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Indicators for the definition of land quality as a basis for the sustainable intensification of agricultural production

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Abstract

Sustainable intensification (SI) is a concept for increasing agricultural production under sustainable conditions to meet the needs of the growing population of the world. To achieve this goal, the intrinsic potential of soils for SI has to be considered. This report aims at identifying indicators for arable soils in Germany, which have the best natural resilience and performance and therefore can be used for SI. Six intrinsic land and soil characteristics (organic C content, clay + silt, pH, CEC, soil depth and slope) were selected as indictors for defining the resilience and performance of land. New data from arable sites from LUCAS topsoil survey 2009 were used and attributed to arable land, applying the Arc Geographical Information System (ArcGIS). The results of this investigation reveal that 39% of the actual analyzed arable land can be recommended for SI in Germany. A comparison with the Muencheberg Soil Quality Rating shows that most of this land reflects the highest potential for agricultural yields. Approximately 61% of the analyzed agricultural land is not suitable for intensification, about 1.5% should be reduced in intensity with a possible conversion to avoid environmental harm. The most frequent limitation factor for SI is a too low cation exchange capacity in German soils.

Keywords: Agriculture; Soil resilience; Soil performance; Soil properties; Environmental protection

1. Introduction

By 2050, the world population will reach more than 9 billion people according to UN projections (Alexandratos & Bruinsma, 2012). Besides population growth, higher per-capita income will increase the demand for food (Godfray et al., 2010). The process of agricultural intensification, including the introduction of new crop varieties, the use of agro-chemicals, and fossil energy driven mechanization, has caused positive effects such as the growth of agricultural output, increasing consumer wealth (Schönhart, Schauppenlehner, Schmid, & Muhar, 2011). However, for future predictions there are serious concerns that the actual increase of yields will be too slow to meet the growing demand for food in many areas (Ray, Mueller, West, & Foley, 2013). Moreover, the ecosystems of the world that produce

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food, feed and fiber, are to a great extent degraded or used unsustainably (Montanarella & Vargas, 2012). The intensification of agriculture is accompanied by negative impacts on the quality of soil, water, air and biodiversity. On the contrary, studies show that high-yield farming can protect natural habitats from conversion to agriculture, and it therefore has less negative impacts on biodiversity than enlarged wildlife-friendly farming (Phalan, Balmford, Green, & Scharlemann, 2011).

A possible solution to meet the increasing food demand of future generations without harming the environment is sustainable intensification (SI). Garnett and Godfray (2012) define SI as "increasing yields per unit inputs" which means that (per area land) higher yields should be produced with less environmental impacts (per unit yield). In the sense of SI, any system which depends on non-renewable inputs is unsustainable. It cannot consistently and predictably deliver desired outputs, except by requiring the cultivation of more land, thus causing adverse and irreversible environmental impacts which threaten critical ecological functions (The Royal Society London, 2009).

Soils perform a variety of environmental, social and economic functions like (1) biomass production for different uses; (2) buffering, filtering and biochemical transformation; (3) gene reservoir; (4) physical basis for human infrastructure; (5) source of raw materials and (6) geogenic and cultural heritage (Blum, 2005). Sustainable land use has to harmonize the use of these six soil functions in space and time, minimizing uses which cannot be reversed within 100 years or 4 human generations (e.g. sealing, excavation, sedimentation, severe acidification, contamination, and salinization).

An environmental friendly intensification of agriculture cannot be implemented without considering the capacity of soils to fulfill additional ecological functions besides the provision of food and biomass. As food security is intimately related to soil security and sustainable agriculture (The Royal Society London, 2009), the resilience and performance of soil under intensification must be considered (Blum & Eswaran, 2004).

In this context, we only consider the three ecological functions: biomass production; filter, buffer and transformation processes and gene reserve (biodiversity).

In this sense, sustainable agriculture combines the concepts of resilience (the capacity of systems to return to (a new) equilibrium after disturbance) and performance (the capacity of systems to produce over long periods), thus addressing wider economic, social and environmental targets.

