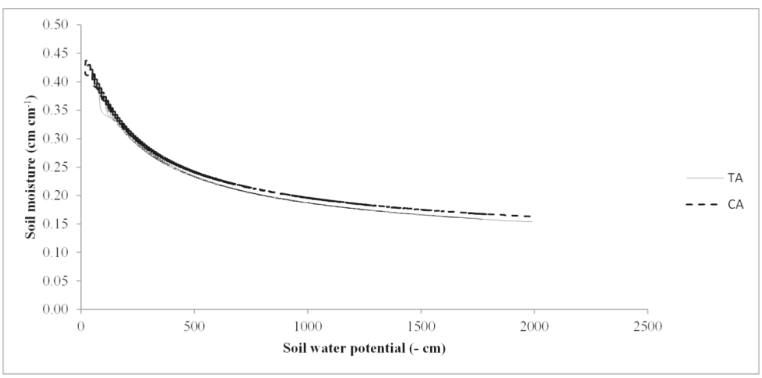


**Figure 5.** Soil moisture content (cm $cm^{-1}$) at different water potential levels for conservation agriculture (CA; P.12) and tillage agriculture (TA; P.13).

**Table 3.** Mean values for soil moisture conservation agriculture (CA; P.13) and tillage agriculture (TA; P.12) at different water potential levels observed ($n$ = 6713).

| Soil Moisture (cm $cm^{-1}$) (CA) | 95% Confidence Interval (CA) | Soil Moisture (cm $cm^{-1}$) (TA) | 95% Confidence Interval (TA) |
|---|---|---|---|
| 0.28 (0.69) a | 0.28–0.29 | 0.26 (0.56) b | 0.25–0.26 |

Note: Means with different letters denote statistically significant difference at the 5% level (standard deviation in parenthesis).

Likewise, hydraulic conductivity in the topsoil (0–20 cm) was also significantly higher under CA ($p < 0.05$) (Figure 6 and Table 4). Hydraulic conductivity or permeability is the capacity of the soil to allow water to pass through its pores or voids. This is likely an indication of increased pore volume and thus soil water retention capacity [29], a result which was also found by [8] in relative comparisons between a no-till system and conventional tillage system.

**Table 4.** Mean values for soil hydraulic conductivity conservation agriculture (CA; P.13) and tillage agriculture (TA; P.12) ($n$ = 6713).

| Soil Hydraulic Conductivity (cm day$^{-1}$) (CA) | 95% Confidence Interval (CA) | Soil Hydraulic Conductivity (cm day$^{-1}$) (TA) | 95% Confidence Interval (TA) |
|---|---|---|---|
| 0.32 (0.65) a | 0.31–0.34 | 0.13 (0.21) b | 0.13–0.15 |

Note: Means with different letters denote statistically significant difference at the 5% level (standard deviation in parenthesis).

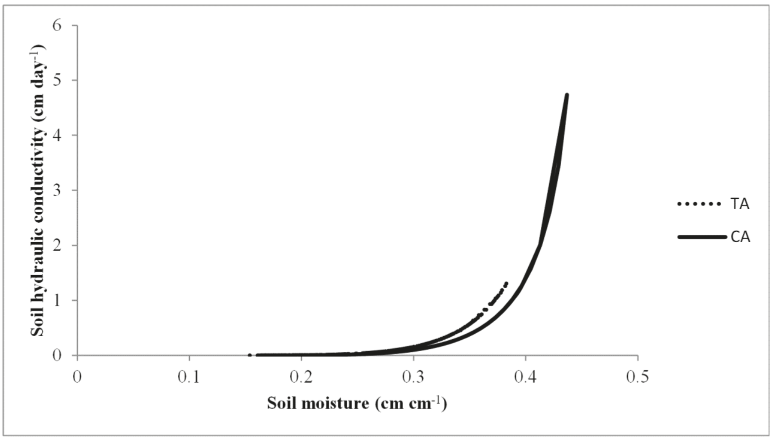


**Figure 6.** Hydraulic conductivity (cm day$^{-1}$) in the topsoil (0–20 cm) for conservation agriculture (CA; P.12) and tillage agriculture (TA; P.13).

### *4.4. Yield, Economic Returns and Market Linkages*

The results indicate that even during the first 2 years of transition into CA, there existed gains for CA yields in the second year for barley intercropped with atriplex and salsola (Table 5) and promising signs of improvement in the grain and straw biomass produced (Tables 5 and 6). Interestingly, if the opportunity cost of mulch is not accounted for, CA would have been more profitable in the first year onwards for the alternative crop mix (Table 6).

**Table 5.** Yields (kg ha$^{-1}$) and partial budget (USD/ha) for conservation agriculture (CA; P.12) and tillage agriculture (TA; P.13) for 2010/2011 and 2011/2012 seasons.

| | CA | | TA | |
|---|---|---|---|---|
| **Budget Item** | **2010/2011 *** | **2011/2012 **** | **2010/2011 *** | **2011/2012 **** |
| Grain yield (barley/ervilia) | 250.0 | 980.0 | 280.0 | 1040.0 |
| Straw yield | 380.0 | 2300.0 | 690.0 | 2040.0 |
| Grain value | 135.0 | 392.0 | 151.2 | 416.0 |
| Straw value | 53.2 | 414.0 | 96.6 | 367.2 |
| Opportunity cost of mulch | 53.2 | 414.0 | | |
| Seed cost | 54.0 | 40.0 | 54.0 | 40.0 |
| Seeding cost | 12.0 | 15.0 | 10.0 | 10.0 |
| Fertilizer cost | 18.0 | 33.0 | 18.0 | 33.0 |
| Land preparation, i.e., ploughing | | | 8.0 | 14.0 |
| Total production costs | 137.2 | 502.0 | 90.0 | 97.0 |
| Total revenue | 188.2 | 806.0 | 247.8 | 783.2 |
| Net revenue | 51.0 | 304.0 | 157.8 | 686.2 |

Note: * Ervilia intercropped with atriplex and salsola; ** barley intercropped with atriplex and salsola.

**Table 6.** Yields (kg ha$^{-1}$) and partial budget (USD/ha) analysis of conservation agriculture (CA; P.11) and tillage agriculture (TA; P.14) for 2010/2011 and 2011/2012 seasons.

| | CA | | TA | |
|---|---|---|---|---|
| **Budget Item** | **2010/2011 *** | **2011/2012 **** | **2010/2011 *** | **2011/2012 **** |
| Grain yield (barley/ervilia) | 170.0 | 870.0 | 130.0 | 590.0 |
| Straw yield | 910.0 | 2760.0 | 460.0 | 1300.0 |
| Grain value | 54.4 | 469.8 | 41.6 | 318.6 |
| Straw value | 54.6 | 651.4 | 27.6 | 306.8 |
| Opportunity cost of mulch | 54.6 | 651.4 | | |
| Seed cost | 32.0 | 56.4 | 32.0 | 56.4 |
| Seeding cost | 12.0 | 15.0 | 10.0 | 10.0 |
| Fertilizer cost | 18.0 | 21.0 | 18.0 | 21.0 |
| Land preparation, i.e., ploughing | | | 8.0 | 14.0 |
| Total production costs | 116.6 | 743.8 | 60.0 | 87.4 |
| Total revenue | 109.0 | 1121.2 | 69.2 | 625.4 |
| Net revenue | −7.6 | 377.4 | 9.2 | 538.0 |

Note: * Seeded with barley intercrop with atriplex and salsola; ** seeded with a mixture of barley (30%) and ervilia (70%) and intercropped with atriplex and salsola.

In fact, straw yields under CA for plot P.14 (Table 6) in 2011/2012 were more than double those of TA (i.e., conventional tillage). Similar yield gains have also been reported [5] for CA under a barley and vetch mixture in Lebanon, a region with a much higher average annual rainfall (550 mm). For semi-arid and dry Mediterranean environments, we estimate, on the basis of information from various sources for barley and wheat [30–35], that at least some 0.5 t ha$^{-1}$ of crop biomass residue is needed in order to provide a 30% ground cover.

In the 2011/2012 season, under a barley and ervilia seeded mixture (Table 6), the straw biomass production was greater than the 0.5 t ha$^{-1}$ required to cover 30% of the soil surface, that is, roughly 2.7 t ha$^{-1}$ (i.e., 2700 kg ha$^{-1}$). We found that the optimum amount that could be put down was 2000 kg ha$^{-1}$, that is, approximately 2 t ha$^{-1}$ (i.e., roughly 4 times as much as is required for some 30% ground cover). Moreover, during the first year under study, for the same crop mix, we calculated the optimum amount that could be put down as ground cover to be 0.63 t ha$^{-1}$ (i.e., 630 kg ha$^{-1}$). This was because any greater amount put down as mulch under the CA system would make a financial loss relative to the conventional system, given the opportunity cost of mulch. Likewise, for the crop mix presented in Table 5, it was only feasible to put down roughly 170 kg ha$^{-1}$ in the second year (i.e., 2011/2012)—any greater amount would have resulted in a financial loss relative to the conventional system.

This highlights the importance of crop mix to the profitability of CA relative to the conventional system. Another argument is that straw biomass, applied as ground cover, should be considered as an economic investment for future benefits in the form of better soil health, increased productivity and resilience, and higher and more reliable profit. However, farmers, and particularly poor and marginal farmers, are likely to be more myopic and cost conscious as opposed to investment savvy.

How to bridge this short-term deficiency becomes a key question for innovation systems to address. Our analysis, however, excludes other costs such as labor, which may provide additional gains for the CA system relative to the TA system (see [5]). The results support the contention that even in very dry areas, enough biomass can be generated (and increased over time) to allow for in situ mulching of crop residues produced from the cropping system to meet the minimum CA requirement for ground cover, that is, 30% surface coverage. It has been suggested by [21] that the trade-off for feeds and livestock may not be as pronounced given the increase in biomass that offsets the input of the mulch residue retained. We agree with the assessment of [21] but note that the time-lag in reaching a sufficient level of increase in biomass may be a deterrent to wide-scale adoption, even where there is already a utilization of straw for ground cover as well as the simultaneous feeding of livestock.

This is because it is possible to start harnessing economic and environmental benefits during the early transitional years of the CA adoption process while still building up biomass output, soil mulch cover and soil health.

Further, the in situ production of biomass from the cropping system (which would be enough to maintain a 30% ground cover) may certainly be possible in an above-average or good rainfall year, particularly in the initial stages of CA establishment. However, progress can be made where the commitment for residue retention is managed through improved grazing, such as rotational grazing agreed upon by all sides, including at the community level.

There are clear trade-offs that exist in marginal dryland areas at the start of the transformational process to establish a CA system, particularly within a setting in which livestock is central to crop farmers' and pastoralists' livelihoods, and where fodder biomass (straw) production is valued more highly over grain production. Moreover, this is exacerbated in a region with frequent droughts and dry spells. It has been estimated [36] that the shadow value of straw in a drought year is 3-fold the price of grain, signifying its importance to crop–livestock farming communities for which crop–livestock integration is based on pastoralists relying on access to fodder produced by settled farmers. The value of fodder during the growing season and of straw during the dry season, particularly in a drought year, may however further complicate the problem noted by [8], where difficulties were found in farmers adopting CA in Syria as a result of competing uses of biomass for livestock. Thus, [5] notes the importance of conducting research to determine the "optimum quantity of crop residues" that can be retained for ground cover without restricting the amount of biomass needed for livestock, whilst also ensuring that enough residues are left on the soil surface to capture the full productivity, socio-economic and environmental benefits that can occur over time.

Notwithstanding this, there are a number of options that exist within many dry environments, which may enhance the variety of feed sources available and thereby limit or minimize the competition between crop biomass (including post-harvest waste) for livestock feeding and that required for building and maintaining ground cover under CA. In Syria, the prominence of olive trees and pruning waste provides one avenue—as do other forms of compostable waste. Grass, leaf litter and other dead-plant biomass may also be utilized as a source of ground cover, and these are showing promise in parts of sub-Saharan Africa [37]. Suggestions have also been made to incorporate a range of agro-industrial waste combinations into supplemental sources of livestock feed (e.g., molasses and olive-oil pomace) with potential beneficial outcomes for joint products produced—such as milk and yoghurt quantity and quality [38]. Supplementary feed sources may thus reduce the amount of feed needed from crop fodder biomass and residues.

From the standpoint of a collaborative research and developmental initiative, there are also likely to be significant gains made in assessing the efficacy of testing contractual agreements between farmers in marginal zones and farmers within irrigated zones. Given that barley is no longer protected under government subsidy support, at least at the time of this study or likely in a stable Syria in the future, there is a need to appeal to the incentives for barley production between zones. As previously mentioned, the incentive in irrigated areas is for grain production, with straw biomass a joint by-product typically sold into the market for supplementary livestock feeding. The potential for farmers in marginal zones to contract farmers in irrigated areas for the production of both grain suitable for their production environments (drought tolerant or locally adapted) and straw has yet to be tested and validated. It would appear that the incentives for both cohorts of farmers would be aligned under such an arrangement, and particularly so given that rainfall levels within marginal zones do not permit the regular production of grain or therefore a continued reliance on nascent (local) grain markets. Why such contractual arrangements have not taken root organically is an equally important research question. One conjecture is that the markets for rural finance (credit, insurance, and deposits) in Syria are still not mature enough to handle such arrangements; they therefore risk mitigating the potential for efficiency in contractual agreements across agro-ecological zones.

### *4.5. Land Rental Markets, Rural Finance and Social Stability*

As has been mentioned repeatedly, the key incentive for the production of barley within marginal zones in Syria is as green and dry fodder for livestock. Grain is only produced in years of adequate and timely rainfall. There is, however, a qualifier to this statement. The production of fodder and dry straw, as the primary economic objective, is not in the form of a harvested product but rather an in situ product for on-site consumption by nomadic livestock. It is the ability to capitalize on land rental rates for direct grazing that is the key motivation for producing a stand of fodder barley and often a stand without any grain production. Why does this observance interest us in a study on the relevance and broad applicability for CA in marginal zones?

Firstly, in an environment where access to credit has typically been constrained, the provision of microfinance within rural communities has played a significant role in relaxing working capital constraints such that greater areas of marginal land are brought into production. Reliable statistics in Syria are difficult to acquire, and in many cases, they have been pencil-marked in order to ensure that they are consistent with regulatory rules and ordinances. It is difficult therefore to support this claim of a correlation between microfinance availability and the increased amount of marginal land under production. Easier to justify is the argument that standardized norms for the disbursement of microfinance across zones, on the basis of a set monetary value per unit of land, will inherently benefit farmers in marginal zones. Given that quantities and costs of material inputs such as fertilizer and specifically irrigation are much higher for farmers in irrigated areas, fixed rates per unit of land provide marginal farmers with both working capital and an excess of funds to be used in order to smooth out consumption over the growing season.

The incentives to bring more land under production with simplified rules for microfinance are therefore clear. With land rental values for direct grazing increasing within periods of drought, the ability to pay back loans is bolstered. When more productive land use paradigms such as CA offer the potential for improved reliability in yields as well as savings in costs, the incentives for bringing more land into production are greater, and as is the ability to repay loans at the end of the growing season. Microfinance, when coupled with improvements in land use management practices such as CA, has the potential to improve both adoption rates (measured in terms of land under CA) as well as rural household livelihoods through an ability to smooth out consumption throughout the year—notwithstanding improvements in profitability from cropping in marginal zones. The inherent outcomes attainable from the broad adoption of CA are therefore not restricted solely to savings in production costs and beneficial productivity and environmental outcomes (soil health among others), but also are in terms of improving the quality of life for rural households through improving the security of income streams and a reduction in vulnerability from systemic shocks.

Secondly, the ability to capitalize on land rental rates for direct grazing is of immense importance in periods of drought, given the nature of pastoral livelihood systems within the region, and in Syria more specifically. Within an era of subsidized barley production and distribution, it was not uncommon for Bedouins to settle within the vast and often barren rangelands and to rely on a network of marketing agents who supplied subsidized barley, water and necessities of life to their communities. With the removal of state subsidy programs, there has been increased movement of livestock flocks and, in periods of drought, frequent clashes and disputes between settled farmers and nomadic flock herders. Options under CA land use, such as "managed" rotational grazing and/or "communal agreements" at the village/community level for balancing stocking rates with livestock carrying capacity, are applicable as measures for mitigating conflicts [3]. However, these are very much dependent on land use rights and security in land use rights. While there have been significant challenges in the development of a land cadastral system and the issuance of certificates of land ownership, land rental markets have strengthened and continue to strengthen with increased availability of credit (at least prior to the civil conflict in 2011). Improved productivity and the reliability of the production on marginal lands, through shifts in land use management paradigms, are therefore likely to bode well for reducing conflicts between settled farmers and pastoral herders. There is an element of fostering social stability and the reduction of conflict within the set of outcomes desired from the broad adoption of CA, and this is sometimes missed given that much research and attention related to the broad adoption of CA has been within more stable environments.

*4.6. Enhancing Broad Adoption of CA through Lessons Learned*

One of the major limitations of this study was the inability to follow up on the baseline soil sampling, given difficulties in access to the field in light of armed conflict and the heightened lack of security. Similarly, caution should also be used in generalizing the yield and economic returns, given the lack of replicability in the trial demonstration site. Given that the initial objective of the field sites was for on-farm demonstration, these results provide an indication of the validity of the proof of concept and of the applicability for CA to potentially succeed in the marginal dryland environments under which it was tested. Thus, we were unable to ascertain the full impact of the various treatments on soil biological, chemical, hydrological and physical properties and on the cropping system and land productivity and resilience over time, but were buoyed by initial results, which were encouraging. Although the need to replicate the trials should also be considered in future research, a number of published on-farm managed trials have been unreplicated yet have yielded useful insights (see, e.g., [39]). Moreover, other authors have noted that a trial design with no replication on a farmer's field simplifies the demonstration, thereby making it easier for farmers to understand and evaluate the technology [40].

What is worth noting is that wherever CA has been practiced in dryland Mediterranean environments for more than 10 or 15 years, such as in Western Australia, South Africa and southern Europe, the benefits include improved biomass and yield outputs, as soil organic matter and soil health improved with time but also reduced the use of the purchased inputs of seeds, nutrients, pesticides, fuel, water and time, in addition to a reduction in soil erosion and land degradation [41–44]. Such benefits have often led to an increase in the livestock carrying capacity and stocking rates. In Western Australia, with its dryland Mediterranean environment, CA farmers are able to cultivate sustainably and profitably with 200 mm of rainfall [41,43]. It would therefore seem probable that such benefits would be potentially available to farmers in Syria, making it attractive to establish CA crop–livestock systems in which crops and livestock can co-exist productively and sustainably through various forms of win–win integration involving viable arrangements at all levels of rural organizations.

Within the West Asia and North Africa region, agricultural advisory services have largely been within the domain of national systems of agricultural extension. In Syria, the inclusion of non-governmental and international organizations (both research and development) was very recent, with expansion taking place after the death of the last President Hafez Al Assad in 2000, and with initial support from his now President son Bashar Al Assad. A discussion on the background for why more pluralistic forms of knowledge dissemination were not permitted in Syria is a topic for another paper. The general point, and a more global point at that, is that perspectives on the role of agricultural innovation have shifted considerably, moving from linear transfer-of-technology models in the 1960s to, more recently, a focus on *agricultural innovation systems* (AISs). AISs argue that both the development and adoption of contextually relevant technologies and innovations are more likely to be successful when there is a process of continuous learning, jointly undertaken by research organizations, farmers, marketing agents, donors, Non-governmental organizations (NGOs), financial service providers, policy makers, and relevant civil society actors.

Notwithstanding that Syria is currently embroiled in a civil war, there is an unanswered question of whether nations within the region are ready to embrace participatory learning in order to uncover inclusive systems development approaches for (i) identifying and sharing contextually relevant sets of interlinked practices for research and development, (ii) uncovering avenues for strengthening capacities in effectively adapting and adopting paradigm changing agricultural technologies and best practices, and (iii) providing rural communities with an opportunity for greater participation in regional and national policy dialogue.

The success in the adoption of CA globally has been attained in favorable and unfavorable environments, including in dryland Mediterranean environments, such as in Europe, central Asia, South Africa and Australia [3–5,7,10]. Thus, we speak to the question of enabling investment and regulatory policies as well as social and cultural environments that support knowledge, participatory learning and the enhancing of the national capacity to innovate.

While there is anecdotal evidence to suggest that no-till agriculture has been broadly accepted in Syria, one could easily argue that this has been fostered by shortages in fuel, within the post-revolution period, which has influenced a move towards limiting machinery use for tillage in crop establishment and in weed management. In the period prior to the revolution (2008–2011), there were claims that over 30,000 ha in Syria was under no-till systems [21,45–48]. How much of this was influenced through incentives provided by donor funds (gratis use of machinery and equipment, complimentary seed distribution, etc.) and disseminated through research and public extension organizations is not clear and is not well documented. Whether this trend will reverse itself in a stable Syria remains, therefore, to be assessed and is a valid question for future research. What is clear is that without supporting systems for participatory knowledge generation and dissemination, together with an enabling investment and policy environment, the ability for the broad adoption of CA and the desired environmental, social and economic outcomes are likely to be limited.

## 5. Concluding Remarks

CA was shown to maintain higher levels of soil moisture ($p < 0.05$) over the growing season, together with improved hydraulic conductivity, when demonstrated within a dry and marginal agro-ecological zone in central Syria. Notwithstanding the limitations of short-term results such as these, and although it is difficult to ascertain whether there are statistically significant differences in yields within this study (or visible trends in the medium to long term), there were clear economic advantages in the adoption of CA produced in the first two seasons of adoption and system transformation. These included a reduction in fuel used for crop establishment and weeding, which has a particular relevance for the region given the recent fuel and input shortages, within an era of ongoing armed civil conflict. There is also preliminary evidence to support the contention that CA can improve yield and biomass output and overall net returns (although crop mix is important), even in the driest agro-ecological zones. The preliminary results also suggest (at least in the short term) that residue retention may not immediately fulfil the requirements of 30% ground cover for CA and that this may be more difficult to maintain in a drought year. This is due to the marginal nature of the environment and the strong crop–livestock interaction. However, there is evidence that it should be possible to establish and maintain minimum ground cover as greater crop and land potentials are mobilized during the early transitional phase of CA adoption.

The role of soil mulch cover is to improve soil health and biology as well as to provide physical surface protection against soil erosion, suppress weeds and sustain food webs below and above the ground. Thus, soil mulch cover will always remain an important component of CA, however difficult it may be to maintain it against the pressures from and the competition with livestock. The increase in yields vis-à-vis improvements in biophysical parameters in CA relative to TA does suggest, however, that the competition with livestock for biomass is likely to reduce over time and that farmers would be able to return increased levels of straw (as stubble and residue) as mulch, given improved biomass yields. Our data supports previous research in the region on CA, or components of CA cited herein, and also provides an indication that CA has a beneficial role to play in marginal cropping zones such as that under study.

These benefits are much broader than those ascribed to beneficial environmental outcomes and increased profitability through a reduction in production costs and higher yields. We argue that in marginal zones with interactions between pastoralists and settled farmers, and thereby with strong crop–livestock interactions, the CA approach to sustainable intensification has the potential to also foster beneficial outcomes in terms of improvements in social stability, in potentially smoothing out seasonal consumption needs (household and livestock) when supported through inclusive finance provision, and in reducing risks from systemic shocks. The key to the broad adoption of CA in marginal environments is a supportive and enabling environment for participatory innovation, comprised of both research (invention) and avenues for the dissemination of knowledge, which influences shifts in land use management practices (adoption) at all levels, including the community level, within production systems and across components of crop production and livestock production. How ready Syria is for fostering inclusive and enabling environments for agricultural innovation, and towards the attainment of critical mass in the adoption of sustainable long-term shifts towards environmentally, socially and economically sound land use management practices, is a question for future research to answer within a stable environment. The applied research initiative reported herein suggests that there are significant reasons for hope and promise.

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*sustainability*

MDPI

*Article*

# Title "Organic Fertilizers" in Vietnam's Markets: Nutrient Composition and Efficacy of Their Application

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**Abstract:** Organic fertilizers have recently been gaining popularity; however, their governance is not completely assessed in developing countries. This study investigated the nutrient composition of so-called organic fertilizers in Vietnam's markets and issues related to their production, and evaluated their potential to contaminate the groundwater. We analyzed the physicochemical properties of 12 domestic and four imported products of the fertilizers, and conducted a cultivation experiment in sandy soil with the fertilizer applied at a rate of 200 mg N $kg^{-1}$ soil using an automatic watering apparatus in a greenhouse. We further studied the production of an "organic fertilizer" from coffee by-products. The nutrient content greatly varied among domestic products, whereas they were quite similar among imported products. The product packaging of the collected samples lacked information regarding raw materials. Two thirds of the domestic products contained over 30% of the total N in the inorganic form, implying that the N content dramatically increased in the fertilizers rather than in their supposed raw materials. The stages involved in the production were composting, the addition of extra soil as a bulking agent, and the mixing-in of chemical substances to increase the nutrient content before packing. The remarkably high ratio of inorganic N to total N was attributed to excessive N leaching from soil by the application of domestic fertilizers. These results suggested the need for quality criteria guidelines for organic fertilizers in Vietnam that underline not only nutrient levels, but also the control of raw materials and production process of compost, because they are closely related to nutrient uptake and the leaching loss of nutrients.

**Keywords:** coffee by-products; nutrient composition; N leaching; production; so-called organic fertilizer

## 1. Introduction

Organic agriculture according to the internationally accepted standards is a relatively new method of farming in developing countries. Consumers have difficulty distinguishing between genuine organic and other "clean" products [1–4]. Vietnam is one of the most dynamic emerging countries in the East Asia region, with a gross domestic product (GDP) growth rate of 6.8% in 2017. The country's economic performance reflected strong export-oriented manufacturing, strong domestic demand, and the gradual rebound of agriculture [5]. One of the most striking problems for Vietnam is widespread soil degradation in agricultural areas, requiring the use of the land in a more sustainable manner [6–8]. Nguyen et al. [9] reported that improved land tenure security is associated with a higher level of manure use by farm households. Sustainability certification has become increasingly popular in recent years, even though the excessive application of fertilizers and irrigation have made it difficult for farmers to conform to most certification standards and programs. Easy labeling showing environmental performance costs much less than certifying with international agencies has probably led Vietnamese farmers to move away from international certification and opt for a cheaper labeling scheme [10].

In this context, the organic fertilizer industry has recently expanded. The organic fertilizer market is estimated to have increased at an impressive 11% compound annual growth rate from 2016 to 2021. The country annually produces >1.2 million tons of organic fertilizers [11–13]. Various fertilizers labeled as "organic fertilizer" are being sold in the markets; however, criteria of their raw materials and production have not been established. Quality of these fertilizers requires clarification.

On the other hand, composting is considered a proper approach to the rising amount of organic waste from municipal solid waste, sewage sludge, and agricultural by-products in developing countries. In Vietnam, composting the wastes have recently begun. Adding chemical fertilizers to the waste during composting is a common practice [14,15]. There is a lack of empirical evidence for the effectiveness of this practice.

The application of compost is recommended not only for improving soil productivity, but also for reducing eutrophication because of excessive application of chemical fertilizers [16–20]. Under the Asian monsoon climate, nutrient leaching via surface runoff or percolation through the unsaturated zone into groundwater is predicted to be high because of the high frequency of heavy rainfall [21]. Thus, the evaluation efficacy of the fertilizers should involve assessing the leaching of nutrients from agricultural soil.

The objectives of this study were to clarify the nutrient composition of the so-called organic fertilizers and elucidate the effects of their application on cropping plants and the leaching loss of nutrients from agriculture land. Therefore, nutrient composition was analyzed, and a cultivation experiment was conducted using some typical "organic fertilizers". Moreover, to determine the reasons why nutrient content greatly varied among "organic fertilizers", we investigated the flow of raw materials and manufacturing processes for an "organic fertilizer" made from coffee by-products.

## 2. Materials and Methods

### 2.1. Sampling and Chemical Analysis

We acquired 16 so-called organic fertilizers (12 domestic products, V1–V11 and VC, and four imported products, I1–I4), which were being sold in the markets of Hanoi, Thua Thien Hue province, Lam Dong province, and Ho Chi Minh City in Vietnam. Hanoi and Ho Chi Minh City are two of the largest municipalities located in Northern Vietnam and Southern Vietnam, along with large suburban areas for vegetable production to meet urban vegetable demand. Lam Dong province in the Central Highlands is known as the largest vegetable producer, it also has the second largest area of coffee plantations in Vietnam. Vegetable production is characterized by a high level of fertilizer input. Thua Thien Hue province is located in the Central Coastal Region of Vietnam, which is dominated by poor-quality sandy soil. Samples were collected in November 2015 and June 2016; replicate samples were deleted. These goals were to ensure that the selected samples were representative of "organic fertilizers" in Vietnam. Samples were then brought to the Laboratory of Environmental Soil Science of Okayama University, Japan to analyze their physicochemical properties and conduct a cultivation experiment.

The pH was measured using a pH electrode (1:5 fresh sample: water, *w*/*v*). The total C and N were determined using a CN-analyzer (CN Corder MT-700; Yanaco, Japan). In the organic form ($NH_4^+$, $NO_3^-$), N was extracted using 2 mol $L^{-1}$ KCl, and concentrations of $NH_4^+$ and $NO_3^-$ were measured using the phenate method and vanadium (III) chloride reduction method, respectively, with a spectrophotometer (UV-1200, Shimadzu, Japan) [22,23]. Exchangeable cations (Exch.K, Exch.Mg, and Exch.Ca) were extracted using 1 N $NH_4OAc$. The remaining total nutrient content was assessed by wet digestion with $HNO_3$ and perchloric acid. Available phosphorus (Truog P) was extracted using 0.002 N $H_2SO_4$. Total K, Ca, and Mg contents were measured using atomic absorption spectrophotometry. The total P and Truog P contents were determined using the ascorbic acid sulfomolybdo-phosphate blue color method [24].

### 2.2. Investigation of the Flow of Raw Materials and Manufacturing Process of an "Organic Fertilizer"

The research site of this study covered two districts (Duc Trong district and Lam Ha district) of Lam Dong province in the Central Highlands, which is the main coffee producing area in Vietnam. The coffee processing industry, whether employing either a wet or dry method to remove the shells from the cherries, generates a large volume of coffee by-products. Most of the waste was deposited on land, causing environmental pollution, and composting is suggested as an attractive solution for handling the waste. Consultation with local experts in coffee production and sampling coffee by-products for nutrient analysis were conducted as preliminary work in the early 2016. In June 2016, we visited coffee plantations that are mainly operated by households, with a small production scale of several hectares. During the harvest time, they collect the cherries and sell them to processing companies in the area.

A survey using face-to-face interviews was conducted at three of the 11 coffee processing companies and a private fertilizer company that made a so-called organic fertilizer from coffee by-products (VC) in the area. In the coffee-processing companies, we gathered data on the working capacity, technology employed (wet method or dry method), input materials and output materials, waste generation, and disposal costs, and we also visited the disposal sites of coffee by-products. In the fertilizer company, we collected information on source of raw materials, composting technique, stages involved in the manufacturing process, the purpose of each stage, the target customers, and the price of coffee by-products and the commercial product of fertilizer. We also took samples at each stage of the manufacturing process and brought them to Japan for analyses, aiming to evaluate changes in the nutrient levels during the process. Parameters were measured as described above.

### 2.3. Cultivation Experiments

Japanese Komatsuna (*Brassica rapa* var. perviridis) was cultivated in 1/5000a Wagner pots in a greenhouse using an automatic watering apparatus for six weeks. The design was completely randomized, with three replicates per sample, using nine selected "organic fertilizers", a chemical inorganic fertilizer, and a control (soil only). Sandy-textured soil was first passed through a 2-mm sieve. Then, 2.2 kg of the graded soil was placed in planting pots, followed by 1 kg of the graded soil into which the fertilizer was mixed. Table 1 presents the pH value and nutrient contents of the soil used in this experiment.