The main objective of this work is to identify the most important soil intrinsic indicators, which define the concept of soil resilience and performance according to the ecological functions provided by soil. The chosen indicators were applied in Germany and identified SI land categories compared to the Muencheberg Soil Quality Rating, thus allowing the SI scheme applicability for testing. Moreover, we analyzed the relationship between land suitability for SI and its agricultural yield potential.

2. Definition and identification of indicators for SI

Indicators provide information for understanding and managing land according to soil resilience and performance. Criteria for indicators reflect ecosystem processes and integrate physical, chemical, and biological properties and their sensitivity to management and climatic variations (Doran, Sarrantonio, & Liebig, 1996). Moreover, indicators must be easily measurable and understandable for specialists, as well as for politicians, decision makers and farmers at the grassroot level (Doran et al., 1996). To define the capacity of soil systems providing the above mentioned goods and services, no single indicator can cover all aspects, nor would it be feasible (or necessary) to analyze all possible influencing indicators (Kibblewhite, Ritz, & Swift, 2008).

The methodological concept of this study is based on the fact that fertile soils with specific characteristics have a high resilience against physical, chemical and biological disturbances and also show a high performance by producing a maximum amount of agricultural commodities if managed safely. We selected 6 specific land and soil characteristics, which indicate the resilience and performance of land based on available literature and expert knowledge.

The intensification of an environment friendly agricultural production by cropping should be avoided on sites located on slopes with a steepness above 25%. An increased erosion probability could cause irreversible soil losses. Generally, deep soils with a high clay and silt content retain nutrients and avoid the contamination of groundwater. Those soils also have a better water retention capacity and can therefore withstand periods of drought. An important factor concerning SI is soil organic matter (SOM) which is the basis of soil biology, also further influencing soil properties such as the filter, buffer, transformation and water holding capacity. Soil organic matter is defined as all dead organic material in or on the soil, such as dead plant or animal material including leaf litter, woody debris and dead roots (Sollins, Homann, & Caldwell, 1996), which is of special interest in agriculture as it maintains the productivity and yield stability of cereals (Pan, Smith, & Pan, 2009). Organic matter, too, is a source of energy for biological activities and provides a better nutrient availability, bulk density and cation exchange capacity (CEC), which by themselves are important factors for a high resilience and performance. CEC and pH are responsible for the mobility of nutrients and their availability for plants. Soils with low pH and reduced microbial activity show an increase of solubility and mobility of metals, facilitating the contamination of groundwater. Choosing soils with the above mentioned parameters can help to reduce environmentally adverse impacts through agricultural production and influence biodiversity and the delivery of goods and services provided by soil in a positive way.

Indicators arise from data and create values (Singh, Murty, Gupta & Dikshit, 2009). In this case, the data were taken from the Land Use/Land Cover Area Frame Survey 2009 (LUCAS) (organic C content, clay + silt, pH and CEC) and from the European Soil Data Base (ESDB) (slope and depth). The LUCAS was carried out in 23 Member States (Malta and Cyprus were plotted subsequently) and provided soil data from ~20,000 geo-referenced sites which were all analyzed in one central laboratory. The LUCAS dataset was chosen because the results were obtained recently and analyzed homogeneously. A detailed description of the LUCAS topsoil survey and its results is given by Toth, Jones, & Montanarella (2013). The density of the sample points is around 1 per 199 km^2, corresponding to a grid cell size of 14 × 14 km^2 (Panagos, Meusburger, Ballabio, Borrelli, & Alewell, 2014) and includes topsoil data down to 20 cm soil depth. Land above 1000 m altitude was not considered in the LUCAS survey.

The six indicators (organic C content, clay + silt, pH, CEC, soil depth and slope) were scored according to threshold levels in terms of poor (1), medium (2), good (3) and in some cases excellent (4) (Table 1). Soil samples representing low conditions received the score 1, and good conditions received the score 3. Organic C and the clay + silt contents of soil are strongly controlling indicators for SI, and thus a score for excellent conditions was introduced to weigh these two indicators more highly. The threshold values are set by considering textbook knowledge, literature findings and evaluation of the available LUCAS data. The scores for soil depth are based on the soil type description in the World Reference Base (WRB) 2006 as LUCAS provided no information for this criterion (Table 2).