**Table 1.** pH value and nutrient contents (g $kg^{-1}$) of soil used in the cultivation experiment.

| Constituents | Values |
|---|---|
| pH ($H_2O$) | $8.99 \pm 0.17$ |
| Total C | $\leq 0.001$ |
| Total N | $\leq 0.001$ |
| Total P | $0.01 \pm 0.00$ |
| Total K | $2.26 \pm 0.04$ |
| Total Mg | $1.72 \pm 0.00$ |
| Total Ca | $3.24 \pm 0.10$ |

Values are means ± SD (n = 3).

The following two nutritional supplementation treatments were used: N-fertilizer alone and N-fertilizer + P, K. For the N-fertilizer treatments, "organic fertilizers" and a chemical inorganic fertilizer were applied at a rate of 600 mg N per pot (equivalent to 300 kg N $ha^{-1}$). To prepare the N-fertilizer + P, K treatments, we calculated the total P and K contents contributed by the "organic fertilizers", and supplemented these with P as super phosphate and K as potassium chloride to bring the P content to 410 mg per pot and the K content to 1150 mg per pot (except for the soil-only control). Twelve seeds of Komatsuna were sown in each pot. One week after germination, the seedlings were thinned to a density of eight seedlings per pot.

Plant and soil samples were taken at harvest (six weeks after sowing). The dry weight of the plants in each pot was measured. Soil samples were collected from each pot from the top and bottom soil stratum. Plant and soil samples were dried in an oven at 105 °C for 24 h, ground, and stored for further analysis. An analysis of variance (ANOVA) was used to compare the effects of the fertilizer type and nutritional supplementation on the dry weight and nutrient uptake of plants. Differences between individual averages were tested using the *post-hoc* least significant difference (LSD) test at $p < 0.05$.

## 3. Results and Discussion

### 3.1. Characteristics of "Organic Fertilizers"

Figures 1–3 show the N, P, and K contents of the collected samples. Table 2 presents the summaries of pH ($H_2O$), the C: N ratio, and the concentrations of other nutrients.

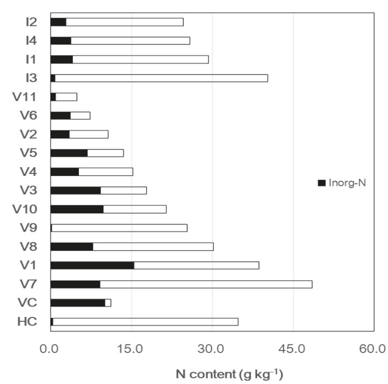


**Figure 1.** N content of so-called organic fertilizers in Vietnam's markets. Notes: V1–V11, VC: domestic products; I1–I4: imported products; VC: the so-called organic fertilizer made from coffee by-products; HC: coffee by-products compost.

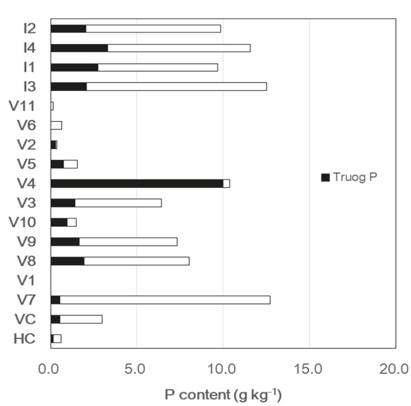


**Figure 2.** P content of the so-called organic fertilizers in Vietnam's markets. Notes: V1–V11, VC: domestic products; I1–I4: imported products; VC: the so-called organic fertilizer made from coffee by-products; HC: coffee by-products compost.

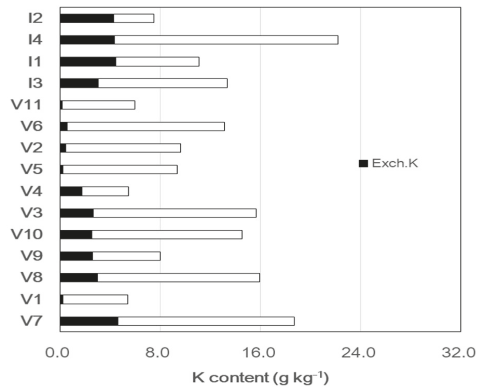


**Figure 3.** K content of the so-called organic fertilizers in Vietnam's markets. Notes: V1–V11: domestic products; I1–I4: imported products.

**Table 2.** pH, C:N ratio, and concentration of other nutrients in the so-called organic fertilizers in Vietnam's markets.

| | **Domestic Products** | | **Imported Products** | |
|---|---|---|---|---|
| pH ($H_2O$) | 7.22 | (5.14~9.07) | 8.35 | (7.40~8.97) |
| C:N ratio | 8.88 | (3.22~19.43) | 9.16 | (7.71~10.62) |
| Total Ca | 28.45 | (10.44~61.78) | 60.14 | (40.29~69.59) |
| Exch.Ca | 0.02 | (0.00~0.05) | 0.04 | (0.03~0.05) |
| Total Mg | 3.88 | (0.88~7.19) | 5.20 | (4.34~6.40) |
| Exch.Mg | 2.40 | (0.13~5.77) | 3.92 | (2.91~4.40) |

Values are average and the ranges are given in parentheses. Total Ca and Total Mg are expressed in g kg$^{-1}$. Exch.Ca and Exch.Mg are expressed in cmol kg$^{-1}$.

We found that N and other nutrient contents greatly varied among the domestic products, whereas these were quite similar among the imported products. In the domestic products, the total N, P, and K contents were in the ranges of 4.9–48.5 kg$^{-1}$, 0.0–12.7 kg$^{-1}$, and 5.8–26.0 g kg$^{-1}$, respectively, whereas in the imported products, these were in the ranges of 24.6–40.2 kg$^{-1}$, 9.7–12.5 kg$^{-1}$, and 14.2–29.0 g kg$^{-1}$, respectively. The ratio of inorganic N to total N in most domestic products was high. Two-thirds of domestic products contained approximately 30% of the total N in the inorganic form, and the imported products contained approximately 10%. In contrast, the ratio of Truog P to total P greatly varied among domestic products.

Raw materials, which are the foundation for the quality of organic fertilizers, are varied. They are by-products of vegetable, animal, and human origin that have been popularly used worldwide for over a thousand years. They are organic materials from municipal solid waste, sewage sludge, and waste of agro-industrial origin whose use recently markedly increased in modern agriculture as organic waste-based fertilizers [25]. These wastes are becoming important recyclable organic materials in developing countries. Composting the wastes has recently begun in Vietnam; however, governance instruments and policies on this recycling activity have not been established. There is no standard for raw materials of organic fertilizers in regulations regarding fertilizer production, distribution, and use [26]. Varied raw materials and poorly controlled manufacturing could cause a wider range of nutrient content of domestic "organic fertilizers" compared with that of the imported ones.

Since there was no information regarding raw materials on the product packaging of our collected "organic fertilizers", we guessed their feedstock based on their N content and appearance. The N content of organic fertilizers depends on the raw materials. The percentage of N recorded in poultry manure, dairy manure, municipal solid waste, crop residue, and sewage sludge are in the range of 2.0–4.0, 1.0–2.0, 1.0–1.5, 1.5–2.5, and 3.7–5.0, respectively [16,27,28]. Two-thirds of domestic "organic fertilizers" contained less than 2% N (Figure 1) and various pieces of litter, branches, nylon, and stones were observed in the fertilizers (Table 3). To date, the waste has not yet been separated at the source in Vietnam. It appeared that most of the domestic products might have been produced from municipal solid waste.

**Table 3.** General available information on collected samples.

| Product Name | Sample Label | Ingredient Descriptions | Foreign Objects Mixed in Products | Product Shape, Instructions for Use | Market Price (USD/kg) |
|---|---|---|---|---|---|
| Domestic products | | | | | |
| TRIMIX—N1 | V7 | Without indication | | Small granules, For horticulture | 1.46 |
| SONG HUONG | V1 | Without indication | Small pieces of branches and litter | Small granules, For all crops | 0.09 |
| HADICO—THANG LONG 03 | V8 | Without indication | Small pieces of branches and litter | Small granules, For horticulture | 0.33 |
| CFARM Pb02 | V9 | Without indication | Small pieces of wood and nylon | Small granules, For vegetables, horticulture | 0.56 |
| TRIBAT T—O | V10 | Without indication | | Small granules, For all crops | 0.40 |
| DAU TRAU HCMK7-HUU CO TRICHODERMA + TE | V3 | Without indication | | Small granules, For all crops | 1.56 |
| ORMIC 02—TRICHODERMAR sp—AZOTOBACTER sp | V4 | Without indication | | Fine powder For all crops | 2.22 |
| HUU CO VI SINH MOI TRUONG HA NOI | V5 | Without indication | Small pieces of wood | Small granules, For vegetables, horticulture | 0.22 |
| SONG GIANH 1 | V2 | Without indication | Small pieces of stone | Small granules, For all crops | 0.18 |
| QUE LAM 01 | V6 | Residue of crops, fish, and seaweed | Small pieces of wood | Small granules, For all crops | 0.44 |
| SONG GIANH 2 | V11 | Without indication | Small pieces of wood, branches, stone | Small granules, For horticulture | 0.22 |
| PHAN CA PHE | VC | Coffee by-products | | For vegetables | 0.11 |
| Imported products | | | | | |
| MIEN TAY—WOPROFERT (Holland) | I3 | Without indication | | For all crops | 2.22 |
| NEUTROG—RAPID RAISER (Australia) | I1 | Without indication | Pieces of rice husks | For all crops | 2.22 |
| VIMAX 3-3-3 (Malaysia) | I4 | Without indication | | For vegetables, fruits, tobacco, coffee tree, flowers, and rice | 2.22 |
| NEUTROG—BOUNCO BACK (Australia) | I2 | Without indication | Pieces of rice husks | For all crops | 2.22 |

It must be emphasized that the percentage of inorganic N within the total N in most collected domestic "organic fertilizers" was noticeably high. Many studies show that inorganic N comprised less than 10% of compost N [27,29,30]. The ratio of inorganic N to total N in our collected samples of imported products was approximately 10%. Meanwhile, the ratio for two-thirds of the collected domestic products was over 30%. For example, V6 sold at Hanoi as named Que Lam 01 contained 7.3 kg kg$^{-1}$ N, but approximately 50% of it was the inorganic form. V1 sold at Thua Thien Hue province and named Song Huong contained 38.6 kg $kg^{-1}$ N, but inorganic N also accounted for approximately 40% of the total N.

Figure 4 shows the relationship between the total N and P of the collected samples. We categorized them into two groups: the first included four imported and five domestic products (V3, V4, V7, V8, and V9) containing both N and P, and the second included the remaining seven domestic products containing N, but less P. Interestingly, the price of the former group was higher than that of the latter group (Table 3). It implies that the adjustment of N and P plays an important role in the price of the fertilizers. Thanh and Matsui [14] reported that the addition of N, P, and K to matured compost is typically the final step in the production process for organic solid waste compost in Vietnam. This supportably explains the common increase in the ratio of inorganic N to total N of domestic "organic fertilizers" in this study. Since the product packaging of the collected samples lacked information regarding raw materials, we could not precisely compare the nutrient content of commercial products with those of their supposed raw materials. To determine the reason for the remarkable proportion of inorganic N in domestic products, it was necessary to investigate the manufacturing processes and changes in nutrient composition during each process of a so-called organic fertilizer made from coffee by-products.

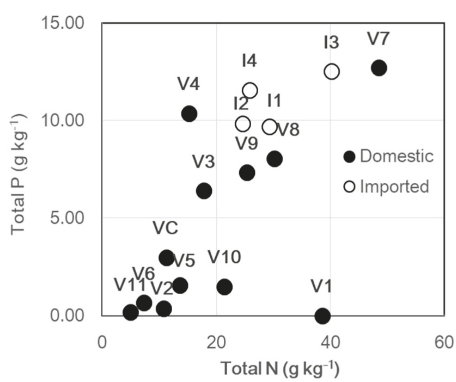


**Figure 4.** Relationship between total N and P of the so-called organic fertilizers.

## 3.2. Production Method of an "Organic Fertilizer" from Coffee By-Products

Figure 5 illustrates the flow of raw materials and manufacturing processes for an "organic fertilizer" made from coffee by-products. After harvesting, coffee cherries were processed by one of two methods: dry or wet. In the wet method, the outer covering of the coffee bean was removed when the cherries were still fresh. This is a popular technique in this area, which generates a large volume of by-products (coffee pulp). For example, a medium-scale processing factory with a working capacity of 150 tons per day generates approximately 100 $m^3$ of coffee pulp. Companies arrange brokers to collect the waste, and the fee is based on the disposal volume (currently 1.3 USD per $m^3$). The brokers then deposit it on private land or sell it to fertilizer companies (currently at a price of 3.3 USD per $m^3$).

The composting companies use aerobic composting over several months, after which extra soil is added to increase the volume and density. Finally, they add chemical substances such as urea and phosphate to enhance the fertilizer effect before packing the product for sale in the markets as "organic fertilizer" at a price of 11 USD per 100 kg (current price). Our investigation results are in accordance with the findings of Thanh and Matsui, as reported above. However, the authors did not provide evidence of changes in the nutrient levels during the manufacturing processes. Our study clarifies this limitation.

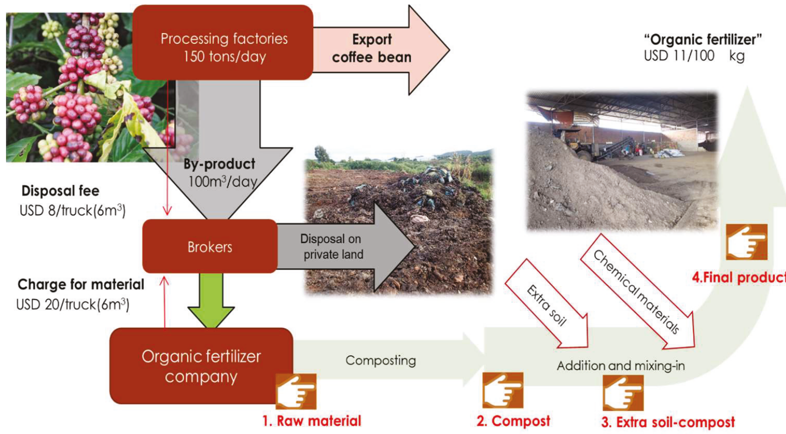


**Figure 5.** Flow of raw materials and production method of an "organic fertilizer" from coffee by-products.

Table 4 shows changes in the nutrient levels during the manufacturing processes of an "organic fertilizer" made from coffee by-products. It indicates that coffee by-products are rich organic material, with nitrogen and potassium. The total C content was high, being up to 423.2 g $kg^{-1}$, and the N and K contents were 32.80 g $kg^{-1}$ and 9.71 g $kg^{-1}$, respectively. However, the P content was very low. After composting, the carbon content slightly decreased, but the concentration of total N and K increased. The compost contained were 34.8 gN $kg^{-1}$ and 12.54 gK $kg^{-1}$, respectively. After bulking out the compost with extra soil, the total C, N, and K contents were reduced to 83.20 g $kg^{-1}$, 6.40 g $kg^{-1}$, and 4.48 g $kg^{-1}$, respectively. The concentration of exchangeable K was reduced from 25.68 cmol $kg^{-1}$ to 4.13 cmol $kg^{-1}$. After packing, the total N content nearly doubled from 6.40 g $kg^{-1}$ to 11.20 g $kg^{-1}$. $NH_4^+$ concentration increased 34-fold, whereas $NO_3^-$ concentration remained unchanged. The total P content tripled from 0.99 g $kg^{-1}$ to 2.99 g $kg^{-1}$, and the Truog P content increased 13-fold from 0.04 g $kg^{-1}$ to 0.54 g $kg^{-1}$.

**Table 4.** Changes in the nutrient levels during the production of the "organic fertilizer".

| | Raw Material | After Composting | After Bulking out | Final Product |
|---|---|---|---|---|
| pH | NA# | 8.51 | 8.03 | 9.01 |
| Total C | 423.20 | 417.20 | 83.20 | 64.20 |
| Total N | 32.80 | 34.80 | 6.40 | 11.20 |
| $NH_4^+$-N | NA# | 0.37 | 0.25 | 8.47 |
| $NO_3^-$-N | NA# | 0.01 | 0.19 | 0.16 |
| C:N ratio | 12.92 | 12.01 | 13.02 | 5.76 |
| Total P | 0.70 | 0.61 | 0.99 | 2.99 |
| Truog P | 0.28 | 0.17 | 0.04 | 0.54 |
| Total K | 9.71 | 12.54 | 4.48 | 4.20 |
| Exch.K | 37.87 | 25.68 | 4.13 | 5.06 |
| Total Mg | 0.41 | 0.71 | 0.37 | 0.65 |
| Exch.Mg | 2.39 | 2.30 | 0.66 | 0.82 |
| Total Ca | 1.55 | 2.49 | 0.83 | 3.05 |
| Exch.Ca | 3.26 | 4.69 | 2.02 | 7.98 |

Nutrients content is expressed in g $kg^{-1}$. Exchangeable cations are expressed in cmol $kg^{-1}$. NA#: not analyzed.

### 3.3. Effects of "Organic Fertilizers" on Plant Growth and N Leaching

The dry weight and N uptake of plants were significantly influenced by the fertilizer type and nutritional supplementation. The combined interaction of these factors had no significant effect on the dry weight and N uptake (Tables 5 and 6, respectively). The P uptake was significantly influenced only by the fertilizer type (Table 7).

**Table 5.** Two-way analysis of variance (ANOVA) testing the effects of fertilizer type and nutritional supplementation on the dry weight of plants.

| Source of Variation | SS | df | MS | F | *p*-Value | F Crit |
|---|---|---|---|---|---|---|
| Fertilizer type | 153,238.00 | 10 | 15,323.80 | 9.32 | $4.7 \times 10^{-8}$ | 2.05 |
| Nutritional supplementation | 13,825.79 | 1 | 13,825.79 | 8.41 | 0.0058 | 4.06 |
| Interaction | 12,841.96 | 10 | 1284.19 | 0.78 | 0.6463 | 2.05 |

**Table 6.** Two-way analysis of variance (ANOVA) testing the effects of fertilizer type and nutritional supplementation on N uptake.

| Source of Variation | SS | df | MS | F | *p*-Value | F Crit |
|---|---|---|---|---|---|---|
| Fertilizer type | 155.23 | 9 | 17.25 | 6.14 | $2 \times 10^{-5}$ | 2.12 |
| Nutritional supplementation | 17.67 | 1 | 17.67 | 6.29 | 0.016 | 4.08 |
| Interaction | 15.08 | 9 | 1.68 | 0.60 | 0.792 | 2.12 |

**Table 7.** Two-way analysis of variance (ANOVA) testing the effects of fertilizer type and nutritional supplementation on P uptake.

| Source of Variation | SS | df | MS | F | *p*-Value | F Crit |
|---|---|---|---|---|---|---|
| Fertilizer type | 0.08 | 9 | 0.01 | 6.24 | $18 \times 10^{-6}$ | 2.12 |
| Nutritional supplementation | 0.00 | 1 | 0.00 | 0.86 | 0.3601 | 4.08 |
| Interaction | 0.05 | 9 | 0.01 | 3.82 | 0.0015 | 2.12 |

The dry weight and nutrient uptake effects of the fertilizer type and/or nutritional supplementation are presented in Table 8. Generally, the order of treatments for dry weight and nutrient uptake was as follows: domestic fertilizers $\geq$ chemical fertilizer $\geq$ imported fertilizers > control. Conversely, the effect of the domestic V4 treatment was not significantly greater than that of the corresponding control. With a single application (N-fertilizer), there was no significant difference in the dry weight among the domestic V6 and VC treatments and chemical fertilizer. In treatments with additional P and K (N-fertilizer + P, K), the dry weight was significantly greater for half of the domestic treatments (V2, V5, V6, and VC) than that of the corresponding chemical fertilizer. There was no significant difference in dry weight among treatments using the remaining domestic products, imported products, and chemical fertilizers.

The measurement of N uptake by plants and N stored in soil enabled us to estimate N leaching. A single application of chemical fertilizers and most domestic "organic fertilizers" resulted in significantly higher N leaching from soil than that by the application of imported products. The positive correlation between N leaching, and the ratio of inorganic N to total N in the applied fertilizers is illustrated in Figure 6 (r = 0.77, $p < 0.01$).

**Table 8.** Dry weight and nutrient uptake of treatments.

| Treatment | N-Fertilizer | | | | | | N-Fertilizer + P, K | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Weight (g m$^{-2}$) | | Uptake (mg kg$^{-1}$) | | | | Dry Weight (g m$^{-2}$) | | Uptake (mg kg$^{-1}$) | | | |
| | | | N | | P | | | | N | | P | |
| V1 | 41.83 | ab | 2.60 | b | 0.03 | ab | 52.33 | ab | 2.64 | ab | 0.04 | ab |
| V2 | 161.67 | c | 3.70 | bc | 0.13 | c | 174.83 | b | 5.33 | b | 0.11 | b |
| V3 | 77.33 | ab | 4.61 | c | 0.21 | d | 86.17 | ab | 4.81 | b | 0.04 | ab |
| V4 | 7.67 | a | 0.17 | a | 0.01 | a | 12.50 | a | 0.52 | a | 0.02 | a |
| V5 | 37.50 | ab | 2.29 | b | 0.06 | b | 109.67 | b | 4.37 | b | 0.08 | ab |
| V6 | 106.75 | b | 0.96 | ab | 0.07 | b | 191.50 | b | 4.44 | b | 0.11 | b |
| VC | 81.00 | b | 3.99 | bc | 0.09 | b | 119.17 | b | 5.15 | b | 0.06 | ab |
| I1 | 24.83 | ab | 0.26 | a | 0.02 | ab | 69.50 | ab | 0.80 | a | 0.04 | ab |
| I2 | 30.33 | ab | 0.37 | ab | 0.03 | ab | 69.67 | ab | 1.07 | ab | 0.05 | ab |
| Chemical | 69.83 | ab | 1.63 | ab | 0.05 | ab | 71.83 | ab | 2.29 | ab | 0.05 | ab |
| Control | 9.50 | a | 0.07 | a | 0.01 | a | | | | | | |

Different letters within a column indicate difference among treatments at the 0.05 level.

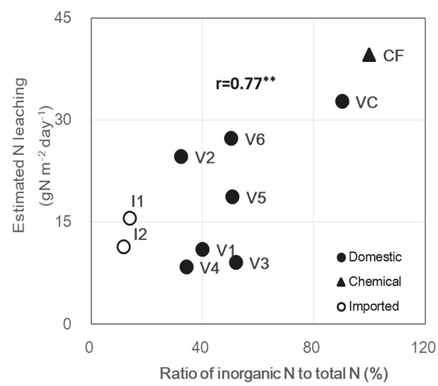


**Figure 6.** Correlation between N leaching and ratio of inorganic N to total N in the applied fertilizers. **, significant at $p < 0.01$.

It has been reported that the majority of N in manure or compost is in the organic form that must first become mineralized before plants can uptake it, or it becomes susceptible to loss by leaching. Only a small fraction (3.5%) of their total N was mineralized within the growing season, resulting in the lowly met N requirement of crops. Compost is often reported to be less effective in supplying available N to plant during the first year of application compared to inorganic mineral fertilizer [28,31,32]. Organic fertilizers have been commonly applied to the soil to increase soil fertility and minimize N leaching. The application did not increase the loss of N through leaching compared with controls, and the compost provided advantages over mineral fertilizers from a water quality perspective [16–20].

However, the so-called organic fertilizers collected in our study showed the opposite effect. Our study ranked dry weight and nutrient uptake as follows: domestic "organic fertilizers" $\geq$ chemical fertilizers $\geq$ imported organic fertilizers > control. In addition, a single application of either chemical fertilizers or most domestic "organic fertilizers" resulted in significantly greater N leaching from the soil than that by the application of imported products. This indicates clearly that in poor-quality sandy soils, the application of chemical fertilizers or "fake" organic fertilizers should be considered a significant threat to groundwater (from excessive N leaching). The high leaching rate can be attributed to the high proportion of inorganic N to total N in the applied fertilizers. Figure 7 illustrates the relationship between dry weight and N leaching under a single application of the fertilizers. The application of chemical fertilizer and domestic "organic fertilizers" V2, V6, and VC resulted in an increase in both dry weight and N leaching, which was probably because of the high ratio of inorganic N to total N in these fertilizers. The application of imported fertilizers (I1 and I2) resulted in a lower dry weight of plants, but reduced N leaching. The poor crop response to the fertilizer, V4, and low level of N leaching from the soil in this treatment indicate N immobilization.

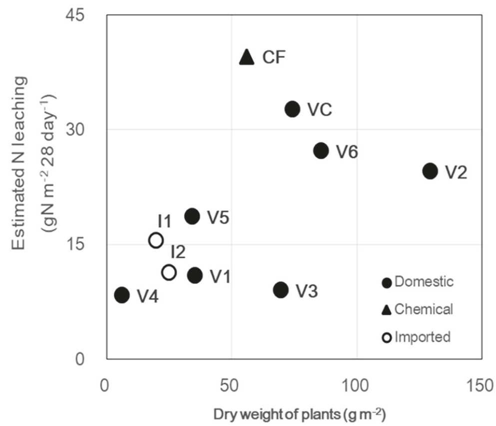


**Figure 7.** Relationship between dry weight of plants and N leaching under single application of the fertilizers.

Finally, the effect of domestic "organic fertilizers" on crop yield was not in accordance with their price, which might be decided by the adjustment of the N and P content of the fertilizers. V6, V2, and VC were categorized as lower priced, and had lower concentrations of total N and total P, but their application was effective on plant growth. Meanwhile, V4 was the most expensive domestic "organic fertilizer", with higher concentrations of total N and total P, but was not effective on plant growth.

## 4. Conclusions and Implications

Various fertilizers labeled as "organic fertilizer" are sold in Vietnam's markets; however, with their manufacture being poorly regulated, their quality has not yet been fully explored. Our study clarified the nutrient composition of these fertilizers and elucidated their effects on plant growth and leaching loss of N from soil. Domestic products greatly varied in nutrient contents, and most of them contained a noticeably high proportion of inorganic N. In poor-quality sandy soil, the application of these fertilizers constituted a threat to groundwater quality because of N leaching. To clearly explain the marked difference in "organic fertilizers", we investigated the production of a typical "organic fertilizer". This helped to confirm that the addition of chemical materials is typically the final step in the production process for organic waste-based compost. No regulations on raw materials and the manufacturing of organic fertilizer, and an insufficient understanding of organic waste-based fertilizers are considered to be the main reasons for this situation.

These findings pose two important recommendations. First, it is necessary to build quality criteria guidelines for organic fertilizers in Vietnam. In developed countries, the criteria usually not only include nutrient levels and properties of compost, but also thresholds for pathogens and heavy metals. The operators of composting sites are cautious about accepting feed materials for composting process that will ensure that the finished compost product will meet requirements. They also give indicators to assess compost maturity level [33]. Second, the following issues regarding compost need to be evaluated and farmers, organic fertilizer companies, and related managers should be cautioned. N and P are the most controlled factors of plant growth, but the quality of compost does not depend on only their content. The addition of chemical substances to enhance the nutrient content in commercial products of so-called organic fertilizers needs to be considered because of both agronomic effectiveness and environmental aspects. Application of immature compost fixes N in the soil and restricts plant growth, and thus, compost must be mature before applying.

Our research provides useful information on the status of so-called organic fertilizers in Vietnam's markets. However, the work has a number of limitations that need to be addressed by further study. Firstly, the collected sample quantity should be greater. Secondly, investigation of the flow of raw materials and production method of compost must be taken into account in various products that were made from different materials. Finally, in order to fully evaluate the effects of "organic fertilizers" on plant growth and nutrient leaching, more cultivation experiments need to be conducted.

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MDPI

*Article*

# Model Prediction of Secondary Soil Salinization in the Keriya Oasis, Northwest China

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**Abstract:** Significant anthropogenic and biophysical changes have caused fluctuations in the soil salinization area of the Keriya Oasis in China. The Driver-Pressure-State-Impact-Response (DPSIR) sustainability framework and Bayesian networks (BNs) were used to integrate information from anthropogenic and natural systems to model the trend of secondary soil salinization. The developed model predicted that light salinization (vegetation coverage of around 15–20%, soil salt 5–10 g/kg) of the ecotone will increase in the near term but decelerate slightly in the future, and that farmland salinization will decrease in the near term. This trend is expected to accelerate in the future. Both trends are attributed to decreased water logging, increased groundwater exploitation, and decreased ratio of evaporation/precipitation. In contrast, severe salinization (vegetation coverage of around 2%, soil salt $\geq$20 g/kg) of the ecotone will increase in the near term. This trend will accelerate in the future because decreased river flow will reduce the flushing of severely salinized soil crust. Anthropogenic factors have negative impacts and natural causes have positive impacts on light salinization of ecotones. In situations involving severe farmland salinization, anthropogenic factors have persistent negative impacts.

**Keywords:** arid oasis; combination of modern and indigenous knowledge; Driver-Pressure-State-Impact-Response sustainability framework; bayesian network

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## 1. Introduction

Secondary soil salinization occurs in non-salinized soil in arid and semi-arid areas when salt accumulates on surface. This is often a consequence of excessive irrigation or other agricultural activities which promote groundwater salinity moving along the soil capillary pores to the surface [1]. Secondary salinization differs from primary salinization. It arises through natural processes including physical or chemical weathering, transport from parent material, geological deposits, and groundwater [2]. Secondary salinization can occur when groundwater tables rise and by the replacement of native vegetation with shallow rooted crops. Excessive irrigation combined with lack of adequate drainage for leaching and removal of salts can induce irrigation salinization [3–5].

Secondary soil salinization is a major threat to agricultural sustainability. It has negatively impacted both agricultural productivity and environmental quality and this is especially problematic in arid and semi-arid areas where evaporation exceeds precipitation [4,6]. The secondary soil salinization affects approximately 77 M ha globally, with 58% of this area being farmland. About 20% of all farmland is affected by salinization [7]. To meet world food demands in the future, more land will be converted to agriculture, thus expanding the area at the risk of secondary salinization [8].

The secondary salinization in the Keriya Oasis fluctuates. The salinized area was 1670 ha in 1991, 1554 ha in 2002, and 1833 ha in 2008. This resulted from the complex interaction of anthropogenic factors (population, land reclamation, economy and policies) and environmental factors such as temperature, evapotranspiration (ET), rainfall, landform, and floods [3,9–14]. The population of this area was 221,483 in 2003 a value 2.7 times the 1949 population. The farmland area has fluctuated (increased $1.55 \times 10^4$ ha in 1950–1961, decreased $0.46 \times 10^4$ ha in 1961–1964, increased $0.39 \times 10^4$ ha in 1964–1968, decreased $0.42 \times 10^4$ ha in 1968–1974, increased $0.14 \times 10^4$ ha in 1974–1979, decreased $0.67 \times 10^4$ ha in 1979–1990, and increase of $0.98 \times 10^4$ ha in 1990–2008) [15,16]. Farmland area is subjected to increasing population pressure and policy influence and also subjected to irrigation-caused salinization land abandonment. Excessive irrigation and water mismanagement also caused secondary salinization in ecotone areas. Irrigation seepage water or excessive surface water flow into the ecotone area by surface water system increased the water table in shallow depressions. "Ecotone" refers to desert-oasis areas typically located between an oasis in the lower reach of inland rivers and neighboring desert in arid regions (Figure 1A). Ecotones are interactive zones between irrigated farmland and the natural desert ecosystem [8]. The increasing flows of the Keriya River are prone to increase ecotone waterlogging by surface or underground water flow, elevate the groundwater table, and increase salinization [9,10,15–18]. Construction of the Pulu (Jiyin) water reservoir on the Keriya River may reduce the risk of waterlogging expansion by moderating the flow of the Keriya River. The anthropogenic impacts on salinization can therefore be either positive or negative [19] and proper control of the salinization issue in the future will be a challenge for sustainable management of land and water resources in the Oasis.

Under changing anthropogenic and environmental conditions, salinity prediction at the Keriya Oasis became increasingly complicated. To achieve more accurate estimation of secondary salinization, interdisciplinary and comprehensive research methods (in which the key anthropogenic and natural causes are considered) need to be developed. Previous studies on the soil salinization in the Oasis focused on either spatial-temporal changes of a few selected factors, or the interrelation of these factors in spatial and in short temporal scales. The factors included monitoring the salinization, spatial and temporal dynamics of soil salinization, land use land cover (LUCC) changes, dynamics relationships of salinity and groundwater, eco-water demand, and soil quality under different land use types [9,10,16–21]. These factors were insufficient for establishing a useful salinization prediction strategy. It is necessary to use long-term, multilevel measurements of anthropogenic and biophysical factors, because all factors interact and influence each other during the salinization process [11,12].

We conducted this study to improve understanding of the Keriya Oasis's secondary soil salinization trend. We sought to build variable sets for secondary soil salinization, and to test the combined use of DPSIR and BNs in prediction of soil salinization. Finally, we wanted to provide policy makers and researchers with information about the dynamic trends of secondary soil salinization.

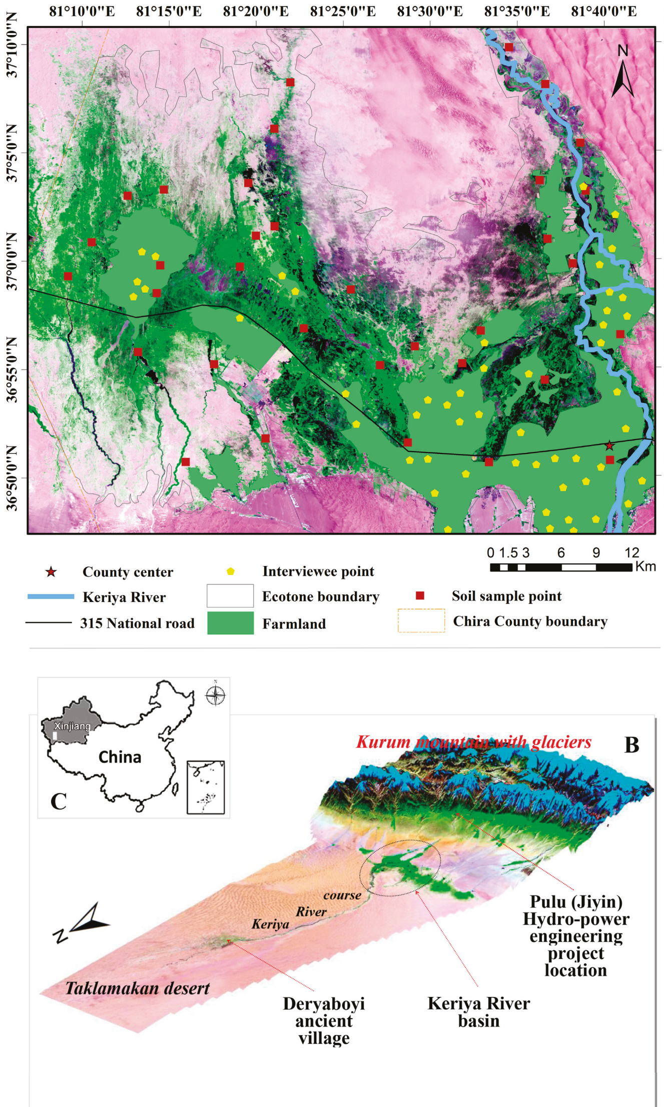


**Figure 1.** Topographic map of the sampling points of the study area (**A**); the Keriya Oasis (**B**); and the PRC and XUAR (**C**) [17].

## 2. Material and Methods

### 2.1. Study Area

The Keriya Oasis (81°08′59″–82°00′03″ E, 36°44′59″–37°12′04″ N) is a typical arid oasis. It is located at the northern foot of the Kurum (in Chine pinyin is Kunlun) Mountains along the southern edge of the Taklamakan Desert in the Xinjiang Uyghur Autonomous Region (XUAR) of northwestern China (Figure 1). It is characterized by extreme fragility with a dry climate. Average annual precipitation, evaporation, and temperature are 45 mm, 2600 mm, and 11.7 °C, respectively.

Water shortages and intensive soil salinization are the major threat to sustainable socio-ecological development, and ecosystem function and services [15,21–24].

Keriya Oasis is largely located on an alluvial plain. The human population is approximately 250,000 with agriculture providing most of the employment and income. The main crops are cotton, maize, wheat, rice, and grapes. Agriculture depends on water from the Keriya River, which is ultimately supplied by 430 glaciers in the Kurum Mountains [15]. After approximately 700 km of flow, the river disappears in the Derya Boyi ancient village [17,18]. Increasing population and economic development have driven the Oasis deep into the marginal ecotone frontier [25,26], Unsustainable planning of land and water resources in the Oasis has caused water shortages in some areas and caused soil salinization due to excessive water logging.

### 2.2. Data Sources

Simulation model data (Table 1) were extracted from the Keriya (Yutian) County annals, publications, the officially classified statistical report of Keriya County, and stakeholder opinions [13]. Supplemental data was obtained from field work (Figure A2).

To collect stakeholder opinions (experience-based knowledge), we used semi-structured questionnaires during group discussions. This technique fully extracts useful information and also verifies and corrects information from the group discussion [27]. Authors organized volunteer assistants (students from the Keriya Oasis) for effective interviewing. During February 2016, the authors randomly visited 354 male farmers (men are traditionally responsible for farm work in this area) from around the Keriya Oasis (Figure A1). All of the farmers had at least a primary education. Farmer ages were >60 years (23%), 40–60 years (56%), and <40 years (21%). A total of 51 interview meetings were conducted, each with 6–9 attendees.

The main questions presented to discussion groups were:
How is the change in irrigation water quantity during 1950–2010s?
How is the Oasis's soil salinization trend during 1950–2010s?

According to the stakeholder information given, additional questions were asked for reasons, choices and trend of each event by changing the condition of the parent factor. The steps and routines of collecting stakeholder opinions are illustrated in Figure 2.

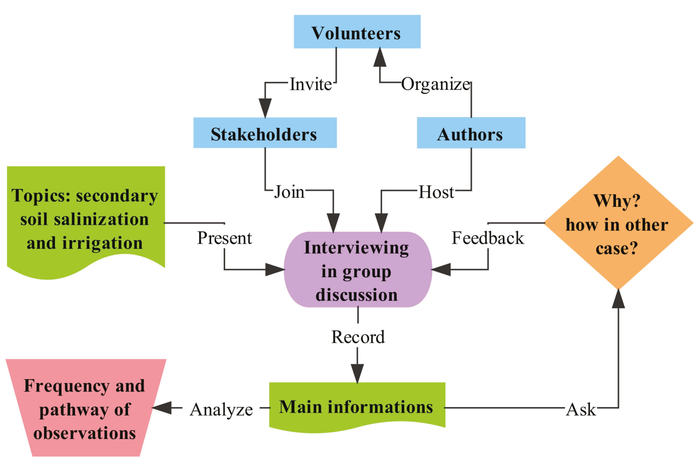


**Figure 2.** Diagram of the consultation of stakeholder's in order to carry out surveys on indigenous secondary soil salinization knowledge.

**Table 1.** Data sources for the variables of the Keriya Oasis simulation model.

| Variables | | Indicators | Data Type | Source | Temporal Coverage |
|---|---|---|---|---|---|
| Drivers | Global warming | Decennary average air temperature (°C) | Time-series | [28] | 1960–2007 [a] |
| | Population growth | Yearly population density of entire county (person/km$^2$) | Time-series | [29,30] | 1950–2014 |
| | Economic growth | Yearly per capita GDP (¥) | Time-series | [29,30] | 1950–2014 |
| | Steady policy force | The ratios of environmental policy number of sustainability to anti-sustainability (%) | Time-series | [31] | 1960–2015 [a] |
| | Flash flooding | Flash flooding (termed "Sel" in Uyghur) usually occurs due to heavy rain in the mountains, is always fast-moving, unexpected, and destructive to roads and fields in some areas. Generally, it leads to bed elevation of drainage ditches, and decreases land slope by depositing mud sedimentation in low areas during its path while creating natural large drainage channels at relatively higher elevated areas during its path by eroding the soil surface | Stakeholder's opinion | Consultation | – |
| Pressures | Surface water quantity | Yearly runoff ($10^8$ m$^3$), measured at the main dike | Time-series | [29,30] | 1957–2014 |
| | ET/precipitation | Yearly quantity of potential evapotranspiration (mm)/Yearly rainfall (mm) | Time-series | [27], MBK [b] | 1961–2012 |
| | Surface water extraction | Sum of the yearly irrigation quantity, extracted from river, reservoir and spring water ($10^4$ m$^3$) | Time-series | [29,30] | 1950–2014 |
| | Land claim | Yearly irrigated area (ha) | Time-series | [29,30] | 1949–2014 |
| | Irrigation water quantity | Traditional flood irrigation frequency (times/year), and normal yearly water consumption is 350 m$^3$, fields are divided into 0.5/0.25 mu, and follows the strict priority along the water channel during irrigation | Stakeholder's opinion | Consultation | – |
| | Farm groundwater exploitation | Yearly exploitation quantity of farmland groundwater ($10^4$ m$^3$) | Time-series | [29,30] | 1978–2014 |
| | Ecotone water logging | RS data of water body area (including wetland area, lake area and reservoir) (ha) | Time-series | [10] | 1976–2011 [a] |
| | Ecotone drainage | Drainage functions and completeness of river course (drainage is one river dual function in the area, due to river seasonality and low elevation), natural drainage ditches (created by flash floods) and natural pits (termed "Dashliq" in Uyghur, means pits with reddish salty water) | Stakeholder's opinion | Consultation | – |
| | Farmland drainage | Drainage functions and completeness of artificial drainage and natural drainage ditches | | | |
| | Farmland tree plantation | Whether fruit-crop is inter-planted | | | |
| States | Farmland salinization | Changes of salt affected cultivated land (ha) were determined by field symptoms: field is relatively wet, but crop withers easily; and field has a shallow groundwater table, but requires regularly irrigation. Under the maximum degree of salt impact, fields would become entirely dead if they lose only one year of irrigation chance | Stakeholder's opinion | Consultation | – |
| | Ecotone light salinization | Remote sensing data of lightly salinized area (ha) | | | 1976–2011 [a] |
| | Ecotone moderate salinization | Remote sensing data of moderate salinized area (ha) | Time-series | [9,10,32] [c] | 1976–2011 [a] |
| | Ecotone severe salinization | Remote sensing data of severely salinized area (ha) | | | 1976–2011 [a] |

Note: [a] Incomplete data serious; [b] Meteorological Bureau of Keriya County; [c] Bold font–main source and others supporting source for ecotone salinization.

To verify the spatial distribution of soil salinization and evaluate its geological and ecological causes a field survey was conducted in May 2015 (Figure A2). A total of 35 soil samples were collected at six profiles (0.0–0.1 m, 0.1–0.2 m, 0.2–0.4 m, 0.4–0.6 m, 0.6–0.8 m, and 0.8–1.0 m depth). Electrical conductivity (EC) was measured using a Hydra probe II for verification of laboratory measurements. The total soluble salt content (g/kg) was calculated using a regression equation previously established between EC and total soluble salt [17].

### *2.3. Modeling Approach*

#### 2.3.1. Modeling Tool

For prediction of secondary soil salinization in the Oasis, the Driver-Pressure-State (DPS) portions of Driver-Pressure-State-Impact-Response (DPSIR) sustainability framework and Bayesian networks (BNs) were combined to construct the research models.

The DPSIR is a framework addressing the needs of environmental data presenting and assessment, and it refines the environmental data. This is a conceptual model of the relationship between the constituent systems of the socio-ecological system. It does not directly model the environment. Because DPSIR shows over simplification and confusion linked to the classification it may fail to indicate how the workings of this sector lie embedded within those of other sectors in real multi-level situation of problems [33], but this defect can be improved in combination with other evaluation tools as BNs [34]. The DPSIR framework provides a systematic mechanism for selecting and structuring indicators [35–37]. Therefore, the framework has often been applied in impact assessment studies [34,38–43], and the employment in soil salinization includes assessing secondary soil salinization risks [12].

Bayesian modeling is applicable for prediction, risk analysis, diagnosis, monitoring, reliability, and dependency [44] and it can act as a decision support system in government [45–48]. A Bayesian Network (BN) was developed to analyze the probabilistic causal relationship between the DPS components and actualize the study models. The BN uses probability theory as a measure of uncertainty [34]. Each BN consists of a series of nodes (variables) joined by a probabilistic causal relationship, which are represented as connecting arcs. Each variable has one to several associated probability distributions. The probability distributions quantify to how much each variable is related to its parent variable, and they use the information of prior events to predict future events [49]. Thus, changes in the probability distribution of upstream variables cascade through the model, and are reflected downstream. BNs act as a common metric, allowing the integration of various types of information (e.g., quantitative, qualitative, and numerical) from the sociological, ecological and environmental systems, featured predictive ability (i.e., quantify the probability of the results of the investigation, rather than as a general method of decision, or complete belief in the findings), and clarity in cause and effect chains. The network can be modified and updated when new data are added, and it does not require specific understanding of the complex systems [34]. The BN also has shortcomings because it requires more data for solving complex problems. Therefore unavailable data must be incorporated using subjective probability. However the BNs are useful tools for modeling multi-faceted processes and may be utilized to increase informed prediction making [23], [46,50–52]. BN application in soil salinization includes assessing the ecological impacts of salinity management [23]. There is a BN software package, Netica TM (version 5.24) for model development, available at http://www.norsys.com/. Netica calculates binary pair-wise correlations of all possible combinations of linked variables based on the Lauritzen-Spiegelhalter algorithm [53].

#### 2.3.2. Model Development

The preliminary model of the Keriya Oasis's secondary soil salinization was constructed by a BN conceptual model of dryland salinity management in the Little River Catchment [15]. This framework incorporated 20 variables from ecological, physical, economic, and social aspects of the salinity problem with no conditional probability table. It needed improvement for use in the Keriya Oasis, so the initial BN was refined and improved by an integrative iterative process of reviewing existing literature and interviewing stakeholders.

The key variables in this integrated prediction of the state of secondary soil salinization problem can be classified as driver variables, pressure variables, and state variable using the DPS framework. The drivers were those with broader coverage of impacts to the environment. They were naturally occurring or externally induced changes in the environmental processes and structures of ecological systems and/or the functions. The pressures were all releases or abstractions by human activities of substances and other natural disturbances. The states were the totality of ecosystem services, conditions and vulnerabilities to pressures in a certain area [38]. Identification of variable indicators for each component of the DPS framework depended on notions of DPS, but also considered the study scale. Since, the study scale is important for determining the category of variable indicators, such as the population growth, it can be categorized in the driver group in scale of the entire Keriya County (Oasis). This is because population growth can increase environmental pressure (such as needs for farmland expansion). However, in the context of village scale for a County, population growth belongs to the state group, since the population density pattern between villages were subjected to the constant influence of environmental resources. Therefore, it can provide a better reflection of environmental states compared to drivers. This study was performed at the level of the entire Keriya County.

However, there are no perfect indicator sets that apply to all regions [37]. During variable selection for the DPS component, the principles of policy relevance, representativeness, temporal dataset length, "understandable", and ready availability were referenced as well [37,54]. The pathways of interlinking between the variables were prioritized by perceived importance, finally resulting in a refined simulation model by certain steps (Figure 3). The actual BN model requires the construction of a conditional probability table (CPT), which presents the strengths of links in the BN graph, applied to quantify the probability distribution of a variable, based on Bayesian theorem [55,56]. This is described below (Equation (1)):

$$p(\alpha|\beta) = \frac{p(\beta|\alpha)p(\alpha)}{p(\beta)} \tag{1}$$

where $p(\alpha)$ and $p(\beta)$ are the probabilities of observing α and β without mutual consideration; $p(\alpha \mid \beta)$ is the conditional probability of α, given β; $p(\beta \mid \alpha)$ is the conditional probability of $\beta$, given $\alpha$; and $p(\beta \mid \alpha)/p(\beta)$ is the Bayesian factor or likelihood ratio.

### 2.3.3. Variable Indicators and Proxies

For selection of appropriate indicators to populate each Driver, Pressure, and State variable in the simulation model, we reviewed previously published literature about soil salinization related to sociological, ecological and environmental systems [11,12,57,58]. This provided major variable sources for the model. Other studies [8,36,46,52,59–65] supplied important information for variable selection and pathway determination. When data were unavailable, proxy datasets were identified. For example, the long time–series measuring data of the groundwater table were unavailable, but it was possible to construct a substitute time–series data of water body area (water logging) which could reflect the groundwater table fluctuations [66,67]. Measured time–series data were unavailable so stakeholder suggestions provided supplemental sources of knowledge [13,52] for choosing variables, determining the pathway, and calculating the CPTs. For example, flash floods, irrigation quantity, farmland drainage, ecotone drainage, and farmland salinization were handled in this way.

Finally, nineteen proper indicators were selected (Table 1) to populate each DPS component in the refined simulation model mapped through BNs (Figures 4 and 5). To enable full consideration of different anthropogenic and natural causes related to the Oasis's secondary soil salinization, different approaches were required. Drainage and secondary soil salinization were featured by typology: the drainage was separated into farmland drainage and ecotone drainage. Secondary soil salinization was separated into farmland salinization (qualitative data from interviews were available only) and ecotone salinization, which was studied at light, moderate (vegetation coverage of around 8%, soil salt 10–20 g/kg) and severe salinization degrees. The surface water extraction was considered by an integrated approach. It included three water types (i.e., river water, reservoir water, and spring water), because during irrigation activity, it is not possible to determine the impact of each water extraction type on farmland groundwater exploitation and irrigation water quantity. The integration approach also simplifies the BN structure.

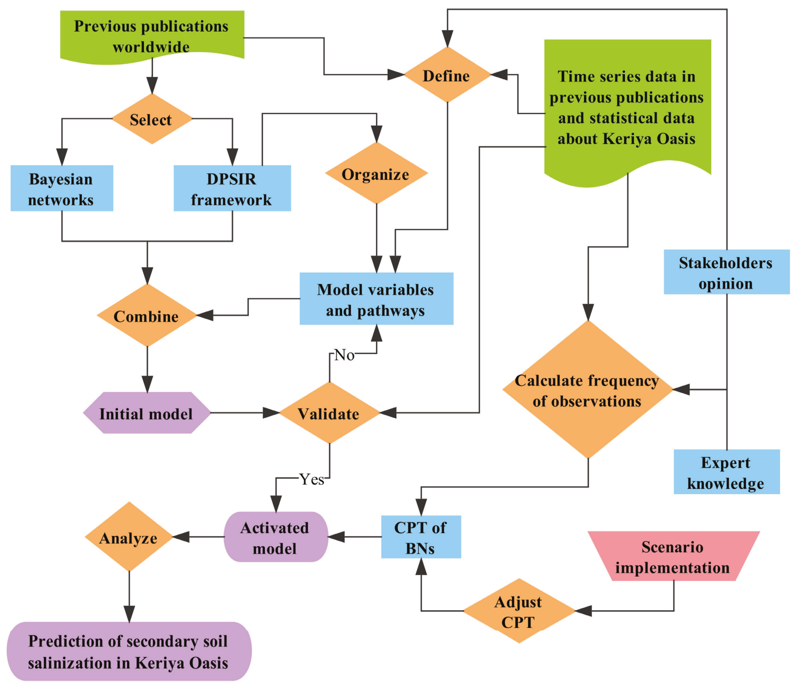


**Figure 3.** Diagram of the modeling approach for the secondary soil salinization in the Keriya Oasis.

2.3.4. Probability Distribution Thresholds

Each variable indicator was assigned a number of probability distributions and most of the variables had two probability distributions (such as, 'increase' and 'decrease' or 'enhancing' and 'subsiding'. As the number of possible probability distributions (calculated by the frequency of observations) was constrained by the short time series available, thresholds between these probability distributions were determined by one of two methods.

(1) The median value was considered the most appropriate threshold for natural variable, since, natural phenomena existed in the past, the initial value is uncertain for a short time intervals, therefore the median value was used. The median value refers to the value in the median position of data series. For example, 3 is the median value for the date series of 1, 2, 3, 4, 5. This allows the greatest possible overlap between linked datasets. The global warming, evapotranspiration/precipitation, surface water quantity, ecotone water logging, ecotone light salinization, ecotone moderate salinization, and ecotone severe salinization datasets were assigned threshold values in this way [34].

(2) When a threshold was known, it was used [34,35]. Anthropogenic events such as population growth, economic growth, policy force, surface water extraction, farmland reclamation,

and groundwater exploitation have known initial values, so a previous value in the data series was used as the threshold for the following data value.

#### 2.3.5. Conditional Probability Table

To achieve the massive data requirements for CPT in BNs modeling is difficult. Lack of data in environmental modeling is a common challenge [34]. All decisions should be based on evidence, but the best decisions are also based on previous knowledge. This is the case in BNs where the Bayesian's rule provides a rigorous method for achieving this [68].

The construction of a CPT is the key step of BNs modeling and providing a platform for BNs formulation. In our study, the CPT data sources were from a statistical book, literature results, stakeholder knowledge [13], and expert knowledge. Subjective estimates can be made with the help of expert knowledge combined with experience [55,68] The experts were informed that time series were lacking for certain data (Table 1) and asked to produce their best estimates for those cases. The probability that a node (variable) will be in each possible state, given its parent states, can be calculated based on the frequency observed in a set of training data by using machine learning methods [69–71]. The observation frequency of A, given B is described as (Equation (2)):

$$A_{frequency} = (A_{quantity}) \div (A_{quantity} + B_{quantity}) \quad (2)$$

### *2.4. Model Validation*

A testing process is essential for validating results of the model.

We used the leave–one–out cross validation technique [34,72] to estimate model performance due to the lack of data. This technique allows all of the available data to be used in model training and also avoids bias in error rates that can happen when datasets are split into training and testing. The model was trained with all datasets, bar 1 year, which was tested against and repeated for every year in turn using the complete datasets from 1950–2015. The testing can be performed easily in Microsoft Excel 2013 [73]. This study used a linear model (linear model shows higher goodness of fit than the index model, logarithmic model, or exponential model) such as (Equation (3)):

$$= INDEX(LINEST(Bn : Bm, An : Am), 1) * A2 + INDEX(LINEST(Bn : Bm, An : Am), 2) \quad (3)$$

where $n$ and $m$ refer to the initial and end of a column in Excel work sheet. For an incomplete dataset, average values were calculated from its pair for temporal coordination. The cumulative error rate was calculated to estimate model performance. Some variables (e.g., flash flooding, irrigation water quantity, farmland tree plantation, farmland salinization, farmland drainage and ecotone drainage) that were based on stakeholder's opinions could not be validated in this way, since there were no time–series data to validate.

### *2.5. Model Prediction*

The near term BNs model (Figure 4) predicts the state of the secondary soil salinization trend using current predictions (i.e., expectations in demographic, economic and climatic terms, based on all available predictive information (Table 1). However, the probability distribution of surface water quantity and global warming may change in future predictions compared to the near term model. This is because construction of the Pulu reservoir in the upper Keriya River will stabilize the River flow (surface water quantity), but the stabilized surface water quantity will require time to produce a decrease in salinization due to ecological hysteresis [74,75].

The Pulu reservoir will be completed in the 2020s, but ecological hysteresis could delay the influence of the reservoir on salinization changes. This was also the opinion of stakeholders who observed limited reservoir construction and its impacts on salinity from 1970s to 2010s during the study. They estimated that it would take approximately 10 years for the Pulu Reservoir to impact ecotone soil salinization. Hence the term "recent" indicates an approximate decade long time period and the term "future" refers to a time period exceeding one decade.

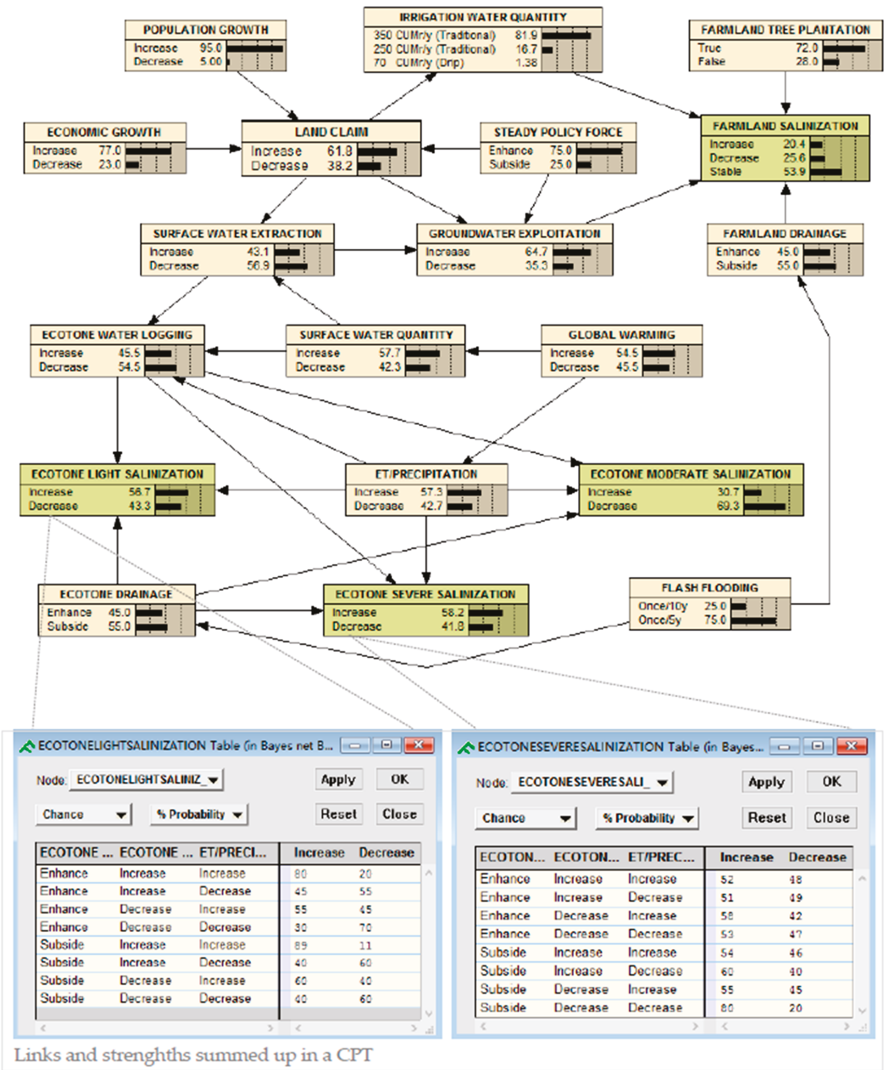


**Figure 4.** Model structure of the Bayesian belief network of the Keriya Oasis for near term prediction. The State variables are colored in yellowish green, and the Driver and Pressure variables are colored in reddish brown. Full details of the indicators for each variable and supporting data are given in Table 1.

The global warming model simulation shows the global average temperature increasing from 16.32 °C in 2010 to 20.16 °C in the future [76]. The increase in air temperature may be more prominent in arid regions. Glacial melting will accelerate under the influence of warmer air temperatures, therefore, the runoff of the Keriya River is expected to increase. We assumed that which will be offset by the Pulu dam. But warming air temperatures might also change the evapotranspiration/pre-cipitation ratio by thermodynamic and humidity factors [26,77–79]. Therefore, the probability distribution of global warming is expected to change in the future (>10 years) rather than near term (10 years<) for prediction of Oasis salinity (Figure 5).

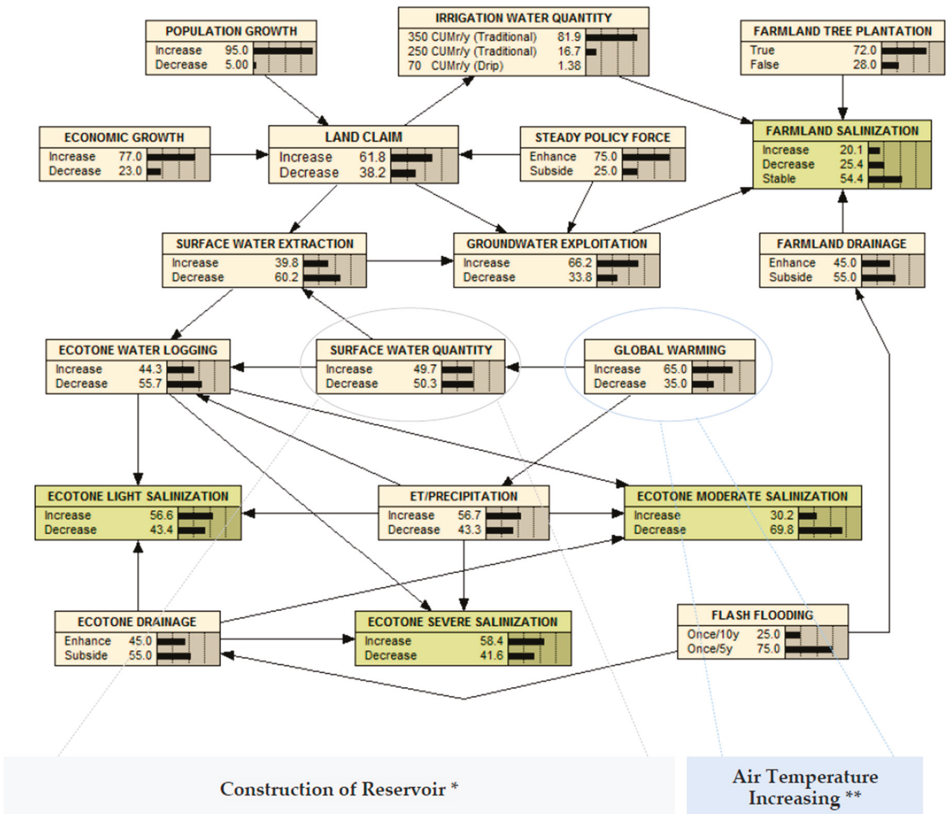


**Figure 5.** Model structure of the Bayesian belief network of the Keriya Oasis for future prediction. The State variables are colored in yellowish green, and the Driver and Pressure variables are colored in reddish brown. Full details of the indicators for each variable and supporting data are given in Table 1. * Pulu Water Conservancy and Hydropower Engineering project located at a tributary of the Keriya River (81°xx′ E, 36°xx′ N) at the upper reaches of Keriya main dike (Figure 1B); the catchment area above the dam site is 6375 km$^2$, the dam height and length are 124.9 m and 594 m, respectively. The storage capacity is approximately 0.82 × 108 m$^3$ and is able to irrigate the 47,176.91 ha farmland, including 1334 ha of newly claimed land, it belonging to the second class of engineering in the PRC. Available via DIALOG http://www.xjslt.gov.cn/. The water harvesting dam (Pulu Reservoir) reduces 2–30% of river runoff and stabilizes [80], so we assigned nearby unconditional state for surface water quantity by adjusting CPT manually. ** According to current data of air temperature of the central Asian area, we assumed that the global warming may be in probability distribution of 65% increase and 35% decrease [26,77–79,81].

## 3. Results

### 3.1. Model Validation

The sensitivity analysis (Table 2) performed for each chain of nodes and the leave–one–out cross validation exercise results indicated that the model was able to predict the state of many variable chains (i.e., a, b, f, h, k, m, and n) with an acceptable error rate (<20%). This result the utility of the datasets which were constructed from different sources. These data represented the best available knowledge of the Oasis. However, some other variable chains (i.e., c, d, g, i, l, p and r) had relatively poor predictability and were associated with relatively higher error rates (20–40%). These error rates may be related to the relatively low number of recorded datasets. Some variable chains (i.e., e, j, o, and q) proved harder to predict and were associated with a high error rate (>40%). These need additional investigation.