3. Material and methods

3.1. Land mapping

All analyses were done with the geographic information system ArcGIS 10.2 using LUCAS topsoil surveys data, the European Soil Data Base (ESDB) 2.0 1:1,000,000 (provided by IES/JRC European Commission) and the Corine Land Cover 2006 (CLC 2006) map.

LUCAS provides "point" data, and an interpolation between these data at a larger scale was difficult. Therefore, different "land units" were created according to soil types from the WRB 2006. A "land unit" in this research is presented by at least one LUCAS sample for a special soil type in a region. If a "land unit" contained more than one LUCAS soil sample, an average of soil indicator values was calculated for this "land unit". As a last step, the map of

Table 1
Threshold levels and scoring of land indicators. Score for each indicator is given in parenthesis.

	Excellent (4)	Good (3)	Medium (2)	Poor (1)	Unit
Soil organic carbon	> 4	2–4	1–2	< 1	%
Clay + silt	> 50	35–50	15–35	< 15	%
pH		6.5–8	5.5–6.5	< 5.5; > 8	in H_2O
Cation exchange capacity		> 25	10–25	< 10	cmol/kg
Soil depth[a]		> 60	30–60	< 30	cm
Slope[b]		< 8	8–15	15–25	%

[a]Estimated according to WRB 2006 (see Table 2).
[b]Sites with slopes > 25% were excluded from calculations.

Table 2
Soil types and scores for soil depth estimated from WRB 2006 soil description. 1= < 30 cm depth; 2=30–60 cm depth; 3= > 60 cm depth.

Soil type	*Score*	*Soil type*	*Score*
Histosols	3	Chernozems	2
Anthrosols	–	Phaeozems	2
Technosols	–	Calcisols	2
Cryosols	–	Albeluvisols	2
Leptosols	1	Alisols	3
Vertisols	3	Acrisols	3
Fluvisols	2	Luvisols	3
Solonetz	3	Umbrisols	2
Gleysols	2	Arenosols	2
Andosols	2	Cambisols	2
Podzols	2	Regosols	1

non-irrigated and permanently irrigated arable land from Corine Land Cover (CLC 2006) was spatially overlapped in ArcGIS with the created “land units” to exclude sites which are not under agricultural cropping. Data for all arable land are not available at the moment. Therefore not all agricultural land could be considered in this study.

3.2. Land scoring

For each land unit the measured values for the indicators were derived from the LUCAS topsoil data and the ESDB according to defined threshold values (see above). By summing up all the scores, a minimum value of 6 and a maximum value of 20 (4 points for organic C content as well as clay + silt content and 3 points each for pH, CEC, depth and slope) could be attributed to a land unit. The total score points were separated into four different categories of SI potential (Fig. 1).

Land with lowest quality has only a final score between 6 and 10 (category 1). This means that the soil has intrinsic properties which cannot support environment friendly intensification, and therefore, even extensification is suggested. Land in category 2 can show medium or good conditions (score > 10), but one or even more indicators are in a poor condition, and therefore an intensification is only possible with a high risk. A total score of 11 to 15 represents the medium category 3, where a poor potential for SI is given, which means that intensification should only be done with much caution. Land that can be recommended for SI (category 4) presents soils which can compensate environmental impacts through agricultural production and which have a total score from 16 to 20. This land was recommended for intensive agriculture under the precondition that it is managed in a sustainable way.

4. Results and discussion

4.1. Recommendation of land for sustainable intensification

A total area of 79,475 km^2 arable land in Germany was analyzed which is only 47.4% of the total agricultural land in Germany (~170,000 km^2; Eurostat, 2010). It must be considered that CORINE Land Cover has a minimum land mapping unit of 25 ha (Buettner, Kosztra, Maucha, & Patak, 2010), and therefore, small farm holders are not considered in this study. These small farm holders do have a valuable contribution to the agricultural production but are usually extensive producers of agricultural commodities. Fig. 1 shows that some regions are not well represented by LUCAS soil survey. Although LUCAS is a very good and suitable dataset for this study, a future soil sampling campaign should be expanded to reach clear and safe conclusions.