**Table 2.** Results of the leave–one–out cross validation exercise (performed using data from 1949 to 2014). Not all datasets are complete across this range so the number of tests on each variable chain is provided.

| No | Cause-Effect Variable Chain | Error Rate (%) | Number of Tests |
|---|---|---|---|
| a | Economic growth—Land claim | 10.39 | 54 |
| b | Population growth—Land claim | 12.60 | 54 |
| c | Land claim—Farm groundwater exploitation | 36.29 | 37 |
| d | Land claim—Surface water extraction | 22.33 | 37 |
| e | Surface water extraction—Farm groundwater exploitation | 60.55 | 37 |
| f | Global warming—Surface water quantity | 16.16 | 6 |
| g | Surface water quantity—Surface water extraction | 25.52 | 37 |
| h | Surface water quantity—Ecotone water logging | 19.70 | 4 |
| i | Surface water extraction—Ecotone water logging | 35.00 | 4 |
| j | Farm groundwater exploitation—Ecotone water logging | 44.47 | 4 |
| k | Ecotone water logging—Ecotone soil light salinization | 5.01 | 4 |
| l | Ecotone water logging—Ecotone soil moderate salinization | 29.77 | 4 |
| m | Ecotone water logging—Ecotone soil severe salinization | 18.65 | 4 |
| n | ET/precipitation—Ecotone soil light salinization | 2.97 | 4 |
| o | ET/precipitation—Ecotone soil moderate salinization | 75.64 | 4 |
| p | ET/precipitation—Ecotone soil severe salinization | 35.12 | 4 |
| q | ET/precipitation—Ecotone water logging | 55.89 | 4 |
| r | Global warming—ET/precipitation | 29.5 | 6 |

The lack of historic time-series data and short time-series data is a common problem in complex system modeling. Other limitations include ignoring the influence of groundwater exploitation on ecotone salinization because groundwater exploitation only stands at approximately 4% of its capacity [15]. Also, the reciprocal influence between decreasing water quantity and increasing evapotranspiration/precipitation on the soil salinization is uncertain. However, our knowledge of the cause-effect links of the Oasis's complex system was revealed in model validation.

### *3.2. Model Prediction*

We produced BNs to learn the impact of factors on the secondary soil salinization in the Keriya Oasis, northwest China (Figures 4 and 5). The software yielded a total of 274 conditional probabilities among 19 nodes and 28 links in the BNs.

#### 3.2.1. Prediction of Farmland Salinization

The modeling results (Figures 4 and 5) indicated that, in the near term, the probabilities of farmland salinization increasing, decreasing and stabilizing were 20.4%, 25.6% and 53.9%, respectively. In the future, the probabilities of farmland salinization increasing, decreasing and stabilizing were 20.1%, 25.4% and 54.4%, respectively. This means that a decreased trend of farmland salinization is expected in the near term and this trend will accelerate in the future due to a decreasing groundwater table which is attributed to water shortages caused by increasing amounts of farmland and building an upstream water reservoir. The reservoir will reduce the water quantity that enters into the Oasis [82]. This will increase water deficiency. Regarding water shortages and expanding farmland area, there will be increased, but limited, exploitation of groundwater (limited due to restrictions on pumping) [83,84], Water withdrawals enhance the salt leaching condition of farmland by decreasing the groundwater table. Furthermore, fruit trees (crop-fruit mixes), agriculture also reduces the pressure of evapotranspiration on farmland salinization. Therefore, decreased trend of farmland salinization was expected.

#### 3.2.2. Prediction of Ecotone Light Salinization

In the near term, the probability of light salinization increase or decrease were 56.7% and 43.3%, respectively (Figure 4). In the future, the probability of light salinization increase or decrease was estimated to be 56.6% and 43.4%, respectively (Figure 5). This predicts that, in the near term, an increasing trend of light salinization is expected. In the future, this trend is expected to decelerate a little. This is attributed to decreasing ecotone water logging [85]. The increasing groundwater exploitation and decreased surface water quantity achieved by the Pulu reservoir will lower the risk of ecotone water logging. In the future, accelerated global warming may also decrease the evapotranspiration/precipitation in the area. We observed that the significant decrease in ecotone water logging between 1977 and 1999 caused a slight decrease in light salinization, but the increase in the 2000s caused a larger expansion in light salinization. These fluctuating correlations of light salinization and water logging are related to characteristics of spatial distribution of light salinization such as wide range (Figure A2), relatively flat and closed terrain geomorphology [10,17], but also responded to the increased runoff and increased ratio of evapotranspiration/precipitation in the near term (Figure A1c–e) and to flash flood induced drainage subsiding conditions. Therefore, the light salinization predictions show weak reversibility but indicate that changes are likely to occur.

#### 3.2.3. Prediction of Ecotone Moderate Salinization

The model results indicate that the near term probabilities of moderate salinization increase or decrease were 30.7% and 69.3%, respectively (Figure 4). In the future, the probabilities of increase or decrease of moderate salinization are 30.2% and 69.8%, respectively (Figure 5). This predicts that, the moderate salinization is expected to decrease substantially in the near term, and this decreasing trend will accelerate a little in the future which is likely caused by intensive land reclamation. This is confirmed by the close match between the abrupt decrease of moderate salinization and the large increase of farmland (Figure A1b,e), showing the land reclamation playing a main role in decreasing moderate salinization. This is also supported by stakeholders who noted that the Oasis experienced land reclamation from 1990–2000 at the edge of and inside the Oasis (areas that were once salinized by salt drainage activities from previous farmland in adjacent areas). Therefore, according to the requirement for farmland expansion and the same principle as light salinization, the moderate salinization was expected to decrease.

#### 3.2.4. Prediction of Ecotone Severe Salinization

In the near term, the probabilities of severe salinization increase or decrease were estimated at 58.2% and 41.8%, respectively (Figure 4). In the future, the probability of severe salinization increase or decrease are estimated to be 58.4% and 41.6%, respectively (Figure 5). Severe salinization is therefore expected to increase in the near term and it will slightly accelerate in the future. The estimates for severe salinization are mainly related to geographical location. Severe salinized areas were mainly located in very flat and pit areas, such as the lower reaches of river banks and end parts of natural drainage channels (Figure A2) [10,17], where there is sufficient underground seepage, a permanent shallow groundwater table, and a location far from the Oasis. These conditions made the severe salinized area less responsive to most of the disturbances from anthropogenic and natural systems, except for the floods. The stakeholders verified that floods can wash away the more severe salinized soil crust around the riverbank and floods are the only factor that can conquer severe salinization. Floods can also enhance the drainage condition of the river by sand transmission function. As demonstrated by the close correspondence between the significant runoff increase and delayed severe salinization increase after 1999 (Figure A1c,e), which means that increasing runoff produced certain opportunities for crust washing. But in the future, the decreased and stabilized runoff would eliminate the chance of crust washing completely, so an increasing expansion of severe salinization of the soil crust is expected.

## 4. Discussion

The Keriya Oasis is a typical fragile arid ecosystem, and it has experienced intensive anthropogenic and natural disturbances, which have led to changes in soil-water transport and fluctuations in salinization. The objective of this study was to understand the dynamics of secondary soil salinization and forecast future salinization trends given such anthropogenic and natural changes. The modeling results of coupled anthropogenic and natural impacts on the salinization indicates that the farmland salinization is expected to decrease in the near term and it will accelerate a little in the future; the ecotone light salinization is expected to increase in near term, and it will decelerate in the future; the ecotone severe salinization is expected to opposite with light. From this we conclude that anthropogenic factors play a negative role in both the farmland salinization and ecotone light salinization, but play a positive role in ecotone severe salinization. This result provides policy makers with informative guidelines for soil salinization management in the Oasis.

### *4.1. Combined Modeling of the DPSIR and BNs*

The combined modeling of the DPSIR and BNs has proven to be an effective method for using the different types of information for oasis environmental management. The DPSIR is a useful tool that provides researchers with a framework of selecting, integrating and organizing variables; this enables researchers to efficiently divide variable indicators amongst the complex environmental system, but we need to further study the relationship between each variable. The BNs serve as inter-linked networks that reasonably represent a relationship of variables that allow for efficient construction of models. To the authors' best knowledge, this study is the first model used to predict secondary soil salinization trends given the combined effects of anthropogenic and natural systems in the Keriya Oasis, Northwest China [86] (Table 3).

**Table 3.** Properties of the related issues of BNs models and DPSRI framework compared with the presented model.

| Issue | Scale | Data Types | Scenario | Validation | Approach | Reference |
|---|---|---|---|---|---|---|
| Secondary soil salinization trend | Keriya Oasis, NW China | Time–series, Stakeholder opinion, | No | Yes | BNs, DPSIR | This study |
| Soil salinity controlling | Crane Brook, NSW, Australia | Time–series | Yes | No | BNs | [87] |
| Secondary soil salinization risk | The Yinchuan Plain, China | Spatial data set | No | No | DPSIR | [12] |
| Dry land salinity management | Little River Catchment, Australia | Spatial data set | Yes | No | BNs | [14] |
| Water resource management | Qira Oasis, NW, China | Stakeholder and expert opinion, | Yes | Yes | BNs, IWRM | [88] |
| Water supplies capacity | Sub–China | Time–series, model output | No | No | BNs | [89] |
| Aquifer planning | Eastern Mancha, Spain | Stakeholder's opinion, Time–series, | No | Yes | BNs | [90] |
| Ecosystem services | NW China | Literature, book, Stakeholder's opinion | Yes | – | IWRM, BNs | [91] |
| Wildlife management | – | expert opinion | – | Yes | BNs | [55] |

### *4.2. Model Evaluation*

Knowing the limitations of a model can advance informed decisions when utilizing it. Limitations of the modeling approach include the following: The lack of historic time–series data posed a challenge for model refinement, which is a common problem in most modeling approaches. For instance, the farmland salinization trend under water saving technology is uncertain, although water saving technology has been implemented (i.e., drip irrigation) in a very limited area of the Oasis, and it is worth noting that economic growth enabled farmers to afford more effective water saving facilities. Since the behavior of farmers is unpredictable and attitudes about drip irrigation vary, there is a lack of quantified data. It is difficult to assess the impact of water saving irrigation on farmland salinization, which is still uncertain and needs further research.

However, it is rational to think that water saving technologies led to decreased irrigation water per hectare. These incentives will decrease the maintenance of groundwater levels to the required depth at salinization threatened areas; at the fertile areas, salt accumulation will be induced on the surface due to the lack of water for soil salt leaching and drip irrigation will threaten the fertile land [65,91]. Therefore, implementation of drip irrigation requires very strict salt leaching practices regularly.

In addition, there are unreasonable correlations between farmland groundwater exploitation and ecotone water logging (leave–one–out cross validation error rate was >70%); this limitation may be related to the small amount of exploitation of farmland groundwater [15], and it is easy to infer that adequate exploitation of groundwater would decrease the water logging. However, this study ignores the pathway from groundwater exploitation to water logging in an ecotone area.

We adapted the key strengths (S), opportunities (O), weaknesses (W) and threats (T) of BNs from study of Benjamin [55]. Then built the SOWT of Keriya Oasis BNs model (Table 4). Decision makers should consider the SOWT and weigh risks with benefits. Strengths and opportunities suggest that benefits of employing BNs to model secondary salinization problems. Lastly, researchers should aim to decrease weaknesses and threats. We strongly recommend additional refinement and validation analysis when data become available by strengthening collaboration among researchers and decision makers to allow for the exchange of information.

**Table 4.** Strength, opportunities, weaknesses, and threats of applying BNs modeling in Keriya Oasis salinization.

| Strength | Opportunities | Weaknesses | Threats |
|---|---|---|---|
| Expert knowledge utilization | Knowledge acquisition | Knowledge–driven validation tools | Reliability |
| Stakeholder opinion utilization | Knowledge acquisition | Knowledge–driven validation tools | willingness of Experts and Stakeholders to participate |
| Combination of empirical data to quantified data | Enables adjusting easily | May produce bias | Limited scientific model acceptance |
| Applicable to adaptive management | Analyzing synergetic implications | Absence of feedback–loops | Perceived level of knowledge varies |
| Probabilistic treatment of uncertainties | User–friendly computational software | Data discretization | – |
| Observation of conditional probability table | Comprehensive understanding of scope | Absence of enough data sets | – |

### 4.3. Management Recommendation

The trend of the oasis secondary salinization problem was solved using comprehensive modeling of DPSIR and BNs, which highlighted the complexity of the salinization problem, and validation was conducted via leave–one–out cross validation technique. The BNs model result clearly indicates that secondary salinization management practices should be adapted to reduce the groundwater table. This achieved by enhancing the drainage conditions and decreasing water logging.

We adhere to the logic that digging efficient artificial drainages in the salinized areas and conducting rational irrigation in the inner oasis may be the only solution to minimize salinization hazards [4]. Although, the construction of Pulu water reservoir proved to reduce the groundwater table by decreasing the River flow and ecotone water logging, however, the construction of a water harvesting dam enables people to have more options regarding land reclamation around the Oasis to satisfy increasing population demands. According to stakeholders, serious caution must be paid when land reclamation occurs in the higher southern part of the oasis, since agricultural activities in the higher southern part can causes salinization threat to former fertile farmland in the lower northern area in the Oasis [8]; therefore, top priority should be paid to land reclamation and to creating ideal drainage and irrigation plans.

## 5. Conclusions

This study examined the trend of secondary soil salinization by using of the modeling approach in Keriya Oasis, northwest CHN. In this work, the DPSIR sustainability framework and BNs model were combined using and developed a practical BNs model to estimate the trend of secondary soil salinization and to recognize the main causes. Our primary findings are that, in the near term, an increasing trend of light salinization in an ecotone is expected, in the future, this trend is expected to decelerate a little. And decreased trend of farmland salinization is expected in the near term and this trend will accelerate a little in the future. All these trends were attributed to decreased water logging, increased groundwater exploitation, and decreased evapotranspiration/precipitation. In contrast, the severe salinization in an ecotone will increase in near term, and it will accelerate a little in the future because decreased river flow in the future will reduce the flushing chance of severe salinized crust. From this we conclude that the anthropogenic factors play a negative role in both the farmland salinization and ecotone light salinization, but play a positive role in ecotone severe salinization. The BNs model result clearly indicates that secondary salinization management practices should be adapted to reduce groundwater table, this is achieved by enhancing the drainage conditions and decreasing water logging. So, building efficient artificial drainages in the salinized areas and conducting rational irrigation in the inner oasis may be the only solution to minimize salinization hazards. Besides, the construction of the Pulu water reservoir will be helpful for reducing the groundwater table. In our study the combined modeling of the DPSIR and BNs has proven to be an effective method for using different types of information from the anthropogenic and natural systems for oasis salinization management. However, it is necessary to obtain additional refinement and validation analysis when new data become available by strengthening collaboration among researchers and decision makers to allow for exchange of information.

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**Author Contributions:** Jumeniyaz Seydehmet and Lv Guang-hui conceived and designed and wrote this paper; Ilyas Nurmemet was responsible for manuscript proofreading; Tayierjiang Aishan analyzed the data; Abdulla Abliz designed figures; Mamat Sawut, Abdugheni Abliz and Mamattursun Eziz performed the experiments.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

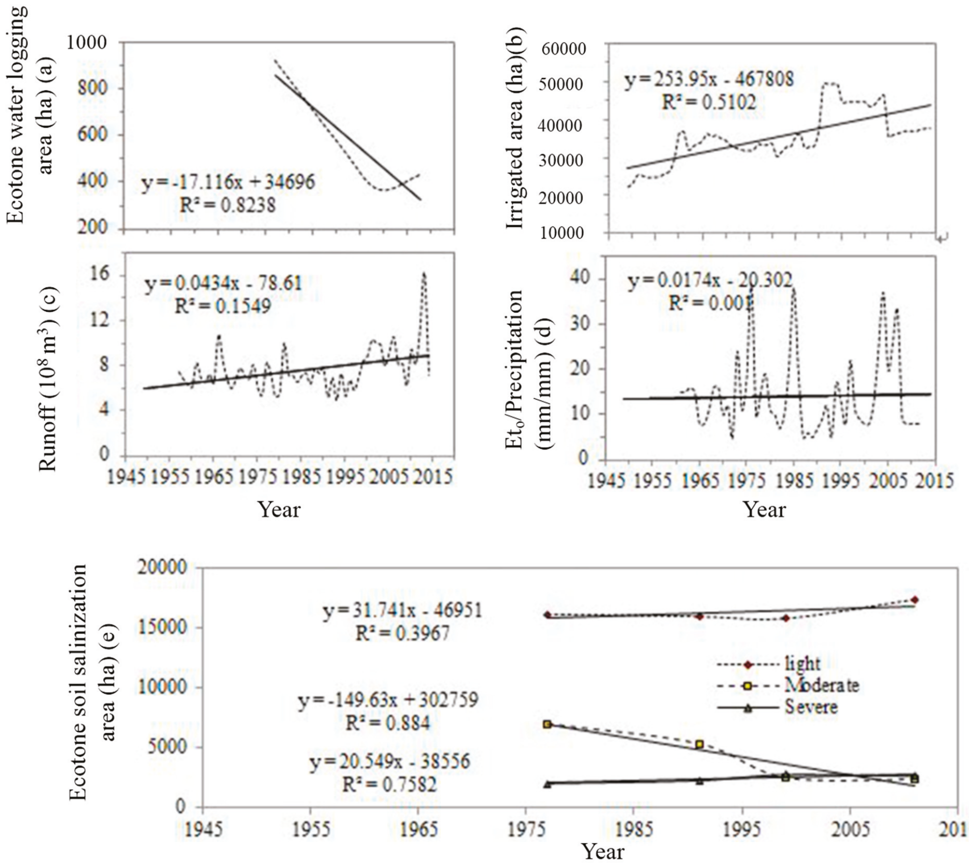


**Figure A1.** The Data Time–series from 1945 to 2015.

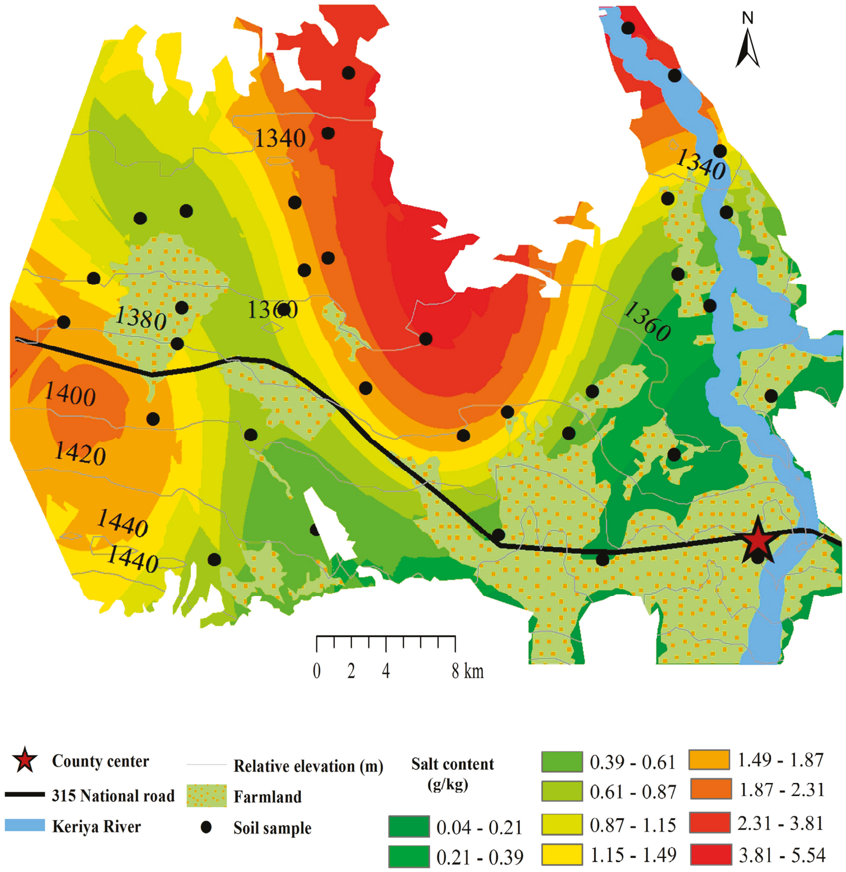


**Figure A2.** Spatial variation of salinization in the Keriya Oasis. Spatial variation of salinization in the Keriya Oasis was studied by Ordinary Kriging (subject to normal distribution, Sig. is 0.58). Each point represents the average value of six soil profiles; higher values can be found at the top of the soil surface in general (Max is 35.6 g/kg), and lower values at the sub soil surface (Min is 0.01 g/kg). Keriya Oasis information, except desert area, was obtained from Landsat TM and DEM [92,93].

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*sustainability*

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# The 'Invisible' Subsoil: An Exploratory View of Societal Acceptance of Subsoil Management in Germany

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**Abstract:** Subsoil, commonly defined as horizons below the working depth of 30 cm, has traditionally received little explicit attention in policy discussions on soils. Recently, however, there has been growing recognition among scientists of the issues of subsoil (re-)compaction and of the role of subsoil as a resource that can offer valuable nutrients and water for plants. Subsoil management could provide an option to sustainably maintain yields in the context of climate change and resource scarcity, and it is a central question in addressing subsoil compaction. Yet how socially acceptable are different methods for subsoil management? Drawing on in-depth interviews with farmers and stakeholders in Germany, we show that biophysical conditions, the timing of operations, economic considerations, and awareness of subsoil functions are key factors in the acceptance of management methods. Views towards methods involving mechanical intervention are more diverse and in some cases more critical because the benefits are not always certain, the costs can outweigh the benefits, and/or because they entail risks for soil structure and functions. Alfalfa cultivation is seen to be beneficial for yields without risks for soil structure and functions; however, economic barriers limit its uptake. Awareness of multiple subsoil functions is associated with more critical views of mechanical interventions.

**Keywords:** subsoil; compaction; agricultural yields; soil functions; societal acceptance; farmer motivations; subsoil loosening; alfalfa; sustainable soil management; resource scarcity; Germany

## 1. Introduction

Soils tend to receive less public attention than other environmental resources. Whereas water, air, or biodiversity tend to be more visible publicly, soils have historically not been a focus for environmental campaigning or large societal debates. At the policy level, in the European Union, soils are the only resource without a binding overarching legislation at the EU level [1,2]. In recent years, some attention on soils has been refocused, for example, with the UN declaring 2015 as the Year of Soils, as well as initiatives such as '4 per mil' within the international climate change negotiations. Nonetheless, society tends to have less direct engagement with soils compared to other resources.

The subsoil, commonly defined as the horizons below the working depth of 30 cm, is also physically invisible to societal stakeholders, including farmers. In practice, farmers' interaction with the soil tends to focus on the topsoil, which is the medium with which they interact (e.g., through tilling or ploughing in conventional farming systems). The topsoil is also where the effects of management decisions are most clearly seen. Subsoil tends to become an issue for farmers and farm advisers when it becomes compacted and when waterlogged subsoil layers decrease yields. Similarly, subsoil has been explicitly addressed in the scientific literature, often in relation to problems with subsoil compaction, a persistent and damaging process that severely restricts the ability of soils to perform soil functions and deliver ecosystem services (for example, [3]).

In terms of policy discussions, the main issue has also been subsoil compaction. However, because subsoil compaction does not always have immediate visible effects, such as is the case with soil erosion or topsoil compaction, and because of difficulties with designing a policy response to it, it has also not been a widely discussed soil protection issue. Compaction in general has been described as a "hidden problem" [4]. Yet, it has also been argued that it should be treated as a priority problem, as "with the increasing frequency and gravity of weather extremes under climate change (drought spells; intense precipitation; flooding), subsoil conditions in terms of hydraulic properties and ability to support deep rooting will increase in importance" [5] (p. 86).

From a more positive perspective, subsoil has the possibility to attract more attention in policy discussions within the agenda on climate change adaptation and with the increasing awareness of resource scarcity issues (see for example [6,7]). Subsoil can offer valuable nutrients and water for plant growth. Recent research has shown that, although nutrient availability to crops can vary, subsoil can contain a large share of the total Nitrogen and Phosphorus contained in the soil and retain water under drought conditions [8–13]. Moreover, subsoil is also important for other soil functions and ecosystem services, including flood protection, water filtration, or carbon storage [14,15]. Integrating subsoil in management decisions may be an opportunity to tap an additional resource of nutrients and water. In the context of climate change, subsoil management can also potentially be seen as an option to sustainably maintain or increase yields [10,12]. While its role as a source of nutrients and water is hinted at in policy, and potentially fits well with the discourse of the Bioeconomy and Circular Economy Agenda in the EU, it is not yet an explicitly articulated aspect of any policy discussions.

In this context, researchers have begun to look more systematically at subsoil functions/the role of subsoil for soil functions and to develop and investigate new strategies of mechanically or biologically intervening in subsoils that aim to tap the subsoil as a resource [10–13,16–18]. Yet how relevant, feasible, and acceptable are different methods for subsoil management as a strategy that can contribute to the sustainable management of soils and to securing long-term agricultural yields? How do farmers and other stakeholders view subsoils, and are farmers interested in adopting different subsoil management measures? Are these measures also acceptable from a broader societal point of view? These questions have not yet been addressed in social science or policy discussions. If one or more subsoil management measures are framed as having the potential to deliver benefits for agricultural yields and to be implemented (more) broadly in agricultural management, it is important to understand how societal stakeholders see these measures and which factors either increase their appeal or present a barrier to their uptake and social acceptance.

This article presents an exploratory look at stakeholders' perceptions of subsoil and societal acceptance of subsoil management methods in Germany. The article is based on research in an interdisciplinary project on subsoil management, titled "Soil$^3$—Sustainable Subsoil Management" (The Soil$^3$ project explores strategies to optimize a plant's uptake of nutrients and water from the subsoil in order to stabilize or increase crop yields. See https://www.soil3.de). The method combines a literature review with in-depth interviews. The exploratory examination is not comprehensive. Rather, we identify key issues and develop a basis for a more extensive social acceptance analysis that will take place in the second phase of the Soil$^3$ project and will combine a broad survey with targeted focus groups, as well as ongoing stakeholder engagement with the development and testing of subsoil management methods. The options for subsoil management broadly fall into mechanical and biological management methods [12]. In this study, we explored views towards four methods: (1) deep ploughing, (2) mechanical subsoiling, (3) a new method of mechanical subsoiling with an injection of organic matter, and (4) the cultivation of deep-rooting alfalfa crop.

The article is structured as follows. We first outline the method and the overall conceptual approach for the study. Second, we show how stakeholders perceive the subsoil and what kind of awareness of the subsoil they have. Third, we show how stakeholders view the different management methods, and what positive and negative aspects they emphasize in relation to each method. Finally, in the discussion, we relate the results of the study to broader discussions on sustainable (sub)soil management and the questions raised for further research.

## 2. Materials and Methods

The research for this article included a literature review on farmers' decision-making around sustainable soil management, which showed that the topic of subsoil management has mostly been absent as an explicit topic in social science research so far. We could not identify any published research that looks at how farmers use or do not use subsoil management measures. However, the review provided an overall framework for approaching the societal acceptance analysis, which we present in Figure 1. We also examined how the soil science literature approaches subsoil management. In addition, in-depth interviews in Germany were conducted with nine soil management stakeholders and nine farmers who practice either arable or mixed farming systems. While farmers are of course also societal stakeholders, in this article, we make the distinction between farmers and other stakeholders to simplify the terminology and presentation of results. The overview of interviewed stakeholders and farmers is given in Table 1.

**Table 1.** Overview of interviewed soil stakeholders and farmers.

| No. | Occupation | Organisation | Federal State |
|---|---|---|---|
| 1 | Farm advisor | Farmers' association | Brandenburg |
| 2 | Farm advisor | Farmers' association | Mecklenburg-Western Pomerania |
| 3 | Farm advisor | Chamber of agriculture | North Rhine-Westphalia |
| 4 | Farm advisor | Independent farming consultancy for farmers and policy-makers | National level |
| 5 | Public official | Environmental ministry | Lower Saxony |
| 6 | Public official | Agency for the environment and energy, federal soil association | Hamburg |
| 7 | NGO representative | Environmental NGO | National level |
| 8 | Scientist | Soil protection advisory board | National level |
| 9 | Scientist | University | Lower Saxony |
| 10 | Farmer | Organic farm, mixed farm (cattle): 180 ha | Brandenburg |
| 11 | Farmer | Mixed farm (cattle): 700 ha, 250 dairy cows | Mecklenburg-Western Pomerania |
| 12 | Farmer | Mixed farm (pigs): 500 ha | Mecklenburg-Western Pomerania |
| 13 | Farmer | Mixed farm: 1300 ha, 2000 pigs | Mecklenburg-Western Pomerania |
| 14 | Farmer | Arable farm: 800 ha | Mecklenburg-Western Pomerania |
| 15 | Farmer | Mixed farm: 100 ha, 1150 pigs | Bavaria |
| 16 | Farmer, part-time farm advisor | Mixed farm: 50 ha, 500 pigs | Bavaria |
| 17 | Farmer, part-time farm advisor | Arable farm: 190 ha | Bavaria |
| 18 | Farmer | Arable farm: 2700 ha | Brandenburg |

The stakeholders included representatives of a range of institutions associated with soil management and soil protection, including practitioners working in farmers' organisations, non-governmental organisations, and public authorities. Four practitioners worked at a national level and four in federal states (Mecklenburg-Western Pomerania, Brandenburg, Lower Saxony, and North Rhine-Westphalia). Farm interviews were conducted in Northern and Southern Germany (Mecklenburg-Western Pomerania, Brandenburg, and Bavaria). We identified farmers with the assistance of regional farm advisors. The aim was to capture a range of farms practicing arable or mixed farming. The interview guide focused on three main themes: (1) views on good agricultural practice and soil management, (2) views on soil functions and the role of subsoil, and (3) views on acceptable solutions to addressing soil threats associated with agriculture. Interviews were recorded and transcribed, and the transcripts were then analysed.

In this exploratory stage, we intentionally approached professional and larger, likely more intensive, farms who might have already experienced problems of subsoil compaction and who might be more open to new technologies. While the sample size is small, the diversity of interviewees and open-ended/in-depth nature of interviews allows us to identify a range of perspectives and explore diverse variables and interactions among them. This qualitative and exploratory examination provides the basis for a broader survey and focus groups that we will conduct in the second phase of the project.

*2.1. Farmers as Actors in Context*

Conceptually, the starting point for our analysis is the framework of farmers as actors in context. This means that farmers are seen as active agents who operate and negotiate their decisions with regards to farming practices within a context of various constraints, and as participants in complex spatially and temporally specific horizontal and vertical networks and processes [19]). Farmers' decision-making is therefore a result of a complex interplay of processes and influences from the broader farm environment, the biophysical and economic conditions on the farm, which are mediated by farmers' agency, their views, perceptions, and norms (compare Figure 1). The relative role of different variables and their interactions differ across space and time.

Mills et al. (2016) differentiate between the 'ability to adopt' and 'willingness to adopt' certain farming techniques [20]. Farmers' ability to engage with a particular method or to adopt an environmental measure depends to a large degree on farm characteristics such as farm size, tenure, and income.

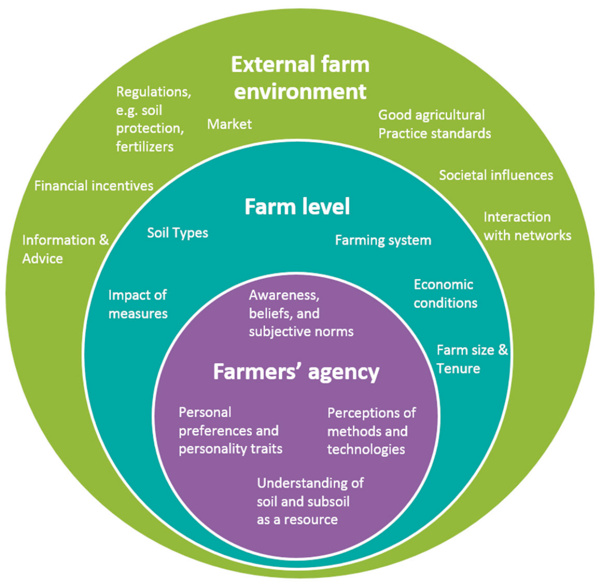


**Figure 1.** Farmers as actors in context (adjusted from [20]).

The willingness to apply a technique, on the other hand, is more strongly related to intrinsic factors such as personal norms and beliefs. Farmers' understandings, problem framings, and mental models regarding soil and agriculture have an influence on how soil is managed and which management options are accepted [21–23]. For example, Prager et al. (2016) observe: "How a person perceives soil degradation will influence how they interpret this phenomenon, what attitude they adopt towards it, and how they will ultimately decide to act" [21] (p. 36). Awareness and knowledge of soil risks can thus be a motivating factor for adopting soil protection measures [24]. In addition to these influences, there is also a need to consider farmers' technical knowledge of soil management: if farmers lack confidence or competence in certain new management practices, this can present further barriers to uptake [25]. Exploring the acceptance of subsoil management measures therefore requires attention to a broad range of factors.

### 2.2. Subsoil Management Methods

We consider four different subsoil management techniques that aim to enable crops to better access subsoil resources (compare Table 2).

**Table 2.** Subsoil management methods.

| Deep Ploughing | Mechanical Subsoiling | Injection of Organic Matter Furrow-Wise into the Subsoil | Alfalfa |
|---|---|---|---|
| The soil is ploughed to the depth of 50 cm and turned | Mechanical subsoil loosening, also referred to as "subsoiling", uses deep blades to loosen the soil and break up compacted layers without turning soil over | New technique combines mechanical subsoil loosening with the injection of organic materials in the subsoil. In furrows of about 30 cm width (and intervals of about 1 m between furrows), organic material is mixed into the subsoil by means of specially designed machinery | Alfalfa cultivation is a biological method of subsoil loosening by means of deep-rooting plants to create vertical root channels (biopores) for subsequent crops |

Deep ploughing involves digging into and turning the soil at a depth of about 50 cm or deeper, leading to an inversion of the soil profile (i.e., former subsoil is brought to the surface while topsoil is buried). It aims to break up root-restricting soil layers and to optimise crop growing conditions [18]. Deep ploughing used to be widely practiced in Germany and the Netherlands in the 1960s for the reclamation of peatlands for agricultural use, as well as to improve cropping conditions on Podsols and Luvisols [12]. The technique requires great physical effort, i.e., heavy machinery and a high input of energy. Among the four subsoil management techniques included in our analysis, deep ploughing is the most intense operation on the soil.

Mechanical subsoil loosening, which is often referred to as "subsoiling" or "deep ripping", aims to loosen the soil and is primarily applied to counteract subsoil compaction. Loosening the subsoil is supposed to increase crop yields by enabling deeper and wider root growth, improving water infiltration and transport, as well as facilitating nutrient uptake [26]. Various tillage tools exist for the purpose of subsoil loosening; often, grubber-like appliances with one or several grongs are used and the depth of application can vary between 35 and 50 cm (compare for example [26,27]). In contrast to deep ploughing, mechanical subsoil loosening does not turn the soil.

A new technique to meliorate the subsoil that is currently tested in field experiments [10] combines mechanical subsoil loosening with the injection of organic materials (green cuttings, organic compost). The aim of the technique is to modify the soil structure to enable the deeper rooting of crops, trigger microbial activity, and eventually enhance yields. To farmers and stakeholders we interviewed, we explained the procedure as follows. The technique is applied furrow-wise with intervals of about 1 m between furrows, with the furrow being approximately 30 cm wide. First, the topsoil layer (upper 30 cm) is lifted and put aside. Second, organic materials are inserted into the furrow. Third, the organic materials are mixed into the subsoil down to a 60 cm depth. Finally, the topsoil is laid back on top. The technique does not involve turning the soil profile and the topsoil remains untreated. Ideally, plant roots will grow into the furrow from the top as well as from the sides. The first results of the field experiment testing the technique on a loess soil showed that one year after implementation, yields of spring barley increased by up to 20%. Positive yield effects could be observed up to 50 cm sideward of the treated furrow [10]. The technique can be site-specifically adapted, e.g., regarding intervals between the furrows, depth of application, and choice of input materials.

A biological approach—also referred to as "biodrilling" or "bioporing"—to loosen and meliorate the subsoil and enhance water infiltration is the cultivation of deep-rooting primer crops such as alfalfa. These plants create vertical root channels (biopores) and thus facilitate deep rooting and access to subsoil resources for the subsequent crop [13]. Alfalfa is very suitable as it develops a strong taproot reaching deep soil layers, as well as multiple branches that create a broad root network [3,9,17]. It is argued that alfalfa and other deep-rooting plants can alleviate subsoil compaction [3,28,29]. In fact, alfalfa cultivation used to be a standard technique for the reclamation of agricultural soils following degradation through brown coal mining processes. For developing taproots, alfalfa must remain on the field for at least two years.

## 3. Results: Subsoil Awareness and Acceptance of Management Measures

### *3.1. Subsoil Awareness*

We anticipated that farmers have a relatively limited awareness of subsoil since they mostly deal with the topsoil in their everyday operations. Many farmers in the sample shared this view by stating that a typical farmer will think little of soil management and even less of subsoil. Several said that an active consideration of subsoil only occurs in exceptional circumstances, whereas normally, farmers do not come into contact (directly or indirectly) with the subsoil.

> "Soil is often the last thing a farmer thinks of when problems occur—first he checks fertilisation regime, plant protection, choice of crops and so on—soil or subsoil is the last thing he thinks of" (No. 17).

Having said this, farmers included in the sample were well informed and engaged with soil management. They were all aware of good soil management practices and many have been applying these practices, in particular crop rotation and making traffic and tillage decisions based on weather and site conditions. In relation to soil functions broadly, most farmers emphasized the role of soils as a storage for nutrients and water (seven of nine farmers), with carbon storage also mentioned by two farmers. When asked about the role of the subsoil more specifically, farmers spoke about it primarily in terms of a reservoir. In particular, subsoil becomes more relevant in conditions where the topsoil is less productive and has a limited water- or nutrient-holding capacity. Six of the nine farmers mentioned the importance of subsoil as a reservoir for nutrients and water, especially under extreme weather conditions. However, only one farmer/farm advisor emphasized the subsoil's function as a filter for groundwater, implying a more explicit awareness of the role of soils for maintaining water quality. Two farmers did not refer to subsoil specifically and one stated that, on his land, the topsoil transitions very quickly into bedrock so that a subsoil layer is hardly present.

Among the societal stakeholders, three stakeholders from agricultural organisations echoed this focus on the subsoil as a reservoir, emphasizing its crucial role for water balance. In contrast, five other stakeholders with a background in environment protection had a broader view of subsoil, equally emphasizing all soil functions as defined in the German Soil Protection Law, i.e., in addition to the production function (as a reservoir of nutrients and water), the natural and the archive functions of soils were attributed equal importance. In particular, they emphasized the filtration, buffering, carbon storage, and habitat functions. One pointed to the fact that the climate (carbon storage) function is missing from the German Soil Protection Law. One agricultural and one environmental stakeholder also stated that a distinction was not possible and that topsoil and subsoil were equally important. Despite the small sample size, the more 'production' focused view of farmers and agricultural stakeholders is in clear contrast with a more 'multifunctional' view of subsoil by the environmental stakeholders.

If we look at the idea of subsoil as a reservoir, the significance of subsoil in Germany increases in regions with sandy soils, which are also more prone to drought, such as Brandenburg and Mecklenburg-Western Pomerania. To illustrate the limited water-holding capacity of sandy soils, one farmer explained that his soils have the potential to save perhaps up to 50 mm of water in the top 25–30 cm of soil (per $m^2$), which is sufficient to keep plants alive for a week or ten days in warm, sunny, conditions. Beyond this short period, the plants have to depend on the subsoil. Recognizing this function goes along with a higher appreciation of the subsoil, illustrated by the statement of an agricultural stakeholder: "Every centimeter of additional soil volume is a centimeter of additional habitat for plant and soil life, which later on is mirrored in the crop yield and quality of products" (No. 1). This function of subsoil as a reservoir is of importance as one factor that can help to reduce yield fluctuations, in particular on sandy soils. Six of nine farmers stated that increasing the yield stability, or achieving the optimum yield, and reducing annual fluctuations due to changing weather conditions, were important objectives of their farm management. The appreciation of the subsoil as a reservoir is not necessarily limited to areas with sandy soils, since farmers in Bavaria also emphasized this. The two out of three Bavarian farmers that mentioned it, however, were also part-time advisors for soil management so it may still be possible that in Bavaria, where soils tend to be more productive, the overall awareness of subsoil is lower.

In addition to poor topsoil quality, compaction problems are another motivating factor that farmers gave as reason to think about subsoil. Six of nine farmers mentioned the issue of compaction as an important soil threat, with several speaking of the role of heavy machinery and inappropriate timing of operations in worsening the problem, and several also had either a positive or negative experience with subsoil mechanical loosening. While compaction affects sandy soils more, farmers with other soil types also reported issues of compaction, especially along driving lanes. Another aspect mentioned by a couple of farmers in relation to subsoil was the issue of drainage, which, in many parts of Germany, allows the cultivation of rich organic soils.

### *3.2. Acceptance of Subsoil Management Methods*

#### 3.2.1. Deep Ploughing

The first method that farmers and stakeholders were consulted on was included in the study as the most invasive form of mechanical intervention in the subsoil. Farmers' and stakeholders' views on deep ploughing are summarised in Table 3. Views are quite similar, with the general opinion being that the method is not an effective one to deal with subsoil compaction. While deep ploughing was once quite popular in Germany, and often applied on organic rich soils (peatland) (No. 6, No. 13), it is no longer practiced widely in Germany.

**Table 3.** Stakeholders' views on deep ploughing.

| Positive | Negative |
|---|---|
| On a case-by-case basis acceptable, if there is no other solution (5, 9, 7)[1] | Strong opposition to mixing topsoil and subsoil and bringing soil to the top (1, 2, 3, 4, 5, 6, 7, 8, 18) |
| | Detrimental effects to soil structure, soil functions and soil life (2, 4, 5, 6, 7, 8, 16, 17) |
| | Heavy machines necessary and lots of energy (3, 6, 8, 10, 11, 12) |
| | In no case acceptable (1, 2, 3, 4) |

Numbers in parentheses indicate the No. of stakeholders and farmers who mentioned the respective aspect.

A few farmers and stakeholders referred to it as an outdated technique and one stakeholder characterized it as a 'purely desperate measure'. Nearly half of the interviewees mentioned the high energy and time effort as a negative aspect. Several stakeholders explicitly stated that it is not acceptable under any circumstances. Half of the interviewees, primarily the stakeholders, voiced strong opposition against the mixing of topsoil and subsoil. Eight emphasized that this leads to the destruction of the soil structure and thereby seriously affects all soil functions. One farmer mentioned the following negative experience:

> "I know the method from the farm where I worked on in Denmark. We used a very large plough to till peatland. This was done only for a few years. We don't do it anymore. We stopped doing it because these organic soils . . . they collapse even faster, the more oxygen you add to it, the faster they collapse" (No. 13).

One stakeholder said the mixing of layers as deep as 90 cm affects the soil organic matter (SOM) content in the topsoil, a negative impact especially for topsoil with an already low SOM content (No. 2). Another stakeholder also referred to the method as bringing up 'dead soil', by which they meant that a layer of soil with a very low biodiversity is put on top, and some organisms are pushed down to the depth where there is not enough light and oxygen for them to survive (No. 4). This could lead to the destruction of biodiversity in topsoil and subsoil, potentially being counterproductive in both ecological and economic terms. Only three stakeholders mentioned that they found the method acceptable only as a one-off measure if it is associated with a shift in a system change:

> "I can understand that if you have to do it, you do it. But if you don't change your whole management, then you'll end up at the same point in a few years that you'd have to repeat it again, and that's no solution" (No. 7).

One of these three stakeholders also emphasized that its acceptability depends on the time horizon; if it is done infrequently, there is still the question of how the topsoil responds to the measure and how long it has to recover, since the immediate negative effect (in this case, the reduction of SOM in the topsoil) would eventually be evened out.

#### 3.2.2. Mechanical Subsoil Loosening

Overall, interviewed farmers and stakeholders see mechanical subsoiling rather critically (compare Table 4). They see a high risk of damaging the soil when the technique is not applied carefully. A number of farmers and agricultural stakeholders describe mechanical subsoiling as a standard technique for loosening compacted soil layers underneath driving lanes and headlands. Yet, many emphasise that a field-wide application of the technique needs to be considered with caution and is only acceptable under certain restrictions: i.e., the technique is performed on dry soils, as a one-time measure, and in combination with a suitable crop rotation.

**Table 4.** Stakeholders' views on mechanical subsoiling.

| Positive | Negative |
|---|---|
| Suitable for heavily compacted sites, primarily under driving lanes and headlands (1, 2, 3, 4, 5, 7, 11, 12, 13, 14, 18) | Risk of re-compaction, complete loss of soil structure or shift compaction into deeper layers (2, 5, 7, 10, 16, 17) |
| Accepted on dry soils/ light and sandy (1, 2, 10, 12, 13, 16, 18) | High efforts and costs, heavy machineries and high energy input is needed (3, 6, 7, 8, 10, 12, 15) |
| Only in combination with biological activation, catch cropping or diverse crop rotation (2, 4, 6, 7, 10, 12, 18) | Not suitable for subsoils with stones and drainage systems (14, 15) |
| | Short-sighted solution, without implementing any changes in the farming system that aim to prevent new compaction, lead to the need to repeat the procedure again after a short period of time (1, 5, 6, 7) |

Subsoiling requires heavy machinery and a high input of energy to loosen deep soil layers, making it an intense operation that involves high efforts and costs. One rather sceptical farmer therefore described the technique as a "gigantic technological effort" with rather marginal results (No. 10). Nonetheless, it appears acceptable to alleviate compaction on specific sites and five of the nine farmers reported experience with mechanical subsoiling at a depth varying between 35 cm and 120 cm. Four farmers stated that they currently used mechanical subsoiling on their farms, primarily to loosen driving lanes and headlands, emphasizing that they use the subsoiler on parts affected by compaction but not field-wide. Two farmers applied the technique once on a larger scale: one of them (No. 13) when he took over the farm and found that many fields were heavily compacted due to frequent traffic, and the other (No. 11) when he changed his farming system from ploughing to no-till cultivation. Another farmer (No. 16) had a very negative experience with mechanical subsoiling. After applying the technique at a 45 cm depth, he found that the soil structure was lost, water infiltration decreased, and the soil's carrying capacity collapsed.

The high risk of re-compaction and the increased loss of soil functions are the most critical issues that limit the acceptance of mechanical subsoiling. Many see it as a short-sighted solution, stressing that it should be combined with biological measures, such as deep-rooting catch crops, in order to be effective. The roots reactivate the soil life and stabilise the loosened structure. As an illustration, one farmer described mechanical subsoiling without subsequent catch cropping as a "waste of fuel and effort" (No. 12). A second farmer took on an even more critical perspective, stating that mechanical subsoiling "only removes agronomical mistakes a farmer has made in the past. Although it does not really remove them, but rather shift compaction into deeper layers if not done under dry conditions and if not combined with catch cropping" (No. 10). Mechanical subsoiling damages the soil when applied under wet conditions: "You can make mistakes with mechanical subsoiling, which result in structural damages. It is important to apply the technique under dry conditions. To look at the soil, combine the technique with catch cropping, with deep-rooting catch crops. Most importantly, you need to consider the water conditions in the soil. Otherwise you exponentially increase harmful compaction" (No. 2).

Particularly the environmental stakeholders that have a multifunctional view of soils expressed concern about the frequency of application. A few stakeholders mentioned that farmers exploit this technique as a quick solution to compaction, enabling them to continue with business as usual—e.g., maintaining a wheat-dominated crop rotation—without implementing any changes in the farming system that would prevent new compaction. In this way, the technique fixes the symptom but not the cause of compaction issues and regular application is neither justifiable nor sustainable (No. 6): "Experiences with mechanical subsoiling show that the technique can definitely cause damages when applied under unfavourable conditions" (No. 9). This view resonates with the opinion that "soil should be cultivated in a way that the transition to subsoil remains intact and no mechanical intervention is needed" (No. 1).

Regular application, indeed, appears to be quite common, except in conditions that limit its application because of biophysical factors—i.e., in areas with a high frequency of stones, drainage systems, or very heavy soils. Interviewees report of a widespread opinion in certain regions of Northern Germany that subsoiling on a regular basis is an adequate farming practice for light and sandy soils, which tend to compact easily (No. 2, 12, 14), as well as on all soils on farms with root crops (potatoes, onions, sugar beets) that use heavy harvesting machinery. This hints to an apparent lack of awareness of the long-term damage to subsoil. However, even when farmers are aware of the risk of compaction, economic and time pressures often outweigh the concern about the compaction risk. This is illustrated by a farmer in the sample who used a subsoiler to get rid of water on a field he wanted to harvest—although aware that this is harmful for the soil: "It's a catastrophe for the soil what we are doing, but we have to get the beets out and it's too wet" (No. 14). Farmers are pressured to harvest by conditions set out in their contracts to supply specific amounts at certain times. Given that six of nine farmers mentioned the prevention of compaction as part of good soil management, it appears that economic and time concerns outweigh precautionary behaviour.

The technique is in part risky because the damage done to the soil in the subsoil layer is not immediately visible and it is not easy to judge whether the subsoil is wet or dry (No. 16). This aspect of not being able to see the subsoil requires that farmers dig into the soil first and have a look at the subsoil conditions, a practice that farmers do not often do under time pressure. It is also worth noting in this context the sentiment expressed by several farmers in the sample that farmers in general do not pay so much attention to soil conditions compared to the plants and fertilisation. For example, one farmer stated, "who do you see these days doing a spade test?" (No. 17).

### 3.2.3. Injection of Organic Matter Furrow-Wise into the Subsoil

The views on the innovative technique of injecting organic material furrow-wise into the subsoil were quite diverse. While some of the interviewed farmers and stakeholders were enthusiastic and showed great interest, others were rather cautious and expressed concerns, and a few interviewees found the technique unacceptable (compare Table 5).

**Table 5.** Stakeholders' views on injecting organic matter furrow-wise into the subsoil (Soil$^3$ method).

| Positive | Negative | Uncertainties |
| --- | --- | --- |
| Enhancing site conditions/soil structure (in regions with sandy soils and low SOM) (2, 6, 9, 10, 12, 13, 16, 18) | Risk of disturbing soil structure; difficult to preserve the structure of the topsoil (3, 4, 5, 8, 9, 11, 17) | Sustainability of yield increase—how long does the effect last (2, 14, 16, 17) |
| Improve root development, enhance biological activity in lower soil layers and the ability to store water and nutrients and (1, 2, 6, 9, 11, 12, 13, 14, 18) | Risk of anaerobic decomposition process (rotting) in subsoil (especially on heavy soils with low air circulation—nutrients are not available for plants) (3, 4, 8, 9, 10, 12, 15, 17) | Are the expected benefits worth the high effort, in particular in comparison to other management practices (1, 2, 4, 5, 8, 15) |
| Stabilising yields (in dry regions with sandy soils) (1, 2, 6, 10, 11, 13, 18) | High effort and costs, need powerful machinery to implement the technique (prevent particularly small farms to apply the technique) (1, 2, 3, 4, 6, 7, 8, 10, 11, 12, 13, 15, 17) | Doubtful, whether the aims of the Soil Protection Law, Fertiliser Regulation, and waste legislation, i.e., to sustain all soil functions, can be met with this technique (2, 5, 6) |
| Attractive for sites with high yield or for crops with very high added value (3, 10, 12, 13, 16) | Dependence on external consultants (4, 7) | Doubts that soil life will be attracted to go deeper into the soil (7, 4) |
| | Penetrating to such depths mechanically is not advisable (17) | Buffer function of the soil could be affected; risk of contaminants in input material—leads to groundwater pollution, quality of input material needs to be guaranteed (2, 5, 6, 12, 13, 14) |

The interviews showed that in particular farmers and stakeholders in regions with light, sandy soils are interested in the technique and think it has potential to be effective. Interviewees describe sandy subsoils as a rather unattractive environment for plant roots, as water drains quickly and washes out plant nutrients. In this context, they see the technique as a way to improve the site conditions: Injecting organic material into the subsoil would increase the organic matter content and thereby enhance its ability to store water and nutrients, while at the same time attracting soil organisms and enhancing biological activity in the soil. One farmer illustrated this as follows:

> "Roots usually do not want to grow into the subsoil here, due to its physical properties: often it is compacted, it cannot hold water nor nutrients, in the worst case it is toxic and has the wrong pH value. In this case they don't want to grow down there and of course [the technique] has an effect, because substrate is incorporated and the roots like to grow in there. It is like a flower-pot-effect: the substrate holds water and nutrients—things that the other subsoil cannot provide. Hence there has to be a yield benefit" (No. 18).

Similarly, one farm advisor stated:

> "We have a lot of sandy soils, sandy loams, and all organic material that we incorporate into the soil is generally positive. You increase the organic matter, the humus content; enhance biological activity, microorganism, etc. I see positive effects. Particularly for sandy soils I see benefits" (No. 2).

By delivering these benefits, the technique is also seen by some to have the potential to stabilise yields. As mentioned above, yield stabilisation is a strong motivation for farmers, particularly in areas with high annual yield variations such as Mecklenburg-Western Pomerania, Brandenburg, and Saxony-Anhalt. For example, one farmer in Brandenburg reported that he was able to harvest nine tons of wheat per hectare in one year, and only 4.5 tons per ha in the following year. To some farmers, reducing such fluctuations and preventing very low yields in years with droughts is more important than increasing yields on a percentage basis. Finally, as an additional positive effect, interviewees mentioned that the incorporation of organic matter could improve the soil structure and thus prevent re-compaction.

On the other hand, both those that are open to the technique and those who were sceptical found the technique to be associated with a high effort and high costs. One farmer even said that the technique was not feasible even if the effects were positive and sustained. A key open question is whether the expected benefits are worth the high effort, particularly in comparison with the common practices of incorporating compost into the topsoil or in comparison with applying catch crops, which also have the benefit of improving soil structure and reducing the risk of compaction.

Due to the expected high costs of the technique, it is perceived to be attractive only for crops with a high added value, such as in horticulture (for example, for berry production). At the same time, the higher costs mean that it is likely not to be accessible for smaller farms, and as such, also in line with the technical/digitalisation development associated with structural change in agriculture. One farmer likened the high cost of the approach to the investments required for putting in place drainage in organic soils. This farmer, who is quite open to technical innovations, also mentioned that the high work intensity associated with the procedure could be negated if a subcontractor performed the task. For other farmers, this reliance on external subcontractors is seen as a hindrance to the technique. This implies that farmers who value their independence are less likely to be interested in the injection of organic matter: "This technique makes farmers dependent on experts that come from the outside and tell him how he should improve his soils" (No. 4).

Mostly, stakeholders cited the risk of a negative impact on soil structure as a key disadvantage of the technique, questioning whether the assumed positive effect on the subsoil will offset the disruption made to the topsoil. One questioned the sensibility of mechanically penetrating soil at such depths, when the same can be achieved with biological methods. This is particularly a concern when the technique is applied under suboptimal conditions. Moreover, several interviewees voiced the concern about anaerobic decomposition and the risk of rotting, especially in heavy soils with low air circulation. This would also mean that the nutrients brought into the subsoil are not available to plants. One farmer argued that this risk was lower on sandy soils. One stakeholder argued that this measure should be combined with improving soil biology, particularly in conventionally cultivated fields that typically have little soil life, so that there are sufficient soil organisms to convert the input materials.

Several stakeholders stressed the need for rigorous testing and scientific monitoring of the technique, and doubted whether the technique would allow all soil functions to be maintained. Another open question about maintaining the yield increase—one farmer questioned whether the yield effect is primarily associated with the loosening in the first year which brings in oxygen, but that this effect cannot last. The source of organic material was a source of concern for some, i.e., that compost and other organic materials might be polluted with plastic residues or heavy metals; and that the quality of compost is essential. Moreover, there was concern that the technique would cause compaction on the edges of the furrows.

Soil stakeholders with an environmental background raised the concern about interference with natural and archive soil functions, for example, and that this technique would need to be carefully restricted. In particular, ecological effects are difficult to judge since the processes, functions, and organisms in subsoil are not yet well known. The criticism expressed by these environmental stakeholders also focused around the perception that advocates of the technique (including researchers) focus too much on the expected positive impacts for the production and yields, whereas the (potential) negative ecological side-effects are overlooked—for example, the negative impact on the buffering and filtering function of the subsoil (No. 9). Potentially, a key limitation to the technique is linked to the risk of groundwater pollution and the breach of compliance with the Fertiliser Ordinance, i.e., whether plants effectively take up nitrogen that has been injected in deep soil layers, or whether this will leach to groundwater as nitrate (No. 2). This risk is perceived to be higher than in the case of fertilizer input in the topsoil, and the stakeholder thought this would be the primary objection by environmental societal actors.

### 3.2.4. Alfalfa Cultivation

In contrast to the more diverse views on mechanical subsoiling and the injection of organic matter in furrows, both farmers and stakeholders recognised alfalfa cultivation as a positive method for soil management in general and more specifically to ameliorate the subsoil. The large majority of them, however, also stressed the economic disadvantages of cultivating this crop (compare Table 6).

**Table 6.** Stakeholders' views on Alfalfa.

| Positive | Negative |
| --- | --- |
| Improved structure, biological activity, infiltration capacity (1, 2, 4, 5, 7, 8, 9, 14, 16) | Economically not attractive to most farmers due to limitations on usage of the crop and opportunity costs (1, 2, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17) |
| Effective remediation option for compacted soils, suitable for most soil types (1, 3, 5, 6, 7, 8, 9, 10, 13, 16, 18) | |
| Wealth of experience (3, 7, 10) | |
| Good component in the crop rotation, increased yield in the following years when applied for two years or more (1, 3, 4, 8, 9, 10, 12, 14, 17, 18) Effective method to reduce compaction without the risk of recompaction (5, 7, 9) | |

The positive impression of alfalfa is in large part based on a pool of positive experience with this technique in Germany. Biological subsoil loosening by means of alfalfa is a widely known concept among farmers and stakeholders, who were all aware of the deep rooting potential of the alfalfa plant. Moreover, they either had their own experience with alfalfa cultivation or had heard about its successful application elsewhere and thus regard its effectiveness to remediate compacted soils as proven. The following stakeholders' quotes illustrate these points:

> "Alfalfa is an excellent component in the crop rotation in order to loosen the soil. In particular, when it is on the field longer than one year—usually three years maximum—the soil you have afterwards, it is a dream" (No. 1).

> "When comparing to our normal crops, no other crop has such root power" (No. 17).

> "After having had alfalfa a couple of years on a field, you will have a much better harvest of wheat on this field in the three following years than on your other fields, by far. [ . . . ] If I had an organic farm or a dairy farm, I would definitely cultivate alfalfa" (No. 12).

> "We intensely cultivated alfalfa. We have generated our best soils by first ameliorating them through perennial alfalfa cultivation and breaking up numerous compacted soil horizons this way. By this, we accessed many nutrients from the subsoil. [ . . . ] But this is nothing

new. My great grandparents already knew what alfalfa and other deep-rooting crops can do. This is 200-year-old knowledge" (No. 10).

Alfalfa is perceived as a suitable crop for most soil types in Germany. Soil stakeholders estimate that the positive effect of alfalfa on soils and related yield increases of the subsequent crop last about three years or longer. More importantly, what makes alfalfa cultivation an attractive subsoil management technique in the eyes of many stakeholders is that it generates multiple benefits on soils while providing an option to remediate compacted soils. In addition to breaking up compacted soil layers, stakeholders mentioned that it enhances and stabilises the soil structure, increases pore volume and biological activity, activates the self-regulation of the soil, and contributes to an overall recovery of the soil ecosystem.

The multiple positive impacts of alfalfa cultivation on soil functions were particularly important to environmental stakeholders who highlighted the multifunctionality of soils. These stakeholders often expressed a clear preference for biological subsoil management over mechanical approaches (five of the six stakeholders with a multifunctional view of subsoils). In their view, a major advantage of alfalfa cultivation lies in the fact that it does not pose any risks to soils (such as re-compaction or destruction of soil structure), that the effects last longer, and that it is a holistic approach enhancing the entire soil. For example, one respondent explained:

"I think this is by far the best way to improve the subsoil, because you have a lot of positive side effects on the soil, which in the end are reflected in the yields. This means you don't only achieve what you aimed for, but at the same time improve the entire soil structure in the upper horizons and create hotspots of soil bacteria" (No. 4).

However, all farmers and stakeholders except for one believe that this technique is currently not economically attractive for the majority of farms in Germany. One central issue is the usage of the crop: in order to cultivate alfalfa, farmers need to be able to use or sell the alfalfa harvest. Cultivating alfalfa only for improving the soil is seen as very unlikely. The main use of alfalfa is as a fodder crop for cattle. One farmer stated that "Alfalfa is the 'queen of fodder plants'. The complete US-American market for milk production is based on alfalfa and corn. Why don't we do this here in Germany?" (No. 10). A farm advisor argued that feeding alfalfa is increasingly attractive for dairy farms, as nowadays, many dairies demand that fodder is GMO-free, which soy often is not (No. 1).

On farms without cattle, alfalfa can be sold either to neighbour farms or to dry pellet producers. Several farmers reported that in Brandenburg, Bavaria, and Baden-Wuerttemberg, alfalfa cultivation is interesting as a business option within a certain radius of drying units that operate there. Overall, however, the potential for alfalfa seems to be rather limited: for farmers who do not raise cattle, have no neighbouring dairy or cattle farmers, and have no dry fodder unit in the region, alfalfa is at present not an economically attractive option.

In addition to the potential usage for the crop, another economic disadvantage of alfalfa is that the plant has to stay on the field for two or three years to be able to develop its deep rooting system and have its desired effect for soils. The opportunity cost of this cultivation can be significant, for example, in comparison with winter wheat or sugar beets. While many believe this is acceptable for organic farms, this trade-off is a limiting factor for the uptake among conventional farmers—even if there are utilization options for the alfalfa produce. The following statements illustrate this:

"If you cultivate alfalfa systematically over several years, you probably have a very positive effect without risking negative side-effects of technical interventions. But you need time and patience" (No. 9).

"[Alfalfa cultivation is] economically not attractive for farmers, because the investment does not return within a short period of two or maximally four years" (No. 7).

"Having alfalfa or a similar plant for soil recovery in the crop rotation is usually an economic advantage when calculating profit margins over five years" (No. 4).

The dominant way of calculating costs and gains over a short time-period hinders the uptake of such biological approaches to improving the soil. The longer time needed for seeing positive benefits means that alfalfa cultivation is especially a barrier for uptake on land that is leased, since farmers are less willing to invest in such a technique if they do not have the guarantee of benefitting. Especially stakeholders with a multifunctional understanding of soil criticised the focus on cash crops in Germany and the related neglect of biological approaches, such as alfalfa cultivation, as a means to improve the condition of soils. It was suggested that this barrier could be overcome by better informing farmers about the benefits of alfalfa cultivation, and by calculating the cost and benefits over a longer time.

It is worth noting that other deep rooting crops may have a similar positive effect on subsoil. Stakeholders and farmers often mentioned oil radish, lupine, and buckwheat. In addition, one farmer mentioned broad beans that develop roots of about 1.5 m, have a similar effect on the soil as alfalfa, and yet are suitable as feed for pigs. Another farmer recommended red clover, which can be undersown.

One farmer and part-time farm advisor found that the example of alfalfa and other deep rooting crops is reflective of the environmental limitations of farming based on cash crops with limited crop rotation. On the one hand, such production leads to an increased risk of compaction due to the use of heavy machinery, and on the other hand, does not allow the soil any 'room to breathe' nor to benefit from its natural resilience to maintain soil structure (No. 17). The immediate short-term opportunity costs associated with integrating deep-rooting cover crops or cereals in crop rotation also mean that these crops may not be planted after applying mechanical subsoiling, even though they would have the benefit of stabilising the soil structure.

## 4. Discussion

Our research has shown that, although subsoil has not been a visible part of the policy agenda and is not visible to the eye, farmers and other stakeholders included in this study show a clear awareness of its importance for agricultural production. A distinction, however, can be made between a more productivist and a more multifunctional view of subsoil. These views differ in the extent to which the non-productive functions and services are explicitly important. In this sense, the distinction is more narrow than usually made in literature (see, for example [19,30,31]). It is an important consideration since societal acceptance of management methods includes at least two aspects: the 'private' benefit that farmers accrue from implementing the method, mostly focused on yield, and the wider public benefits. The stakeholders that hold a more multifunctional view of subsoil also considered the wider public benefits or risks of subsoil management to a greater degree. If the production function is a key lens through which the subsoil is perceived, the impact on other soil functions appears not to be as important.

This resonates with literature that has shown that individual problem framings and perceptions towards soil degradation influence the interpretation, attitude, and actions that follow and how a soil is managed [21–23]. Our research indicates that how a person perceives the subsoil in terms of its functions is linked to the view they hold on the acceptance of management options. If subsoil functions other than the productive/yield function are not part of farmers' view of the subsoil, the awareness of risks to those functions also appears to be absent. Awareness and knowledge of soil risks, however, can be a motivating factor to adopt sustainable soil measures (see [24]).

The study also shows that the relative importance of subsoil for agricultural production varies depending on the quality of the topsoil, as well as climatic conditions. Nonetheless, the awareness of subsoil as a reservoir of nutrients and water [8,9,12] is present not only among farmers with poor topsoil (light, sandy soils with frequent drought conditions), but also by those with better topsoil. This shows that biophysical conditions and farming system characteristics can have a significant influence on the acceptance of different management methods at a farm level and the 'ability' to adopt a measure. Because biophysical conditions also influence the impact of individual methods on soil structure and functions, these are also limiting factors for practical feasibility and acceptance of methods from a broader societal perspective.

Of the subsoil management methods for which we sought to gain an understanding of farmers' and stakeholders' perceptions, there is quite high agreement among both groups on two methods. First, negative opinions towards deep ploughing dominate due to its perceived harmful impacts on soil structure and soil functions, as well as the high energy requirements needed to implement the technique. This finding is in contrast to the conclusion of Schneider et al. (2017) [12], that deep ploughing can be a suitable technique to increase yields on certain soil types when combined with measures to build up soil organic matter in the new topsoil. Our findings suggest that stakeholders and farmers see deep ploughing as an outdated and problematic method, and at present, it is also unlikely to be implemented in Germany. Only three of 18 interviewees saw the method acceptable as a one-time method for very specific conditions.

Second, farmers and other stakeholders perceive alfalfa cultivation (as well as other deep rooting crops) as a beneficial soil management method with a positive impact on soil structure and soil functions, including the production function and yields. The method is seen as both a prevention and a remediation method and resonates with the stakeholders' and farmers' understanding of good soil management. In line with this, abundant scientific evidence points to the multiple benefits of biological approaches, although not referring to them as subsoil management. Studies show that diversifying crops and crop rotations can enhance soil organic matter, biodiversity, and the provision of ecosystem services [32–34], as well increase the resilience of cropping systems and better adapt them to climate change [35–37]. Schneider et al. (2017) state that, in terms of yields, deep-rooting crops are preferable to mechanical deep tillage options for certain soil types [12].

However, interviewees see the uptake of alfalfa cultivation and other perennial, deep-rooting crops limited by economic constraints (potential usage and opportunity costs) and the prevalent focus on simplified crop rotations, including a focus on cash crops. Similarly, Reckling et al. (2016) [38] show that the cultivation of forage legumes such as alfalfa, despite their various environmental benefits, is restricted to farms which have utilization options. They identify the focus on short-term income as a barrier for the integration of legumes into crop rotations in Europe: "Farmers and advisors seldom consider the long-term benefits, focusing instead on single years. This leads to an underestimation of the services provided by legumes" [38] (p. 12). One question emerging from this analysis is, therefore, how can these barriers be overcome in order to enhance the integration of alfalfa and other deep-rooting crops for the purpose of subsoil management? An increase in the cultivation of alfalfa would be in line with a recent policy initiative to increase crop diversification and improve crop rotations (in particular, via the Common Agricultural Policy), as well as with the German Protein Crop Strategy (see [39]).

Stakeholders and farmers expressed mixed feelings on mechanical subsoil loosening (subsoiling). While some thought it important to have a means to quickly break up severely compacted soil layers, others criticized the technique to be a mere technical short-term fix that does not solve the problem. A further concern expressed by various interviewees is that mechanical subsoiling can severely damage soils when applied under unfavourable conditions (such as wet subsoil). The risk of a negative impact on soil structure and the risk of re-compaction with detrimental consequences is a significant limitation to mechanical subsoiling, both for practice and from the perspective of delivering public benefits. A number of scientific studies mirror this view and argue that the prevention of subsoil compaction is preferable to subsoiling [3,40,41].

In contrast to the cultivation of alfalfa or other deep-rooting crops, stakeholders and farmers in the sample do not see mechanical subsoiling as part of good soil management, as the technique per se does not contribute to the prevention of compaction or soil health in general. Yet, it was also stated that mechanical subsoiling could be accepted when applied as a one-time measure that goes hand in hand with adequate changes in the farming system, such as diversifying the crop rotation, using deep-rooting intercrops, and preventing frequent traffic on the field. Researchers in Sweden who tested inter-row subsoiling on potato fields came to a similar conclusion, depicting subsoiling as "a short-term solution that needs to be repeated time after time, unless it is combined with good cultivation practices and perhaps other methods to alleviate soil compaction" [42] (p. 25). While it is not possible to say exactly how widely subsoiling is practiced (according to a representative of the German Agricultural Soil Inventory, this is limited to approximately 5% of agricultural land in Germany), this study suggests that there is a need for an increased awareness of subsoiling risks, preventing compaction, and re-compaction among practitioners, as well as policy-makers.

For injecting organic material furrow-wise into the subsoil, views are diverse, ranging from enthusiasm over scepticism to opposition. On the one hand, farmers and stakeholders see the potential for the method to improve access to water and nutrients, enhance site conditions and soil structure, and stabilise yields, especially in dry regions with sandy soils. On the other hand, and not surprisingly given the early stages of research on this technique, many open questions remain about the likely effects and thus its societal acceptance. It appears clear though that even if the questions on the effects are resolved in a positive way, the technique is only likely to be an acceptable solution for very specific conditions.

Our analysis suggests that injecting organic material furrow-wise into the subsoil is likely to be an attractive option for North-Eastern Germany with its light, sandy soils and its pronounced drought risk, where subsoil compaction is a common phenomenon. Under these conditions, the technique is perceived to have the potential to contribute to stabilizing yields and delivering a good cost-benefit outcome. Moreover, one could argue that a number of further enhancing factors come together in this region. It seems that from the perspective of farmers, the concern related to impairing soil quality is lower when soil on the farm is poor compared to farms with high soil quality. In addition, it requires less physical strength to work deep soil layers of sandy soils compared to heavier soil types. A further enhancing factor might be that farms in North-Eastern Germany are on average larger compared to Southern Germany, and hiring agricultural contractors for certain field work is more common.

However, while a first valuation of a field experiment of this technique after one year [10] only focused on yield effects, we found that a range of other effects on soil functions and ecosystem service provision are relevant for the acceptance of this technique. These include, in particular, impacts on the buffering and filtering function on the subsoil. Interviews also pointed to the fact that the design of the technique as a furrow-wise application might enhance its acceptance. In contrast to a treatment of the complete field, a furrow-wise application on the one hand saves costs for labour and fuel—which is an important factor for farmers [43]—and on the other hand, it presents a less intensive intervention into the soil with overall less pressure on soil structure and soil biota.

## 5. Conclusions

In this study, we have identified a range of views on subsoil management methods. While the small sample size and exploratory nature of the study mean that we cannot draw conclusions with certainty, the analysis points to a number of key acceptance factors for the different subsoil management techniques. Biophysical conditions and the timing of operations are of significant importance for the impact and acceptance of mechanical intervention methods. Overall, views on mechanical interventions are more diverse and, in some cases, more critical, because the benefits are not always certain, the costs can outweigh the benefits, and/or because they entail risk for soil structure and functions. Awareness of multiple subsoil functions is associated with more critical views of mechanical interventions. The cultivation of alfalfa (and other deep rooting crops) is seen to be beneficial for yields without risks for soil structure and functions; however, economic barriers limit its uptake. The study underlines that yields and impacts on other soil functions, as well as the site-specificity of impacts and economic barriers, need to be taken into account in discussions on the role of subsoil management as an option to sustainably maintain yields in the context of climate change and resource scarcity.

Although farmers and stakeholders currently rarely consider the subsoil in their soil management decisions, we expect that, due to an increasing drought risk and resource scarcity issues, as well as continuing subsoil compaction, the importance of subsoil management will increase in Germany.

The issue requires more attention in policy discussions on soil protection and food security in light of changing climate conditions and ongoing soil degradation.

Future work will examine the acceptance of subsoil management in a broader representative sample for Germany and engage with stakeholders in a participatory process to provide inputs to scientific research on the impacts and design of two methods: the alfalfa cultivation and the injection of organic matter furrow-wise into the subsoil.

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# A Multi-Data Approach for Spatial Risk Assessment of Topsoil Compaction on Arable Sites

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**Abstract:** Soil compaction is a human-induced threat which negatively affects soil functions and is highly dependent on site-specific soil conditions and land use patterns. Proper management techniques are indispensable for sustainable soil protection to ensure its function in the long term. A number of concepts exist to develop risk maps on the basis of soil inherent susceptibility to compaction at a given soil moisture level (mostly field capacity). However, the real soil conditions, e.g., current soil moisture content at the time of field work and the real machinery load, are not taken into account. To bridge this gap, we present a multi-data approach for qualitative risk assessment, which combines spatially and temporally explicit data on soil, soil moisture, and land use information. The contributing components integrate daily probability distribution, including inter- and intra-annual variations in land use and weather. We combined soil susceptibility to compaction and field work for the federal state of Lower Saxony per half-months and identified three clusters with more or less compaction risk for Lower Saxony. In spring, mainly manure spreading to maize and in autumn harvesting of maize and sugar beets are contributing to the yearly probability of compaction risk in top soils. With the presented approach risk areas can be identified. For the evaluation of the current compaction risks, farm specifications on machinery and timing of field work must also be taken into account.

**Keywords:** soil compaction; risk assessment; soil functions; soil management

## 1. Introduction

The use of heavy machinery and intensive field traffic can lead to a soil load that exceeds the intrinsic stability and resilience of soil structure and induces soil compaction. Soil compaction is a worldwide problem in agriculture, but particularly in regions with high mechanization rates in the production chain [1,2] and high precipitation [3]. The process of soil compaction leads to a reduction of pore volume and change in pore structure and negatively influences the gas, water, and nutrient exchanges [1,4–7]. On the one hand, it leads to declines in yield quality and quantity, which requires increased use of water, energy, and nutrients to compensate for the declined productivity. Short term (1–4 years) yield losses due to top soil compaction are generally higher then long term yield losses due to subsoil compaction [6,8–11]. However, the effects of soil physical properties on yields strongly depend on weather conditions [11]. On the other hand, the infiltration and storage capacity of water is reduced, which promotes water erosion associated with a loss of nutrients and chemicals, which in turn leads to pollution of surface waters Furthermore, soil compaction has negative impacts on the formation of floods and on the production of greenhouse gases, e.g., in the form of nitrogen losses [12–14]. Especially the subsoil (mostly below 0.3 cm) is endangered by compaction because this layer is not tilled, thus subsoil compaction is much more persistent and alleviation more difficult [2,15]. A persistent deformation of soil layers between 0.3 and 0.7 cm is often observed in field trials and recognized as almost irreversible [17]. Soil compaction is, on the one hand, controlled by the type and intensity of the mechanical load as external factors. Thereby, for subsoil compaction the wheel load plays a major role [8,17–19] and for topsoil the contact area, tire inflation pressure and mean ground pressure are crucial [19]. On the other hand, soil susceptibility, that is mainly dependent on soil type and water content at the time of mechanical load, plays a decisive role [3,15,20–22]. The increase of extreme climate situations and the intensification of agricultural production will intensify these conflicts in the future. To ensure long-term yield levels and to maintain soil functions, site-specific requirements and circumstances must be taken into account [23]. Identification of the region-specific driving factors of soil compaction helps to determine a suitable type and time of cultivation, as well as the proper machinery for field work to avoid soil compaction and to achieve a desired soil structure. Risk Assessment is a tool to describe the probability that an object is exposed hazard, resulting from human activity, and can contribute to a sustainable and site-specific planning and management of soils [14,24–28].

A number of concepts exist to develop maps, indicating subsoil compaction risk on the basis of soil information maps at different scales and for a static soil moisture content (e.g., Lebert [29] for Germany, van den Akker [30] for the Netherlands, D'Or and Destain [31] for the Walloon Region in Belgium, and Jones et al. [12] for Europe). They represent the soil susceptibility to compaction at a given content of soil moisture. Thus, the variability of soil moisture as well as the variability in crop distribution and associated field operations is not considered. So, the current moisture content at the time of field work and the used machine equipment do not find entry [21,22,30]. In the methodology of van den Akker [30], subsoil compaction risk is expressed as wheel-load-carrying capacity (WLCC). The WLCC is defined as the maximum wheel load for a given tire size, inflation pressure, and soil moisture content where no permanent soil deformation occurs. The method is expanded by Lamandé et al. [27] who developed wheel-load-carrying-capacity maps for Europe for a sugar beet harvester with a specific tire and caterpillar at a soil depth of 0.3 m. These maps assume the use of the same sugar beet harvester all over Europe, which is not fact and thus leads to a distorted image. There are only a few studies that integrate weather and/or land use variability into the assessment of soil compaction risk on a regional scale. In their proposed approach, Jones et al. [12] consider the question of the probable soil water content in the growing season to determine the susceptibility of soil to compaction of these time span for Europe. Troldborg et al. [32] used this concept and extended it by the external pressure in the form of land use and machine properties. In a Bayesian Network (BN), all factors are included with location-specific probability distributions and results in the probability of compaction risk for selected locations in Scotland. A different approach is provided by Edwards et al. [33] who introduce the term "readiness" of a soil for operation within a decision support system to plan soil tillage methods for a given field or farm. The average number of suitable days, as well as the probability of individual days categorized as "suitable" or "not suitable" is evaluated for different time periods for a specific field. Götze et al. [34] model the "Soil Compaction Index" (SCI) for top- and subsoil of a field trial in Germany. Individual years and field operations for whole crop rotations of five years are taken into account. The SCI is modeled by using the methodology of Rücknagel et al. [35] where the prevailing soil strength is compared to soil stress induced by field operations. There are tools or applications to predict the risk of soil compaction for a specific field operation. These are, for example, the REPRO-[35,36], the Terranimo-[37], or the TASC-model [38]. All of them are working with the precompression stress concept, which should not be discussed further in this place; instead we refer to other work [16,39–41]. The existing approaches for a region-wide assessment do not account for spatial and temporal variabilities in crop growing patterns, associated mechanical load, and soil moisture content at the time of field work. The approaches at the farm level or for specific field operations require very detailed soil, land use, and machine data, which is not suitable for a region-wide assessment.

In this paper, we present an approach for the region-wide risk assessment of soil compaction, including crop growing patterns, associated mechanical loads, and soil moisture contents in a long-term perspective. We focus on the topsoil as the results form the basis for further socioeconomic investigations at farm level and compaction in the topsoil has a particular impact on short term yield levels. The presented approach links the probability of mechanical load due to field operation as external pressure, with the probability of soil susceptibility to compaction at high temporal and spatial resolution. We use a time series of daily soil moisture and mass data for field block-specific land use for eleven years (2005–2015) to analyze the various probabilities contributing to a joint probability of compaction risk. This allows an identification of the spatial distribution of areas with more or less compaction risk, including inter- and intra-annual, regional variations in crop cultivation (and the associated mechanical load for different field works), soil characteristics, and weather. The contributing factors in terms of soil conditions, crop growing patterns, and machinery are determined for half-month time steps to identify the main adjustment possibilities for a sustainable soil management and mid- and long-term farm planning. With the analysis of manure spreading on a focus area with two different types of machine equipment, we evaluate the available days in different compaction risk classes on a daily basis.

## 2. Materials and Methods

We analyze the compaction risk to the top layer (0–30 cm) of arable land in the federal state of Lower Saxony, Germany, for the spreading of liquid manure and digestates in spring (only to maize), and for harvesting of silage maize, winter grains, spring grains (which are sown in spring and harvested in late summer or autumn), potatoes, and sugar beets in late summer and autumn. We assumed that manure is spread only in spring because with the new fertilization ordinance in Germany the conditions for manure spreading in autumn are highly restricted. We expect a shift of relevant volumes to be applied in spring. For the evaluation of compaction risk, the susceptibility of soil to compaction is compared to the mechanical load of agricultural machines and assessed by the expert-based approach of Lorenz et al. [22]. Therefore, soil and soil moisture data, as well as land use data of the Integrated Administration and Control System (IACS) for the years 2005–2015 are evaluated. IACS data contain field block-specific information on cropland use in farms applying for area-related payments of the EU Common Agricultural Policy (CAP).

The results provide areas with more or less compaction risk due to soil susceptibility to compaction and mechanical load. Furthermore, a distinction of the contributing factors for the whole time-period and for certain years and time slots within the years is made. Figure 1 shows schematically the developed approach with primary data, assessment schemes, calculation steps, and derived results.

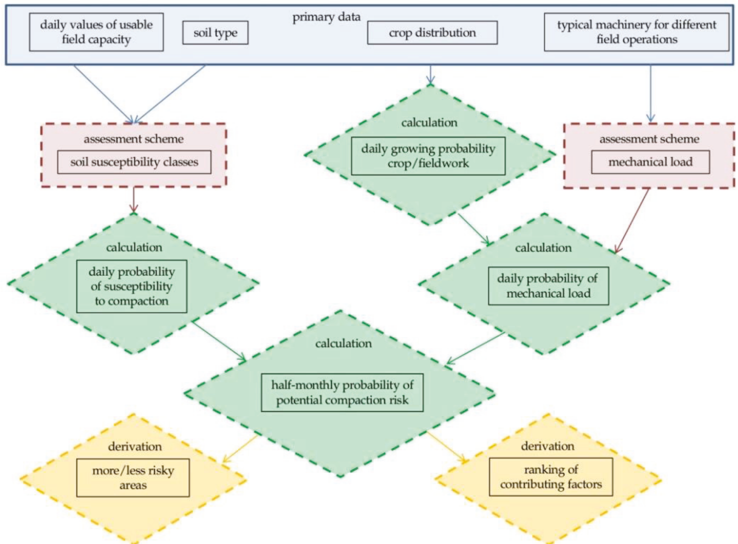



**Figure 1.** Schematic presentation of the used data, assessment schemes and calculation steps.

## *2.1. Primary Data*

### 2.1.1. Soil Data

For soil information, the soil map for Lower Saxony in scale 1:50,000 (BUEK 50) [42] is used. Each soil unit is georeferenced and identified by a unique identification number and described with a profile and the corresponding soil properties for each soil layer. To link the soil data with the modeled effective field capacity (German Weather Service, DWD, Offenbach am Main, Germany; see Section 2.1.2 Soil moisture data), one soil type must be determined for the top soil layer for each profile. The depth of 0–30 cm was chosen to delimit the topsoil as it usually represents the tillage depth. So, the soil moisture was simulated for this depths range by the DWD. In practice, only very few profiles have layers with exact delimitations at 30 cm. For this reason, the major layer between 0 and 30 cm is selected as top soil. Table 1 shows an example of the determination of layered profiles with different depths.

**Table 1.** Example for determining the top soil layer from soil map profile information, lower boundaries for each layer.

| Profile | Layer_1 | Layer_2 | Layer_3 | Layer_4 | Layer_5 | Top Layer |
|---|---|---|---|---|---|---|
| 1 | 10 | 50 | 90 | - | - | layer_2 |
| 2 | 30 | 9 | 60 | - | - | layer_1 |
| 3 | 30 | 51 | 48 | - | - | layer_1 |
| 4 | 5 | 10 | 35 | 80 | - | layer_3 |

### 2.1.2. Soil Moisture Data

The simulated soil moisture data for Lower Saxony were provided by the DWD. The calculations are carried out using the AMBAV model (agricultural meteorological model for calculating the current evaporation [43]). The model is based on the classical Penman-Monteith equation for the calculation of evapotranspiration. Synoptic parameters such as air temperature, precipitation or global radiation are used as input data. The user-defined input parameters for soil and plant properties also determine the output data soil moisture and evapotranspiration. By integrating leaf area indices (LAI), the evapotranspiration, and thus the soil moisture content, is adjusted to crop-and season-specific conditions [43]. Soil moisture is calculated as effective field capacity (eFC) in %, and daily values for the years 2005–2015 are available in a 1 × 1 km grid resolution. Six different soil types (German soil texture classification [44]: slightly loamy sand (Sl2), highly loamy sand (Sl4), medium clayey silt (Ut3), medium clayey loam (Lt3), silty loam (Lu), and loamy clay (Tl)) and four different crops (winter wheat, spring wheat, silage maize, and sugar beet) were considered. Each grid cell is georeferenced and defined by a unique key, and can therefore be spatially located. The determined soil types of the soil map BUEK50 are assigned to the simulated soil types on the basis of their position/proximity depending on their sand-, silt- and clay-content and the associated similar grain size distribution and hydraulic properties [45] (Table 2).

**Table 2.** Classification of soil types for soil moisture simulation.

| Soil Type in Map [44] | Soil Types of DWD eFC Simulations |
|---|---|
| Su2 (slightly silty sand), Sl2 (slightly loamy sand),<br>St2 (slightly clayey sand), Su3 (medium silty sand) | Sl2 |
| Sl3 (medium loamy sand), Sl4 (highly loamy sand), Su4 (highly silty sand)<br>Slu (loamy silty sand), St3 (medium clayey sand), Ls4 (highly sandy loam)<br>Ls3 (medium sandy loam), Ls2 (slightly sandy loam) | Sl4 |
| Us (sandy silt), Uls (loamy sandy silt), Ut2 (slightly clayey silt)<br>Ut3 (medium clayey silt), Uu (pure silt), Ut4 (highly clayey silt) | Ut3 |
| Ts4 (highly sandy clay), Lt2 (slightly clayey loam), Lts (clayey sandy loam),<br>Ts3 (medium sandy clay), Lt3 (medium clayey loam) | Lt3 |
| Lu (silty loam), Tu4 (silty cl), Tu3 (medium silty clay) | Lu |
| Ts2 (slightly silty clay), Tl (loamy clay), Tu2 (slightly silty clay), Tt (pure clay) | Tl |

2.1.3. Land-Use Data

The data from the IACS for the implementation of area-based subsidies within the CAP provide land use data for the years 2005 to 2015 on a field block basis. The information on crop-type with hectare indication in the respective year is used for the evaluation. A field block comprises a spatially defined agricultural area bounded by linear elements (path, course of a river, or edge). One or more fields from one or more farmers with one or more crops may be located within a field block. Each field block is identified by a unique area identifier (ID) with a georeferenced area. If one crop is reported per ID, the spatial location of this crop is clear. However, if more than one crop is reported per ID, the data set includes only the hectares of each crop, but not the specific location within the field block. This results in an uncertainty in the spatial location of crops, which is stated as the probability that a certain crop is cultivated within a defined location (field block). Each year, those cultures that grow on 15 May are reported and are considered to be the only culture for the respective year. In IACS, cultures are recorded very precisely, which is not necessary for this evaluation, since the soil moisture data is only defined for four crops. Thus, the reported crops are grouped according to agronomic aspects into the five groups winter grains, spring grains (+ spring sown oil seed rape rape), silage maize, potatoes, and sugar beets. The corresponding modeled soil moisture values of the DWD can then be assigned to the grouped crops (Table 3). Potatoes are also considered, as they make up a relevant proportion of the area. Due to agronomic similarities, we assigned the soil moisture values of sugar beet to them and grouped spring sown oil seed rape together with spring sown grains. Together, the five groups cover between 73 and 80% of the total arable land in Lower Saxony in the analyzed years (Figure 2).

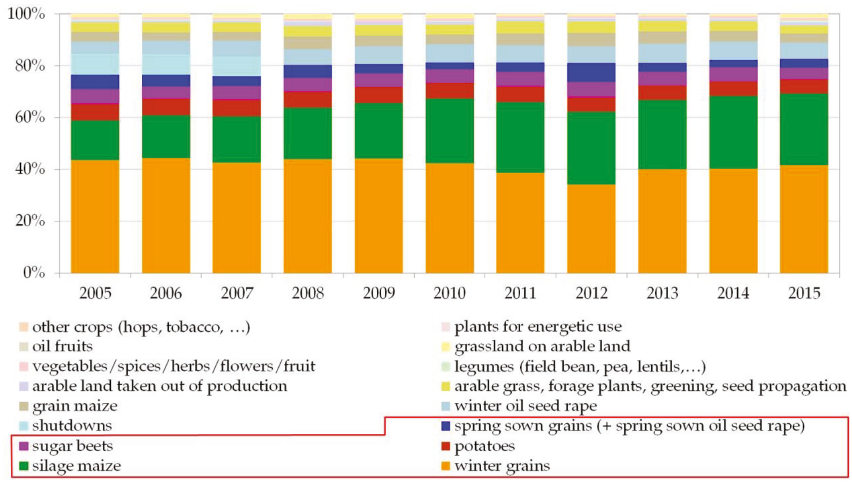



**Figure 2.** Crop groups derived from IACS data 2005–2015, red box: crop groups used for the evaluation.

The field blocks of 2015 are chosen as the reference area for the total growing probabilities of each crop group for 2005 to 2015 because they represent the most up-to-date arable land limitation. The times of field work for manure spreading and harvesting on a half-month basis are taken from a German online-application of the Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL, Darmstadt, Germany [46]) and regionally adjusted for Lower Saxony by expert knowledge [45] (Table 3).

**Table 3.** Connection of the IACS crop-group and the simulated crop by the DWD and the associated field works and time slots.

| DWD-Crop | IACS-Crop Group | Manure Spreading in Spring | Harvesting in Summer/Autumn |
|---|---|---|---|
| winter wheat | winter grains | - | Jul02 to Aug01 |
| spring wheat | spring grains + oil seed rape | - | Jul02 to Aug01 |
| silage maize | silage maize | Feb01 to Apr01 | Sep02 to Okt01 |
| sugar beet | sugar beets | - | Sep02 to Nov01 |
| sugar beet | potatoes | - | Aug01 to Sep02 |

### 2.1.4. Machinery Data

Since there is no available data on the current machinery use for different field operations, locations, and farm-sizes, for this study we defined standard machine equipment with a medium mechanical load according to the method of Lorenz et al. [22] (see Table A1, Appendix A). Table 4 lists the crop-groups and the associated machine equipment for manure spreading to silage maize and harvesting of silage maize, winter grains, spring grains, potatoes, and sugar beets. The mechanical load of the machine equipment is described by the dimensionless characteristic load value which lies between 0.3 and 0.7 [22]. On the one hand, this value represents machine characteristics as wheel load, contact area, tire inflation pressure, or contact area pressure. On the other hand, it represents characteristics of the processing chain as the number of passages associated with the considered field operation or wheeled area, depending on the machine size, field operation, and field shape. Not only are individual machines evaluated, but complete process chains including the organization of field work are taken into account. During maize harvest, for example, the harvester with one transport trailer for street and field transport, or with separated street and field transport trailer, which depends on the organization, labor and machine equipment of the individual farmer, can be evaluated. The two variants differ in the tire pressure of the trailer, as the field trailer can drive at lower pressure when the transport is separated [22]. An example for the calculation of the characteristic load value is given in Appendix A Table A1. With the determined characteristic load value, the mechanical load of the machine equipment can be classified as very low to very high (see Figure 3). As an example for increasing the available days with a lower compaction risk by using machine equipment with a lower mechanical load, we choose manure spreading. Compared to manure spreading with a self-propelled spreader (Table 4, manure spreading (1)), the option with umbilical cord manure spreading (Table 4, manure spreading (2)) is associated with a very low mechanical load. In this option, the manure is stored in a tank on the field edge and pumped via a large cord to the tractor in the field. This reduces the mechanical load by the amount of manure carried on the field compared to the self-propelled spreader.

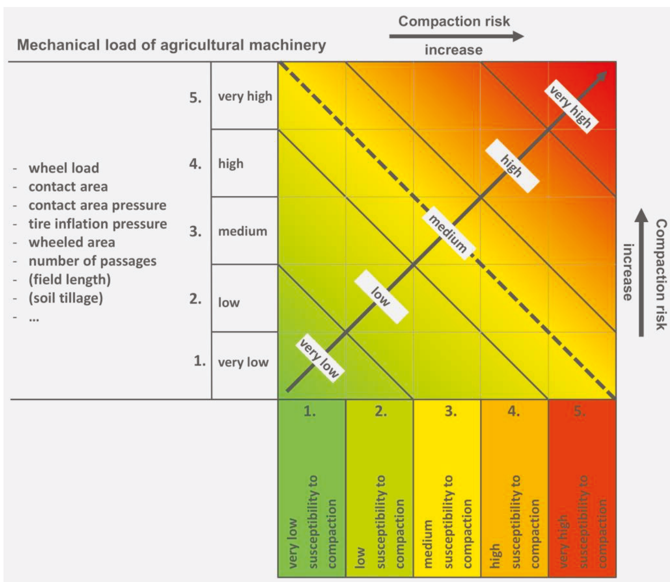



**Figure 3.** Decision matrix (source: modified according to [22]; Reproduced with permission from Lorenz et al., Landbauforschung; published by Johann Henrich von Thünen-Institut, 2016).

**Table 4.** Identified crop-groups, evaluated field works and corresponding machinery (load values and tire pressure see Appendix A, Table 2).

| IACS-Crop Group | Field Work | Machine Equipment |
|---|---|---|
| winter grains | harvesting | Harvester 360 kW 10 $m^3$, dual tires |
| spring sown grains (+ oil seed rape) | harvesting | Harvester 360 kW 10 $m^3$, dual tires |
| silage maize | harvesting | Maize harvester 350 kW, transport trailer 138 kW 40 $m^3$ |
| silage maize | manure spreading (1) | Self-propelled manure spreader 350 kW 20 $m^3$, crab steering |
| silage maize | manure spreading (2) | Tractor 138 kW, umbilical cord 24 m |
| sugar beets | harvesting | Self-propelled harvester, two-axis, and crab steering |
| potatoes | harvesting | Tractor 138 kW, drawn 2-row bunker-harvester |

### *2.2. Assessment of Compaction Risk*

#### 2.2.1. Risk Matrix for Soil Compaction

In the decision matrix of Lorenz et al. [22], the compaction risk is assessed by combining the susceptibility of soils to compaction and the mechanical load applied by machinery, as commonly used in soil compaction risk assessment [2,32,37,47,48] (Figure 3). Thresholds for each soil type to divide them into five susceptibility classes have been defined by an expert consortium (Appendix B, Figure 1). In general, the susceptibility increases with increasing soil water and clay content [15]. The system was verified by Lorenz et al. [22]. In general there were good agreements between the observed and modeled soil susceptibility to compaction. The characteristic load value is also divided into five classes. The intersection of susceptibility and load value class within the decision matrix (Figure 3) leads to five compaction risk classes from very low to very high. An increasing impact on soil functions is assumed with increasing compaction risk classes. For the identification of areas with and without compaction risk, we associate all combinations above the dashed diagonal line with compaction risk and all those below without compaction risk (for soil moisture contents of the susceptibility classes see Appendix B, Table 3). For example, a medium mechanical load combined with very high susceptibility to compaction leads to a high compaction risk (Figure 3).

#### 2.2.2. Spatial Soil Compaction Risk Assessment

For the assessment of soil compaction risk on arable sites in Lower Saxony risk is seen as the probability per time unit that an object is exposed to a hazard [28], which is commonly used in ecological risk assessment [26,32,49–51]. We present a step-wise approach from a general to a case-specific view. The general view means an average compaction risk combining the cultivation and soil moisture data for the years 2005–2015, resulting in an average risk for the whole year per soil-moisture-land-use-unit $j$ ($\mathrm{Pcr}_j$). The soil-moisture-land-use-units $j$ are formed by intersecting georeferenced data sets, namely the soil units; the $1 \times 1$ km grid for soil moisture and the field blocks for 2015 (reference area for crop growing probability) is the most up-to-date arable land limitation. Figure 4 shows a section of the intersected data sets. This means every combination of soil unit, soil moisture grid, and arable land limitation has an individual time series for soil moisture.

The time spans of field work for half-month periods are known (Table 3), but not the exact day or days of field work within these periods. Therefore, we assume field work to be 100% probable every day within the respective half-month of field work. This means that the probability of field work ($\mathrm{Pfw}_i$) is 100% for crop-specific time spans for field work and 0% for all other half-months $k$. To derive the crop growing probabilities, the daily probabilities within a year for the crop groups are calculated as the share of a crop group $i$ within the individual field blocks of the respective year. The growing probability within the individual field blocks is further set in relation to the share in the reference area (field blocks 2015). Furthermore, the mean yearly growing probabilities are calculated, resulting in the average growing probability for 2005–2015 ($\mathrm{Pc}_{i/half\text{-}month\ k}$) for every reference area and crop group $i$. The probability of mechanical load ($\mathrm{Pl}_{i/half\text{-}month\ ki}$) for crop group $i$ grown in a reference area per half-month $k$ is then derived by multiplying $\mathrm{Pfw}_{i/half\text{-}month\ k}$ and $\mathrm{Pc}_i$ (Equation (1)):

$$\mathrm{Pl}_{i/half-month\ k} = \mathrm{Pc}_{i/half-month} \times \mathrm{Pfw}_{i/half-month\ k} \quad (1)$$

The probability of soil susceptibility to compaction in half-month $k$ ($\mathrm{Ps}_{i/half\text{-}month\ k}$) is derived by calculating the mean usable field capacity for each half-month and year. Each value is defined as below and above the diagonal line (see Section 2.2.1, Figure 3). Furthermore, the probability of each half-month is calculated and ranged to be susceptible (above the diagonal line) or not susceptible (below the diagonal line) to compaction. In the next step, the probability of susceptibility to compaction is compared with the probability of mechanical load and the products for all crops within the resulting soil-moisture-land-use-units $j$ as $\mathrm{Psum}_j$ are summarized (Equation (2)).

$$\text{Psum}_j = \sum_{i=1}^{n} (\text{Pl}_{i/half-month\ k} \times \text{Ps}_{i/half-month\ k}) \quad (2)$$

Dividing $\text{Psum}_j$ by the number of half-months (24) leads to the indicator average compaction risk over the entire years $\text{Pcr}_j$ for each soil-moisture-land-use-unit $j$ (Equation (3)).

$$\text{Pcr}_j = \frac{\text{Psum}_j}{24} \quad (3)$$

$\text{Pl}_{i/half\text{-}month\ k}$ = Probability of mechanical load for crop $i$ grown in reference area per half-month $k$

$\text{Pc}_{i/half\text{-}month\ k}$ = Probability of crop $i$ grown in reference area (2015) per half-month $k$

$\text{Pfw}_{i/half\text{-}month\ k}$ = Probability of field work for crop $i$ in half-month $k$ in reference area (2015)

$\text{Ps}_{i/half\text{-}month\ k}$ = Probability of soil susceptibility for soil-moisture-unit per half-month $k$

In addition to the indicator average compaction risk ($\text{Pcr}_j$) over the entire year, the indicator maximum compaction risk per half-month (max ($\text{Psum}_j$)) is identified. This indicator shows the half-month in which the maximum probability of soil compaction is found. With these two indicators for soil compaction risk, a cluster analysis is conducted using the FASTCLUS Procedure in SAS 9.4 [52]. The procedure was run with given numbers of clusters from one to ten and the Elbow Method was used to determine the number of clusters. In the next step, the average value was divided into the contributing factors $\text{Pl}_{i/half\text{-}month\ k}$ and $\text{Ps}_{i/half\text{-}month\ k}$ and analyzed in more detail. For a case specific view, half-months were analyzed by individual days for a focus area in Lower Saxony (red circle in in Figure 5). The focus area has a high average compaction risk (high CR cluster) and three crop groups (sugar beet, silage maize, and winter grains) are grown. The individual days are classified according to the compaction risk classes for each crop group and two special years, representing a wet and a dry year. Years are defined as dry and wet when precipitation shows minimum and maximum deviation from the average precipitation in the period 2005–2015.

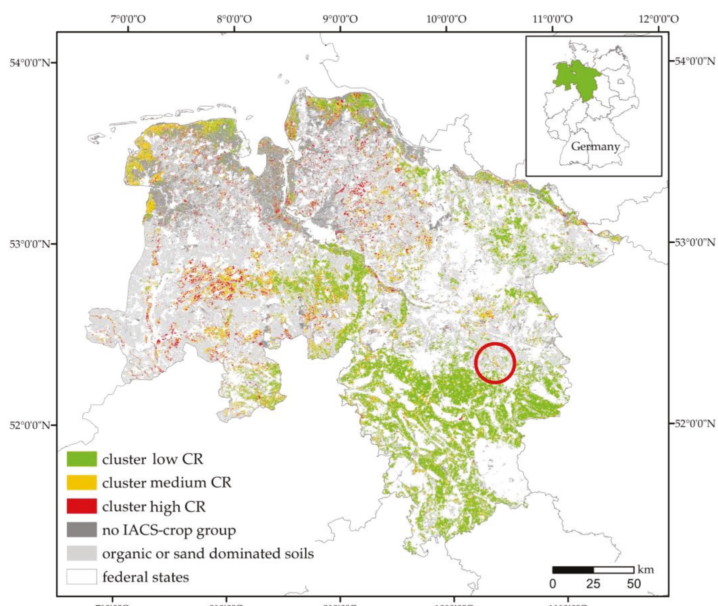
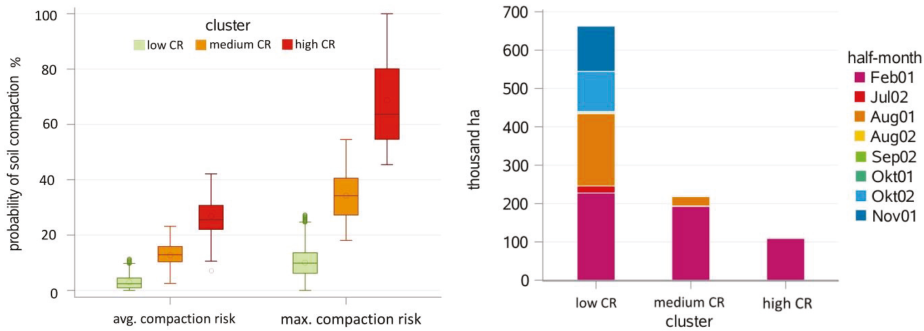



**Figure 4.** Spatial distribution of the derived clusters of topsoil compaction risk for arable sites in Lower Saxony, red circle: case site.




(**a**) (**b**)

**Figure 5.** (**a**) Level of the probability of soil compaction per cluster and indicator average compaction risk and the maximum compaction risk in %; (**b**) area of the evaluated soil-moisture-land-use-units with maximum probability of soil compaction per half-month and cluster (cluster 1: $n$ = 239,131; cluster 2: $n$ = 55,697; cluster 3: $n$ = 89,218).

## 3. Results

There were approximately 1.9 million ha of arable land in Lower Saxony from 2005 to 2015. Due to the reduction of the considered crops to the dominant crop groups and associated soil moisture data, the area for evaluation reduced to approximately 1.7 million ha. The methodology used to assess the soil susceptibility to compaction by Lorenz et al. [22] is not suitable for organic and sand dominated soils. These soils are not considered in the presented analysis (light grey in Figure 5) and lead to a further reduction to 970,000 ha. In total about 50% of the arable land in 2015 was analyzed. The cluster analysis with the indicators $Pcr_j$ (average compaction risk across all years) and $Psum_j$ (maximum compaction risk per half-month) resulted in three clusters with a low, medium, and high compaction risk (CR). Figure 4 shows the spatial distribution of the derived cluster. The areas in the cluster with low CR are spread all over Lower Saxony with a local focus in the southern region. The areas of the clusters with medium and high CR are located predominantly in the central and the coastal regions (Figure 4).

Figure 5a shows the probability in % (y-axis) for the indicators average compaction risk and maximum compaction risk (lower x-axis) for the three clusters (upper x-axis). The low CR cluster has probabilities between 0 and 11% for average compaction risk and probabilities between 0 and 27% for maximum compaction risk. The high CR cluster has probabilities between 7 and 42% for average compaction risk and probabilities for soil compaction between 45 and 100% for maximum compaction risk. The medium CR cluster lies between these two clusters. Figure 5b shows the area of maximum compaction risk per half-months in hectares (y-axis) for the three clusters (x-axis). In the low CR cluster, maximum compaction risk is found in almost every evaluated half-month. In the medium and high CR cluster, the predominant area has its maximum soil compaction risk in Feb01, with a 90–100% probability of susceptibility. Since we have assumed that liquid manure is applied only to silage maize, the determining factors for the maximum compaction risk in February for all three clusters is linked to the probability of silage maize grown in the respective area. In the medium CR cluster, the maximum compaction risk in the first half of August is the result of a 42% probability of winter grains, corresponding with a 60% probability of soil susceptibility to compaction in this time. In the low CR cluster the contributing factors in Jul02 and Aug01 are 50% probability of winter grains with 3% probability of soil susceptibility to compaction in Jul02 and 10% in Aug01. A probability for sugar beets of 15% with approximately 45% probability of soil susceptibility to compaction in Okt02 and Nov01 leads to maximum compaction risk in this half-month.

For all clusters, all soil texture classes are represented by a certain share of area of Lower Saxony (Table 5) (except cluster one; class five). In the low CR cluster, nearly 60% of the area is in soil texture class three, which represents the lower hilly regions in the south with loamy soils. In the high CR cluster, over half of the area has soils in soil class one which represents mostly sandy soils. In the medium CR cluster, the shares are distributed more equally, but with another key area in the coastal region with clayey soils.

**Table 5.** Share of area within the soil classes by cluster.

| Soil Texture Class [44] | | Cluster | | |
|---|---|---|---|---|
| (See Table 2) | Class No. | Low CR | Medium CR | High CR |
| Su2, Sl2 | 1 | 18% | 40% | 52% |
| Sl3, St2, Slu, Sl4, Su3, Su4 | 2 | 9% | 11% | 10% |
| St3, Ls2, Ls3, Ls4, Uu, Us, Ut2, Ut3, Uls | 3 | 59% | 27% | 20% |
| Lt2, Lts, Ts4, Ts3, Lt3, Ut4, Lu, Tu3, Tu4 | 4 | 13% | 20% | 17% |
| Ts2, Tl, Tu2, Tt | 5 | 0% | 1% | 2% |

In the next step, we took a closer look at the individual crops groups and half-months. For an example we chose the high CR cluster with an average of 62% silage maize, 22% winter grains, 9% potatoes, 7% spring grains, and 5% sugar beet grown. Figure 6 shows for each crop the probability of field work (Pfw), the probability of soil susceptibility to compaction (Ps), and the resulting average probability of soil compaction for the analyzed half-months in spring as average for the clusters. The growing probability of a crop group is constant during the year and it is assumed that field operations have the same probability every day (100%) within the defined half-months (Table 3). Thus, the probability of field work is 62% for silage maize each month in the considered time span. Consequently, variations in the probability of soil compaction depend only on the variations in the soil's susceptibility to compaction (Ps). For example, in Feb01 the soil is 100% susceptible to compaction and in Feb02 it is 94%. This results in a decrease in the probability of soil compaction from 68 to 65%. As manure spreading to maize is the only field work in spring, the other crops in the high CR cluster do not contribute to the probability of soil compaction in spring.

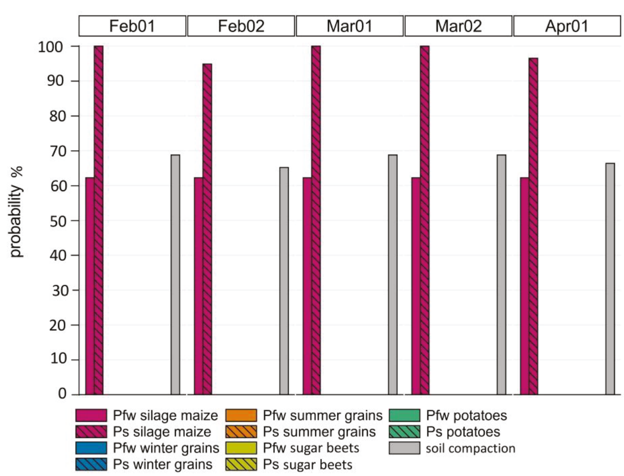



**Figure 6.** Probability of field work per crop groups (Pfw), soil susceptibility to compaction in 0–30 cm (Ps), and probability of soil compaction for cluster three in spring per half-month.

Even if no maximum probabilities of soil compaction are found in summer/autumn for this cluster, there is a certain probability of soil compaction. Figure 7 shows Pfw, Ps, and the probability of soil compaction in summer/autumn. The low probabilities of field work for winter grains, summer spring grains, and potatoes coincide with low probabilities of soil susceptibility to compaction, and thus low probabilities of soil compaction from Jul02 to Sep01. In Sep02, the probability of soil compaction increases (8%) because in this period there is an additional harvesting of silage maize with a field work probability of 62%. In Okt01, the probability of soil compaction rises to 23% because of increased soil moisture content while harvesting silage maize and sugar beets with their associated field work and mechanical load.

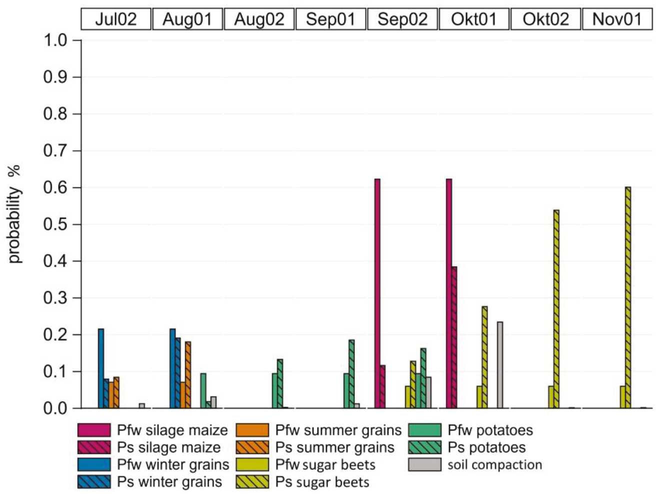



**Figure 7.** Probability of field work per crop groups (Pfw), soil susceptibility to compaction in 0–30 cm (Ps) and probability of soil compaction for cluster three in autumn per half-month.

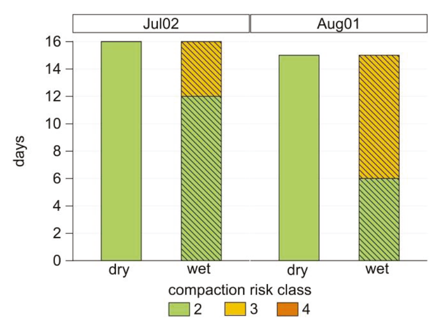
In Okt02 and Nov01, it was assumed that the only field operation is harvesting sugar beets (Table 4). The probability of susceptibility in this time is high (60%), but the probability of field work is low at 5%, resulting in a probability for soil compaction below 1%. So, the main contributing factors to the average soil compaction risk in the high CR cluster are manure spreading to silage maize in spring and harvesting silage maize in the first half of October. Both the high share of silage maize and high soil susceptibility to compaction (due to high soil moisture contents) during field work are the major controlling factors.

A focus area (red circle in Figure 5) for the high CR cluster was chosen to demonstrate, on the one hand, the impact of the used machine equipment on the average soil compaction risk and on the other hand, to point out the variability of days within the compaction risk classes for single years, different machine equipment, and half-months. The chosen site comprises 5.3 ha of sandy loam (Slu) with an average compaction risk of 23%. The growing probabilities are 18% winter grains, 55% silage maize, and 27% sugar beets. The maximum risk, with 55% probability for soil compaction, is found in the first half of February due to manure spreading to silage maize. For manure spreading, two different types of machine equipment were evaluated: the self-propelled manure spreader with a medium mechanical load and the umbilical cord manure spreading with a very low mechanical load. Machine equipment with a medium mechanical load was assumed for harvesting (see Table 4). For spring, 2008 was chosen as a wet year and 2012 as a dry year. For autumn, 2007 was chosen as a wet year and 2011 as a dry year (Table 6).

**Table 6.** Average precipitation in mm (pcp_avg) for spring (Feb01–Apr01) and autumn (Jul02–Nov01), identified values for a dry (pcp_dry) and a wet (pcp_wet) year, and the respective derivation in % (derivation_wet, derivation_dry) from pcp_avg.

| | Pcp_Avg | Pcp_Wet | Pcp_Dry | Derivation_Wet | Derivation_Wet |
|---|---|---|---|---|---|
| Spring | 83 | 145 | 45 | +74% | −45% |
| autumn | 232 | 343 | 174 | +48% | −24% |

The soil compaction risk is categorized into five classes from very low to very high (Figure 3). Figure 8 shows the number of days within the compaction risk classes (y-axis) for harvesting winter grains (a), harvesting sugar beets (b), and harvesting silage maize (c) per half-month (upper x-axis). The number of days is further presented for the wet and the dry year for each half-month (lower x-axis). In general, the days with low compaction risk decrease from Jul02 to Nov01 because of increasing precipitation, soil moisture content, and thus, soil susceptibility to compaction. For harvesting winter grains (Figure 8a) in Jul02 and Aug01 in a dry year, all days have a low– medium compaction risk; in a wet year the days with low compaction risk increase in favor of the days with medium compaction risk. For harvesting sugar beets (Figure 8b) in a dry year, all days in the associated time period have a low compaction risk. In a wet year, days with a low compaction risk are only available in Sep02. The number of days with medium and high compaction risk increase until Nov01. For harvesting silage maize (Figure 8c), in a dry year in Sep02, all days have a low compaction risk, and in Okt01, there are 11 days with a low and 4 days with a high compaction risk. In a wet year, in Sep02, just 12 days have a low compaction risk. For this soil type (Slu) and medium mechanical load compaction risk class 2 is associated with field capacity 0–60.5%, class 3 with >60.5–94%, and class 3 with >94%; for a very low mechanical load class 1 is associated with 0–60.5% field capacity, class 2 with >60.5–94%, and class 3 with >94%.




**(a)**

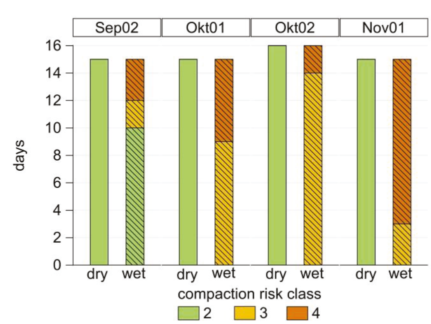
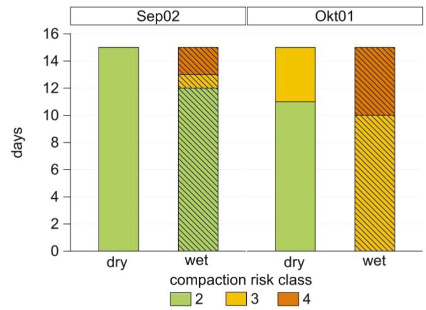



**Figure 8.** *Cont.*

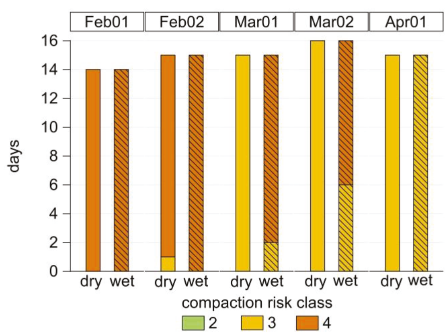
(**b**)



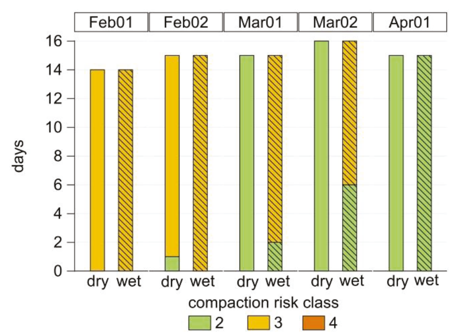

(**c**)

**Figure 8.** Days within the compaction risk classes (topsoil) for a wet and a dry year; (**a**) winter grains harvest, (**b**) sugar beet harvest, (**c**) silage maize harvest; risk classes 2 = low, 3 = medium, and 4 = high.

For manure spreading to maize in spring the opposite holds true for the conditions in autumn. Over the course of the year the days with a high compaction risk decrease and the days with a medium risk increase (Figure 9a,b).




(**a**)




(**b**)

**Figure 9.** Days within the compaction risk classes (topsoil) for a wet and a dry year for manure spreading to silage maize in spring with (**a**) a medium mechanical load and (**b**) a very low mechanical load. Risk classes 2 = low, 3 = medium, and 4 = high.

With the self-propelled manure spreader (Figure 9a), all days are associated with a high compaction risk for both a dry and a wet year in Feb01. In a dry year, there is one day with medium compaction risk in Feb02, there are no such days for wet conditions. In Mar01, all days have a medium compaction risk for dry conditions, and just two for wet conditions. For both conditions, there is an increase to 15 days with medium compaction risk until Apr01. With umbilical cord manure spreading (very low mechanical load) the compaction risk is reduced. While the soil susceptibility to compaction remains the same, the decreased mechanical load leads to a lower risk class for each day (Figure 9b). While all days in Feb01 are associated with high compaction risk with the self-propelled manure spreader, they are associated with a medium compaction risk with the umbilical cord spreader. So, even if soils are susceptible to compaction, the compaction risk can be reduced through the choice of machine equipment. The average probability of soil compaction for the focus area was reduced from 23% for manure spreading with the self-propelled manure spreader to 13% with the umbilical cord spreader.

To answer the question of current soil compaction risk it needs to be evaluated whether the farm specifications are suitable to carry out field operations within the given days or not. This depends on the capability of the machine equipment, the labor force, the size and shape of the field and the current share of the specific crops.

## 4. Discussion

The highest probability for soil compaction was found in the high CR cluster. Over 50% of the areas in this cluster are associated with sand dominated soils. The reason for the high probability of compaction risk is the high shares of silage maize and the corresponding manure spreading in spring. With the high soil moisture contents from Feb01 to Apr01 we find a high probability of compaction risk even on the sandy soils in the high CR cluster which are ranked as low to medium endangered by Lebert [29]. For the determination of compaction risk areas, this shows the necessity to include not only the type of soil, but also the crop growing patterns, times of field work, and mechanical load of the machine. An additional necessity is the consideration of time windows/spans of field work and thus the given soil moisture content at the time of field operation. Comparing the results with those of Lebert [29], there are both similarities and differences. In general, there is a good match for the medium and low CR cluster in the center and north of Lower Saxony, whose soil functions in the subsoil layer are classified by Lebert [29] as highly endangered. We identified differences for the areas in the low CR cluster in the south of Lower Saxony; in this area the soil functions in the lower soil layer are also classified by Lebert [29] as highly endangered, but a low probability of compaction risk is shown in the presented study. The loamy soils in this cluster are inherently more susceptible to compaction but are not faced with a high probability for field operations in critical times with high soil moisture contents. Thus, the probability of compaction risk is low due to patterns of cropping and field operations. In this case, the approach proposed by Lebert [29] leads to an overestimation of compaction risk because the time and mechanical load of field operations is not taken into account. Within the general similarities and differences, there are variations resulting from the spatially explicit analysis of the cropping patterns and the higher resolution of the soil map used. For two fields in northern Germany, Kuhwald et al. [53] evaluated the compaction risk using the SCI. Temporal variations in soil moisture contents as well as crop growing patterns and associated machine equipment are included. The seasonal variations of the derived compaction risks show similar patterns throughout the year with a strong dependency on soil moisture content.

The assessment of the average compaction risk was conducted with a medium mechanical load (method see Appendix A, Table A1). As the comparison for manure spreading showed, with a low or very low mechanical load the magnitude and distribution compaction risk may vary. However, it shows that the use of machines with a low (or very low) mechanical load can significantly reduce the risk of compaction. These findings reflect the physically based results of Schjønning et al. [8] who noticed a lower penetration resistance and higher yields after traffic in springtime with a self-propelled manure spreader with less filling as compared to more filling, or Lamandé and Schjønning [17], who account for increasing soil stress with increasing wheel loads. At the same time, time spans with a lower compaction risk, and thus field working days can be expanded. The work presented is an improvement of Troldborg et al. [32] since both the cropping patterns and the field operating times could be analyzed in a more differentiated form in terms of time and quality. Compared to the approach of Jones et al. [12], which includes soil moisture content as a potential soil moisture deficit during the growing season, we could include the inner annual variations of soil moisture contents to a greater extent and in more temporal detail; this is of particular interest for farm-specific planning.

For the analysis, we made a number of assumptions due to a lack of data and knowledge. The coarse grouping of cultures and assignment of soil moisture values represents an abstraction of reality, as well as the assumption of used machinery and field working times. Additionally, due to the IACS-data, we incorporated a certain amount of uncertainty in the spatial explicit location of the grown crops. Because of the number of assumptions and the uncertainty in the location of the crops, we are not able to assess a prevailing compaction risk, but a potential expressed by probabilities. Specific farm equipment has to be included to evaluate the prevailing compaction risk, as in the study of Rücknagel et al. [35,54] and Edwards et al. [54]. As the used assessment system by Lorenz et al. [22] has been initially verified by the developer, the next step is to further substantiate the system with physically based findings, which is planned in ongoing projects. Further on, the presented approach should be applied with a different underlying soil moisture model (for example, MONICA [55]). On the one hand, this is to test the sensitivity of the approach to soil moisture data; on the other it is to further differentiate crops and their associated soil moisture contents. A comparison of the modeled compaction risk of the same study sites with the approach of Kuhwald et al. [53] could give an indication of the model quality.

## 5. Conclusions

With the presented approach, we clearly identified the main maize cropping area in Lower Saxony as the area with the highest probability of soil compaction, where the main contributing factor is manure spreading in spring. The remaining area of Lower Saxony is associated with a lower probability of soil compaction, resulting from a combination of manure spreading in spring and harvesting in autumn. It has been shown that the use of soil-protecting machine equipment while manure spreading in spring can significantly reduce the risk of compaction. This plays a major role, especially in regions with a high proportion of maize. These areas should be examined more closely to identify farm- and site-specific driving factors for soil compaction and to develop and propose adapted management strategies to protect soil functions in the long-term. Further studies within the SOILAssist-project will use the presented results to evaluate current compaction risk at the farm scale, by determining unsuitable conditions (medium to very high compaction risk) for field work and to evaluate technical and management options to avoid soil compaction in these situations in a socioeconomic sense. This work shows how different (mass) data can be used to identify risk areas in ex-post evaluation. Above all, the inclusion of high-resolution land use and soil moisture data represents an improvement of existing approaches. At the same time it shows the limitations and problems due to a lack of data and information availability.

**Author Contributions:** S.L. designed the study, analyzed the data and wrote the manuscript; M.L. reviewed and edited the original manuscript; M.L. and J.B. are responsible for the funding acquisition and project administration; M.L., J.B., and N.F. are responsible for defining mechanical equipment and the associated mechanical load, and were the expert consortium for questions about the susceptibility of soil to compaction, machinery, crop growing patterns, and the decision matrix used (Methodology).

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## Appendix A

**Table A1.** Calculation method for the "characteristic load value"; example: maize harvester 350 kW, transport trailer 138 kW 40 $m^3$, transport trailer with tire pressure for street transport, and transport in track of harvester [22].

| | | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|---|
| | **Machine and Number of Axles Taken into Account** | **Harvester** | | **Transport Tractor** | | **Trailer** | | **Maximum** | **Mean** |
| | | **Front Axle** | **Rear Axle** | **Front Axle** | **Rear Axle** | **Front Axle** | **Rear Axle** | | |
| | | 1. axle | 2. axle | 3. axle | 4. axle | 5. axle | 6. axle | | |
| 1 | wheel load [t] | 4.8 | 3.5 | 1.2 | 3.2 | 3.8 | 3.8 | 4.8 | 3.4 |
| 2 | tire pressure [kPa] | 100 | 100 | 160 | 200 | 350 | 350 | 350 | 210 |
| 3 | contact area pressure [kPa] | 120 | 120 | 100 | 120 | 150 | 150 | 150 | 130 |
| 4 | number of wheel passages per track | 6 | | | | | | | |
| 5 | share of wheeled area [%] | 40 | | | | | | | |
| | | lower bound | upper bound | weighting | | share of load | | | |
| 6 | wheel load [t] | 0.5 | 12 | 2.0 | | 0.8 | | | |
| 7 | tire pressure [kPa] | 60 | 400 | 1.0 | | 0.5 | | | |
| 8 | contact area pressure [kPa] | 40 | 250 | 2.0 | | 1.1 | | | |
| 9 | number of wheel passages per track | 1 | 6 | 0.6 | | 0.6 | | | |
| 10 | share of wheeled area | 0 | 100 | 0.2 | | 0.1 | | | |
| 11 | sum of weightening | | | 5.7 | | | | | |
| 12 | sum of load | | | | | 3.02 | | | |
| 13 | "characteristic load value" | | | | | 0.52 | | | |
| | load class | 1 | 2 | 3 | 4 | 5 | | | |
| | upper bound | 0.38 | 0.46 | 0.54 | 0.62 | 0.70 | | | |
| | lower bound | 0.30 | 0.38 | 0.46 | 0.54 | 0.62 | | | |

Calculation of the weighting of parameters "number of wheel passages per track" and "share of wheeled area":

(1) C9 = (H1/B6) × C6

(2) C10 = (C9 + (A5/100)

Calculation of the share of load:

(3) E6 = (G1/B6) × C6

(4) E7 = ((H2/B7) × C7)/100

(5) E8 = ((H3/B8) × C8)/100

(6) E9 = (A4/B9) × C9

(7) E10 = (A5/B10) × C10

**Table 2.** Ranges of axial load and tire pressure for the used machine equipment.

| Machine Equipment | Mechanical Load | Number of Axles Considered | Range of Axial Load in t | Range of Tire Pressure in kPa |
|---|---|---|---|---|
| Harvester 360 kW 10m$^3$, dual tires | medium | 2 | 3.1–11 | 100–160 |
| Maize harvester 350 kW, transport trailer 138 kW 40 m$^3$ | medium | 6 | 1.2–4.8 | 100–350 |
| self-propelled manure spreader 350 kW 20 m$^3$, crab steering | medium | 2 | 10–10.9 | 140 |
| Tractor 138 kW, umbilical cord 24 m manure spreading | very low | 2 | 0.7–3.9 | 80–100 |
| self-propelled sugar beet harvester, two-axis, crab steering | medium | 2 | 7.7–8.6 | 150 |
| Tractor 138 kW, drawn 2-row potato bunker-harvester | medium | 3 | 1.1–6 | 80–200 |

**B.**

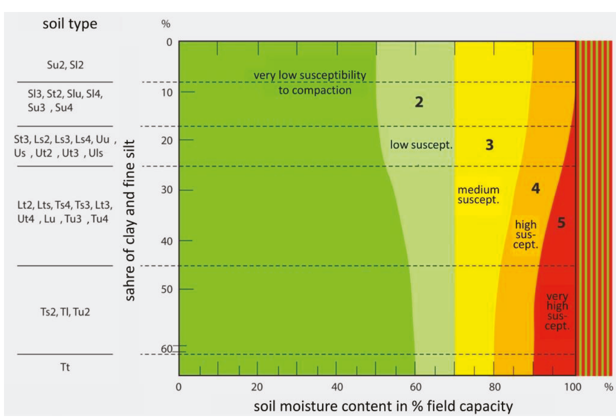


**Figure 1.** Soil susceptibility to compaction depending on soil type and soil moisture content (source: modified according to [22]; Reproduced with the permission from Lorenz et al., Landbauforschung; published by Johann Henrich von Thünen-Institut, 2016).

**Table 3.** Mean values for medium susceptibility per soil type for average risk evaluation.

| Soil Susceptibility Class | Soil Type | % Field Capacity |
|---|---|---|
| 1 | Su2 (slightly silty sand) and Sl2 (slightly loamy sand) | 80 |
| 2 | Su4 (highly silty sand), Su3 (medium silty sand), Slu (loamy silty sand), Sl3 (medium loamy sand), Sl4 (highly loamy sand), and St2 (slightly clayey sand) | 79.5 |
| 3 | Ut3 (medium clayey silt), Ut2 (slightly clayey silt), Uls (loamy sandy silt), Us (sandy silt), Uu (pure silt), Ls2 (slightly sandy loam), Ls3 (medium sandy loam), Ls4 (highly sandy loam), and St3 (medium clayey sand) | 79 |
| 4 | Ut4 (highly clayey silt), Lu (silty loam), Tu4 (silty cl), Tu3 (medium silty clay), Lt2 (slightly clayey loam), Lt3 (medium clayey loam), Lts (clayey sandy loam), Ts4 (highly sandy clay), and Ts3 (medium sandy clay) | 77 |
| 5 | Ts2 (slightly silty clay), Tl (loamy clay), Tu2 (slightly silty clay), and Tt (pure clay) | 75.5 |

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# Applying Soil Health Indicators to Encourage Sustainable Soil Use: The Transition from Scientific Study to Practical Application

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**Abstract:** The sustainable management of land for agricultural production has at its core a healthy soil, because this reduces the quantity of external inputs, reduces losses of nutrients to the environment, maximises the number of days when the soil can be worked, and has a pore structure that maximises both the retention of water in dry weather and drainage of water in wet weather. Soil health encompasses the physical, chemical, and biological features, but the use of biological indicators is the least well advanced. Sustainability also implies the balanced provision of ecosystem services, which can be more difficult to measure than single indicators. We describe how the key components of the soil food web contribute to a healthy soil and give an overview of the increasing number of scientific studies that have examined the use of biological indicators. A case study is made of the ecosystem service of water infiltration, which is quite an undertaking to measure directly, but which can be inferred from earthworm abundance and biodiversity which is relatively easy to measure. This highlights the difficulty of putting any monitoring scheme into practice and we finish by providing the considerations in starting a new soil health monitoring service in the UK and in maintaining biological monitoring in The Netherlands.

**Keywords:** ecosystem services; soil food web; earthworms; monitoring; water infiltration

## 1. Introduction

Human societies are highly dependent upon healthy soils for the delivery of ecosystem goods and services, including provisioning (e.g., food, fibre, timber, fuel), regulation (e.g., climate, disease, natural hazards), waste treatment, nutrient cycling, and cultural services [1]. Many ecosystem services are driven by trophic interactions in the soil food web (i.e., who eats who) [2] and interactions between organisms in the soil food web are the critical determinant of soil function [3]. In this paper we will explain the role of the soil food web for soil health, give examples to demonstrate the linking of soil biology to function (as in Reference [4]) and provide observations on the practical issues of developing and maintaining a monitoring programme for soil health. In particular we discuss the relationship between an easily measured biological indicator (i.e., earthworms) and an ecosystem service that is technically challenging to measure (i.e., water infiltration). We then examine the challenges in rolling out a new soil health monitoring programme for farmers in the Northern UK and those of an established policy-related programme in The Netherlands.

## 2. Ecosystem Services and the Soil Food Web

In terrestrial ecosystems, higher plants are the major primary producers of biomass. Carbon and energy are released into the soil by root exudates and plant residues. In soil, bacteria and fungi are the primary decomposers of dead organic matter such as plant residues, root exudates, decaying micro-organisms, and animal manure. Other groups of organisms feed on bacteria (bacterial-feeders), fungi (fungal-feeders), plant roots (micro herbivores), or animals (predators and top predators). Some organisms are very selective and feed only on a few other species, whilst others, the omnivores, exploit various food sources. All these trophic interactions and biological activity drive carbon and nutrient cycles, soil structure formation, disease suppression, and ultimately soil ecosystem services [5].

Carbon and nutrient cycling is performed not only by microbes but also by microbivores (i.e., grazers) and predators which decompose microbes and other organisms. In a field study at the Lovinkhoeve experimental farm in The Netherlands, microbes, microbivores, and N mineralisation were monitored in a winter wheat field under conventional and integrated management. The microbial biomass was strongly dominated by bacteria and was not significantly larger in the integrated field than in the conventional field, whereas protozoan and nematode biomasses were 64% and 22% larger, respectively [6]. Average N mineralisation was also 30% greater in the integrated field. The differences were attributed to the approximately 30% larger soil organic matter content of the integrated field which appeared to increase the activity (but not biomass because of increased turnover) of bacteria, and biomasses of protozoa and nematodes [6]. A food web model indicated that an important part of the observed N mineralisation can be explained by the grazing activity of protozoa and nematodes [7]. While this study indicated a direct faunal contribution to N mineralisation of up to 45%, other studies have also indicated indirect contributions of the fauna to C and N mineralisation rates. Rashid et al. [8] used a production-ecological model to show that N mineralisation by earthworms, enchytraeids, fungi, and protozoa together added up to almost all the N mineralisation measured as herbage N uptake. There were significant contributions from fungi (32–41%), protozoa (16–35%), and earthworms (9–30%).

There is a positive role of microbial activity on soil structure and stability, with fungi having three types of effect: physical entanglement, production of extracellular polysaccharides, and production of hydrophobic substances [9]. A meta-analysis [10] shows the positive relationship between the responses of fungi and soil aggregate stability, demonstrating a strong functional link between fungi and soil structure. In addition to fungi, earthworms also contribute to soil structure formation, being major ecosystem engineers: accelerating microbial activity; mixing organic matter and creating macro-pores in the soil. Earthworm abundances and functional group composition were shown to be positively correlated with water infiltration rate, with a consistent trend of increased earthworm and fungal community abundances and complexity following transitions to lower intensity and later successional land uses [10]. Andriuzzi et al. [11] found that anecic earthworms, which create vertical macropores, can counteract the effects of intense rain events on soil and plants. This is important information as some of the strongest ecological and agronomic effects of climate change will occur through pulse events, rather than altered average trends.

Carbon sequestration is an important aspect of sustainable agricultural systems, and to increase soil organic matter (SOM) and sequester carbon, decomposition must be slightly slower than the input of plant material, on a long-term basis. The major factors controlling SOM dynamics are: (1) the quality of the incoming substrates, (2) the role of the soil biota and especially the microorganisms, (3) physical protection such as in aggregation, (4) interaction with the soil matrix, and (5) the chemical nature of the SOM itself [12]. Whether plant inputs are first converted to microbial residues before stabilization influences how SOM responds to land use and climate change. Plant residues that accumulate in soil through physical protection (e.g., inside aggregates) or in zones with low biological activity, are susceptible to destabilization following disturbances such as cultivation or in response to environmental change (e.g., temperature increases). If, however, plant materials are synthesized into microbial proteins, lipids or polysaccharides, the resulting organo-mineral associations may include ligand bonds or other strong interactions that have lower temperature sensitivity and may better withstand perturbations. Kallenbach et al. [13] demonstrated that microbial processing of simple C substrates such as sugars and the lignin monomer syringol, produced an abundance of stable, chemically diverse SOM dominated by microbial proteins and lipids. The actual substrate chemistry may be less important for SOM accumulation than how it influences fungal abundance and microbial carbon use efficiency in the long term.

The resistance and resilience of soil food webs to climate change is increasingly recognised as an important inherent property [14]. De Vries et al. [15] showed that the fungal-based food web of an extensively managed grassland soil, and the processes of C and N loss it governs, was more resistant, although not resilient, and better able to adapt to drought than the bacterial-based food web of an intensively managed arable soil in the south of England. Across four European countries of contrasting climatic and soil conditions, soil food web properties strongly and consistently predicted processes of C and N cycling across land-use systems and geographic locations, and were a better predictor of these processes than land use [16]. Beyond the well-known role of arbuscular-mycorrhizal fungi (AMF) in improving plant nutrient uptake, AMF can contribute to water use efficiency and resistance against drought and salinization [17–19]. Laboratory studies have also shown that AMF reduce leaching of N and phosphorus (P). These findings show that more extensive management promotes more resistant, and adaptable, fungal-based soil food webs.

The soil food web is also implicated in disease suppression. Soil-borne fungal and bacterial root pathogens can cause serious losses to agricultural crops and are difficult to manage, especially in narrow rotations. Enhancement of disease suppressive properties of soils is of great importance for sustainable agriculture, by limiting the ability of pathogens to establish or to produce disease symptoms. Postma et al. [20] analysed soil samples from 10 organic arable farms for disease suppressiveness and showed significant correlations between suppressiveness and the occurrence of specific beneficial microorganisms, as well as with more general microbial properties. Probably the soil suppressiveness is a combined effect of general and specific disease suppression.

Soil health is fundamentally underwritten by the assemblages that carry out the various key processes. These assemblages are predominantly biological in origin, but actually involve a particular configuration of the biology, physics, and chemistry of the soil constituents. What is quite clear is that any measure of soil health must be multivariate—single properties will not adequately encompass or integrate the features or issues that underwrite soil health [21].

## 3. Measuring and Monitoring Soil Condition to Preserve Ecosystem Services

Ecosystem services are under threat from biodiversity decline, compaction, contamination, erosion, landslides, organic matter decline, salinization, and sealing, all exacerbated by climate change [22]. Assessments of the condition that soils are in and what policies might be followed for their preservation are very similar across a range of scales. Globally, unprecedented demand is stressing the land and water systems that underpin food production, such that global and national approaches need to be aligned [23]. Indeed, a global soil resilience programme to monitor soil fertility and function and the ecosystem services provided by soils has been suggested [24]. Across Europe the unsustainable use and management of land is leading to increased soil degradation, the control of which requires harmonisation of soil monitoring and data collection programmes [22]. Gregory et al. [25] critically reviewed the effects of soil threats for likely effects on UK soils and yield, noting many reductions in ecosystem services (not just crop yield) as a result and again recommending a monitoring programme. A recent gap analysis at the European level [26] recommended additional soil biological and physical parameters within the LUCAS soils survey and called for further development of national soil monitoring schemes. Given this increasing recognition of the importance of soil, O'Sullivan et al. [27] looked at practicalities of implementing a soil monitoring network for Ireland, suggesting a 16 $km^2$ grid with baseline analytical costs of €0.7–3 million for each sampling round. This strong and increasing policy requirement for the effective monitoring of soils at local, regional and national scales has been recognised previously and consistently [28–34].

Most soil processes are mediated by soil biota in direct relationship with the physico-chemical properties of their environment, although there is still a need to better understand how soil biodiversity links with soil functioning [4]. Biological indicators are relevant in supporting policy and decision-making to achieve sustainable soil management [32,35,36], and the inclusion of biological indicators to assess changes in the delivery of ecosystem functions is accepted practice both at national and European scales [5,32,37–39]. Biological indicators have long been developed and applied in specific environmental situations, making the extrapolation of values and applicability under different conditions difficult. Furthermore, despite recent efforts to standardise, a wide range of different methods and procedures are applied, which makes comparison all the more difficult. National [40,41] and European [42]) initiatives have been undertaken to recommend indicators across Europe and elsewhere [32,43–46].

Reviews have compared a large range of biological indicators for scientific and technical relevance to assist policy-makers in land management [32,33,42,46–48], with the consensus being that major efforts remain to be made in order to standardise operational procedures and to validate them for different types of land use [37]. The selection of potential biological indicators is only a step in developing a practical monitoring scheme [49], as there are operational issues to be solved such as: ease of application, robustness, sensitivity, laboratory accuracy, throughput, economic value and descriptiveness. The selection criteria for biological indicators are well described [33,46,47], but consideration also has to be given to the cost-effectiveness of the indicators and the interpretation of the results from the monitoring. Different stakeholders have different information needs, and different indicators have to be developed to answer their specific requirements [46]. All these factors have been recognised as crucial steps in the development of a soil quality assessment procedure [15].

## 4. Measuring an Indicator Rather than the Actual Ecosystem Service

With global climate changing faster than politicians can discuss, the frequency and intensity of rain storms is increasing, posing threats of flooding and waterlogged soils in agricultural and sedentary areas alike. Land management aiming to enhance the water regulation capacity of soils, and thus climate-proofing agriculture and the urban environment (mitigation and adaptation), is in dire need of cost-effective and policy-relevant indicators to evaluate (e.g., precipitation surplus infiltration capacity and soil porosity). Direct measurement of water infiltration rates in the field (e.g., using a ring infiltrometer, [50]) is a simple method, but is time consuming (it can take several hours to make measurements at a single point) and is logistically challenging as many tens of litres of water are required. So it is not practical as a routine or rapid way to monitor this particular ecosystem service. Earthworms, on the other hand, are relatively easy to measure (approximately 15 min for one point) and it logistically quite feasible to do many tests per day.

Pioneering has been done on establishing and quantifying the relationship between earthworm communities and the water infiltration capacity of the soils they inhabit. Wilfried Ehlers [51] already in 1975 estimated earthworm contribution to soil water infiltration as more than 1 mm/min (via conducting burrows), although the volume of such channels amounted to only 0.2 vol % in untilled grey-brown podzolic soil derived from löss. Tilled soils did not feature effective channels in the plough layer or below, because of lacking connection to the soil surface. Earthworm densities in untilled plots had doubled in four years of no-tillage practice. Bouché [52] in 1977 measured infiltration rates in 17 soils and gave a mean rate of 150 mm $h^{-1}$ per 100 g $m^{-2}$ of earthworms and even 282 mm $h^{-1}$ per 100 g $m^{-2}$ of anecic species. A further study was made in nine sites analysing hydraulic (ctive) burrows and their structural properties. Infiltration rate was correlated to earthworm biomass (r = 0.975), burrow length, surface and volume (r = 0.99), but not with burrow diameter, hydraulic tortuosity or with earthworm number and soil profile depth [53].

Recent studies at 16 arable cropping farms in Limburg in the South of The Netherlands comparing non-inversion tillage to conventional ploughing, have shown that reducing tillage intensity results in: larger earthworm populations, (Figure 1); more functional earthworm diversity (in ecological groups) (Figure 2); and more earthworm activity in the top soil (Figure 3), with the outcome being a significant increase in infiltration rate (Figure 4) and greater aggregate stability across all aggregate size classes.

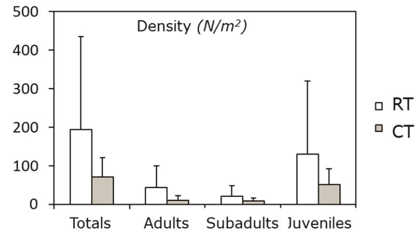


**Figure 1.** Earthworm density (i.e., individual numbers $m^{-2}$) in conventionally tilled fields (CT) and fields under reduced tillage (RT), averaged over a 3-year period (2009–2011).

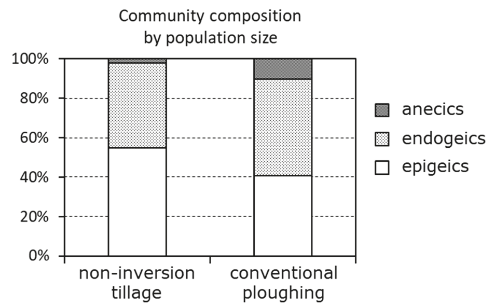


**Figure 2.** Earthworm community composition in ecological groups (anecic deep dwelling species, endogeic soil dwelling species, epigeic top soil, and litter dwelling species) under reduced tillage (various methods of non-inversion tillage were used) and conventional tillage (mouldboard ploughing).

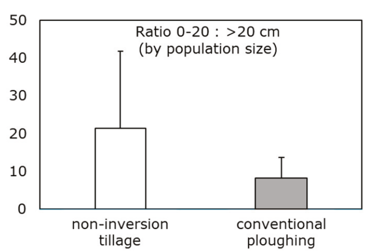


**Figure 3.** Depth distribution ratio of earthworms under reduced tillage (various methods of non-inversion tillage were used) and conventional tillage (mouldboard ploughing), expressed as the ratio of the numbers of individuals found in the 0–20 cm topsoil over the number of individuals extracted by mustard oil (AITC) extraction from the pit after removal of a 30 × 30 × 20 cm soil block (i.e., topsoil, for hand sorting).

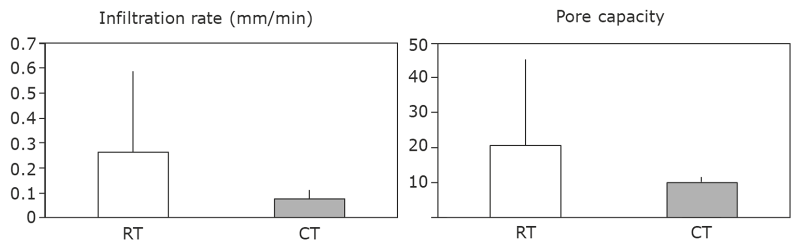


**Figure 4.** Water infiltration rate (mm/minute) under reduced tillage (RT) and conventional mouldboard ploughing (CT) (data for 2011 only), and an estimate for pore volume capacity (imensionless), calculated as the difference between initial infiltration rate and the rate at constant infiltration in a double ring infiltrometer).

Whilst there was a high degree of variability, there was a strong tendency for earthworms to be present in top soil under reduced tillage against populations residing in subsoil in the case of conventional tillage. In a pairwise comparison of adjacent fields, reduced tillage (RT) showed faster rates of water infiltration and a larger pore volume than the neighbouring conventionally tilled fields. Variability under RT was much higher, probably related to the use of different methods of tillage, and while there was no significant relationship with earthworm densities the trend was clearly positive. Soil porosity and water infiltration may be related to soil aggregation, as larger aggregates can have larger pores between them and can hold moisture for a longer time. We found no differences in soil aggregate size in relation to tillage or associated with earthworms (not shown), but the stability of aggregates was significantly higher under reduced tillage particularly in the 0.5–1.0 mm size class (Figure 5).

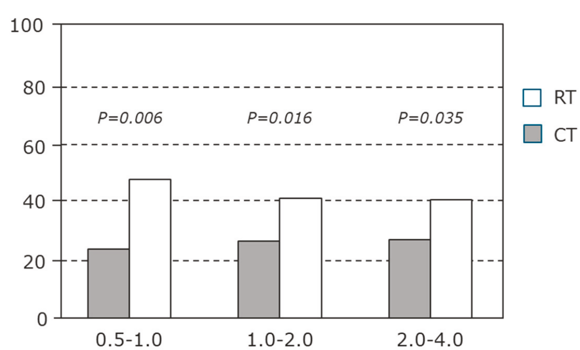


**Figure 5.** Soil aggregate stability (% stable aggregates by weight) in different size classes under reduced tillage (RT) and conventional mouldboard ploughing (CT).

Thus, as the stability of soil aggregates is decisively enhanced by earthworms [54], and earthworms are specifically vulnerable to tillage [55], earthworms would give a general indication of relative changes in soil structure and water regulation, while not being an exact measure of water infiltration, in sufficient detail to justify their inclusion on a soil health monitoring scheme. Guides to earthworm extraction and identification are readily available (i.e., [56]) and methods to calculate soil health indices for earthworms have been published [57].

## 5. Considerations for the practical Use of Soil Health Indicators.

Soil health is no longer an esoteric niche interest for academics but is increasingly in the public domain, as can be seen from these recent UK news clips:

- "African soil crisis threatens food security" (2014) [58]
- "Careless farming adding to floods" (2014) [59];
- "EU pesticide bans could hit UK crops" (2014) [60];
- "UK faces significant shortage of farmland" (2014) [61];
- "Members of Parliament sound alarm over neglected soils" (2016) [62];
- "Nature loss linked to farming intensity" (2016) [63];
- "Prince of Wales joins soil boosting project" (2016) [64];
- "Scottish research finds soil crucial to climate change fight" (2016) [65];
- "Farm subsidies must be earned" (2017) [66];
- "Bread's environmental costs are counted" (2017) [67];

However, setting up a soil health monitoring scheme has a new set of practical criteria in addition to the scientific validation of potential indicators. Soil ecosystems are complex. Therefore, many different aspects need to be measured [68]. It is important to use a set of various indicators, and not a few a priori selected indicators which are supposed to be the most sensitive. Some indicators are more sensitive to contamination (e.g., bacterial growth rate), others are more sensitive to differences in soil fertility and agricultural management (e.g., N mineralisation) [69].

The practical aspects can be seen from the examples of a policy related programme in The Netherlands and an agricultural service in Scotland.

## 6. Biological Indicator of Soil Quality (BISQ) in The Netherlands

The Convention on Biological Diversity (CBD) recognized the importance of biodiversity for ecosystem functioning and the provisioning of soil services to mankind [70]. After the ratification of the CBD, the Dutch government produced a National Action Plan in 1995 to meet the CBD obligations. The role of biodiversity in the maintenance of ecological functions (life support functions) in the soil was one of the subjects needing more attention. More data had to be gathered to enable policy-makers to assess the quality and resilience of soil ecosystem services. Therefore, the Biological Indicator system for Soil Quality (BISQ) was designed in 1997 [71]. In the BISQ, the link between biodiversity and soil functioning is represented in a stepwise and deductive way, from the point of view that the soil food web offers the opportunity to link diversity to specific functions: the life support functions. Thus, BISQ aimed at major trophic groups and processes of the soil food web. BISQ was incorporated into an already operational abiotic soil monitoring programme, The Netherlands Soil Monitoring Network (NSMN). The monitoring network is based on more than 300 sites, arranged in various land use/soil type categories (farms, natural areas and urban sites), and represents approximately 75% of the total land surface area of The Netherlands. Sampling for biological soil properties was carried out in parallel with sampling in the NSMN for soil and chemical analysis. Use was made of the same infrastructure and some of the biological analyses (such as for microbes, nematodes and microbial processes) were carried out using the same mixed samples.

For the application of biological indicators, a lot of methodological choices have to be made [69]. Samples can be taken from replicated field plots, or can be composed from larger areas. In The Netherlands, per category of soil type and land-use 10–20 farms (replicates) spread over the country are sampled. Per farm (about 5 to 50 ha) one mixed sample is composed from 320 cores. These mixed samples are used for chemical, microbiological and nematode analyses. Separate soil cores or blocks (six replicates per site) are taken for mites and springtails (microarthropods), enchytraeids and earthworms. Some reference sites consist of smaller contaminated areas or experimental fields. Here replicated field plots (about 10 × 10 m) are sampled. Sampling depth is best decided by considering soil horizons and tillage depth. In a ploughed arable field 0–25 cm would be appropriate, in grassland and especially in forest thinner, and more, layers would be better. However, this would result in a variable sampling depth or increase the number of samples by taking more than one layer. Given the large number of samples, analysing more than one depth would cost too much time and money. Sampling 0–25 cm would dilute microbial activity considerably in some grassland and forest soils where life is concentrated closer to the surface. Dilution hampers detection of differences. Therefore, in The Netherlands monitoring network samples are taken from 0–10 cm depth and litter is removed before sampling.

For microbiological parameters early spring or late autumn is the best time to sample, as soil conditions are relatively mild and stable and short-term effects of the crop are avoided. In The Netherlands for practical reasons samples are taken from March to June. The soil must be dry enough to access, and farmers prefer sampling of arable land before soil tillage and sowing new crops. Sampling of about 50 farms takes two to three months. Storage is inevitable when large numbers of samples from many sites have to be handled. Soil fauna samples can be preserved for later analysis, so earthworms are hand sorted within 5 days, and enchytraeids, microarthropods, and nematodes are stored in 70% ethanol after extraction. For microbiological samples an a priori storage temperature of 12 °C was chosen, which is close to the average annual soil temperature. The soil is sieved through a 5 mm mesh, as practically it is very difficult to pass field moist, heavy clay soil through a 2 mm sieve. Sieving is useful to reduce variation in process rate measurements such as respiration and mineralisation, and to facilitate mixing and sending identical sub-samples to different laboratories. Sampling and sieving are however major disturbances, which also reduce soil structure and generally increase microbial activity. Therefore, results of the first week of 6-week soil incubations are not used for calculation of process rates (potential C and N mineralisation).

To reduce variation caused by variable weather conditions, samples are pre-incubated for four weeks at constant temperature (12 °C) and moisture content (50–60% of water holding capacity) before microbiological analyses are performed. Since each soil- and land-use type in the monitoring network is analysed once in six years, effects of for instance a dry summer should be minimized.

This pre-incubation applies to the analyses of bacterial and fungal biomass (direct microscopic measurements), bacterial growth rate (3H-thymidine and 14C-leucine incorporation into DNA and proteins) and community level physiological profiles using Biolog$^{TM}$ ECOplates. Soil samples used for measuring potential C and N mineralisation by 6-week incubation at 20 °C, and for measuring potentially mineralisable N by 1 week of anaerobic incubation at 40 °C, are not pre-incubated because incubations are already included in the methods.

From 2004, part of the budget was allocated to study effects of agricultural management and nature restoration in existing long term field experiments. Samples from such experiments are not pre-incubated. One reason is the increasing interest in fungal/bacterial ratios and the observation that fungal hyphal length showed rapid decreases when soil was incubated, especially thinner and non-septate hyphae (presumably mycorrhiza) in soils with low fertilization De Vries et al. [72].

After 17 years within the practical and budgetary limitations, BISQ is still considered as state of the art in soil monitoring Rutgers et al. [71]. Stability and continuity is the basis for building a long term (and therefore valuable) monitoring system. This requires a stable set of methods and indicators. Repeated seasonal measurements and inclusion of protists is still desirable but still not feasible for financial and technical reasons. Molecular DNA and RNA techniques are still developing rapidly, but the information is in line with classic taxonomic methods and does not necessarily offer new or better opportunities for assessment of soil ecosystem services. Instead phospholipid fatty acid (PLFA) analysis is regarded as a more applicable measure of microbial community structure. Besides some major groups of bacteria, it includes a biomarker for saprotrophic fungi. In addition, arbuscular mycorrhizal fungi (AMF) can be included by measuring also neutral lipid fatty acids (NLFA). Based on multi criteria analysis Rutgers et al. [71] proposed a minimum data set for monitoring soil ecosystem services:

- Soil biological indicators: earthworms, enchytraeids, nematodes, microarthropods, fungi, bacteria, N mineralisation, C mineralisation, and root mass (grassland only).
- Abiotic soil indicators: soil type and texture, penetration resistance, bulk density, organic matter parameters including labile fractions, pH, nutrients.
- System indicators: land use, vegetation, agricultural management (crop, rotation, tillage, fertilization, crop protection (pesticides), traffic) and groundwater level.
- If costs are a major aspect for the soil monitoring, these can only be reduced by reducing the number of indicators.

## 7. A Soil Health Test as a Practical Tool for Scottish Growers

Soil health is of practical interest to farmers as the increasingly wet winters in the UK have emphasised the importance of good soil structure to reduce flooding and trafficability issues in soil, and the increasing use of precision farming is also highlighting good and bad areas of their fields. So it was timely to start a soil health testing programme.

Soil health is all about balancing the integrated physical, chemical and biological components of the soil system Stockdale and Watson [34]. Many farmers already have their soils routinely tested for nutrients (P, K, Mg, Ca, Na) and pH, and are used to seeing and interpreting a nutrient report. These analyses are carried out by a commercial analytical laboratory. Thus, there was a base of farmer experience, a network of advisors and analytical facilities on which to base the new soil health testing programme. The primary considerations were cost, interpretability and understandability. Any test had to be affordable and to be seen as value for money. This was related to ease of sampling and analytical practicalities. Thus, while microbial biomass is relatively highly regarded as a key property of soils [33], the scientific standard method of chloroform-fumigation-extraction [73] is not a practical option for commercial laboratories because of health and safety regulations surrounding the use of chloroform. The alternative substrate-induced respiration [74] protocol required either a gas chromatograph for measuring $CO_2$, which our laboratory did not have, or a titration approach that would have been too time consuming (and so expensive). A measure of potentially mineralisable nitrogen was taken as a practical alternative, as it was measureable using existing equipment and expertise and correlated well with microbial biomass measured by fumigation extraction [75].

Another consideration was the understandability of the test, with growers really taking to the test if the measures were ones that they could relate to. Earthworms being a case in point given their almost iconic status in representing healthy soil. For the interpretation of the test results, we required the indicator to have threshold values which would trigger some management options for the farmer. Probably the best known example is soil pH, which has well-known optima for crop production. This then led to a traffic-light system that could be adapted to the existing nutrient management report (Table 1).

**Table 1.** Example of nutrient management report using a traffic-light system as the output from a proposed soil health test in Scotland. The traffic light colours give a quick overview regarding the risk of reduced crop production and/or environmental damage, so "Green" (low risk, continue to monitor), "Amber" (moderate risk, need to investigate further), "Red" (high risk, need to investigate urgently). This example is for an arable farm on a sandy loam soil and would come with management advice on how to improve soil health.

| Measure | Overview | Score | Target range |
|---|---|---|---|
| Potentially Mineralisable N | | 28.7 mg $kg^{-1}$ | >21 mg $kg^{-1}$ |
| Organic Matter (LOI) | | 5.96 % | >9.5 % |
| pH | | 6.1 | 6.5–7.5 |
| Extractable Phosphorus | | 4.39 mg $L^{-1}$ | 4.5–13.5 mg $L^{-1}$ |
| Extractable Potassium | | 87.9 mg $L^{-1}$ | >76 mg $L^{-1}$ |
| Extractable Magnesium | | 154 mg $L^{-1}$ | 61–1000 mg $L^{-1}$ |
| Extractable Calcium | | 1500 mg $L^{-1}$ | >3000 mg $L^{-1}$ |
| Extractable Sodium | | 11.2 mg $L^{-1}$ | >50 mg $L^{-1}$ |
| Visual Evaluation of Soil Structure | | 2.75 | <2.4 |
| Earthworm count | | 6.25 per $20cm^{-2}$ | >8 |

Standardisation is the one common message across all the reports on soil monitoring (see introduction) but in this case that fact that all analyses would be done by the same lab ensured standardisation, but we also made sure to use common protocols where available (i.e., nutrients, pH and potentially mineralisable nitrogen). Finally, we recognised the huge potential for data-mining in future, the accumulation of soil measurements across the country and over many years would provide potentially important information only if the accompanying metadata (GPS location, cropping history, etc.) was collected with every sample. This can be seen from the Australian model (http://www.soilquality.org.au/) where growers can benchmark their soils against regional comparators.

Using approaches as described here, biodiversity and functioning of soil ecosystems can be monitored. In pollution-gradients it is possible to use a local unpolluted control [9]. However, in many cases such a reference is not available. Generally, the value of an indicator is affected not only by stress factors, but also by soil type, land use and vegetation. Therefore, reference values for specific soil types have to be deduced from many observations (e.g., 20 replicates per type). The choice of a desired reference is a political rather than a scientific issue, and depends on the aims of land use. A biologically active and fertile soil is needed in (organic) farming, but a high mineralisation of nutrients from organic matter may hamper conversion of agricultural land to a species rich natural vegetation. Soils showing very low or very high indicator values may be suspect and need further examination. Sufficient data and experience are needed to make judgements of desirable reference values. Monitoring changes of indicators over time can reduce the importance of (subjective) reference values. Such changes may be easier to interpret than momentary values [68]. Spatially extensive and long-term monitoring may be not ideal, but it is probably the most realistic approach to obtain objective information on differences between, temporal changes within, and human impact on ecosystems.

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