The results show that almost half (45.7%) of the actual analyzed arable land (Fig. 1) is not suitable for sustainable intensification (category 1 + 2). Generally, agriculture performed on land in category 1 + 2 must be performed in a rather extensive way. Even 1.5% of this land is suggested for extensification including a possible conversion into

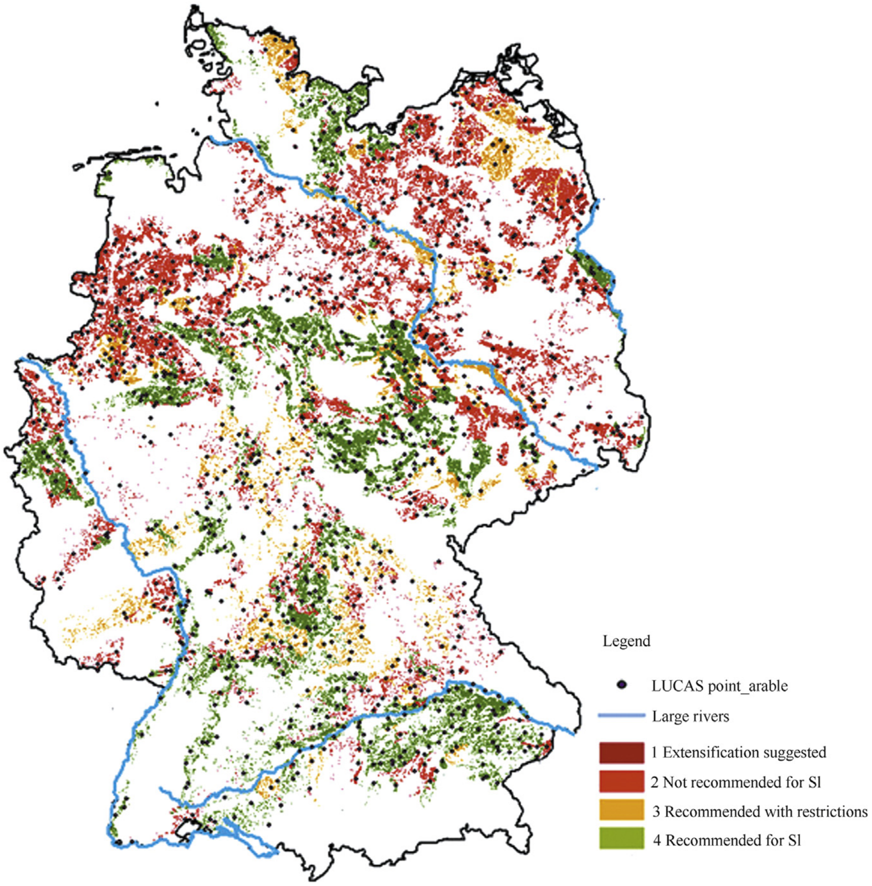

Fig. 1. Land suitability for sustainable intensification in Germany. Land units comprise areas with similar soil type (WRB, 2006), land use (CLC, 2006) and measured soil data (LUCAS, 2009). Category 1: extensification suggested, score 6–10 (dark red); Category 2: Not recommended for SI, score >10 (but at least one indictor out of range) (red); Category 3: Recommendation with restrictions, score 11–15 (orange); Category 4: Recommended for SI 16–20 (green).

grassland (category 1). Special restrictions must be considered for SI at 15.2% of the analyzed arable land (category 3). Local decisions and a closer look at the limiting factors are important for this land.

Germany has a potential of ~39% of analyzed arable land for SI (category 4). These lands have high resilience against adverse impacts from intensive agricultural production, show a high performance, and occur mainly in the alluvial plains of large rivers, such as the Danube in the south, the Rhine in the west and the Elbe with tributaries in the central and northern part of Germany (Fig. 1). Therefore, they can be used with less environmental risks regarding the contamination of groundwater resources and of the food chain through the use of fertilizers and plant protection compounds. However, it is important that any decision concerning SI must be taken at a local level.

4.2. Limiting factors for sustainable intensification in Germany

The most frequent limiting factor to categorize a land for SI (Fig. 2) is the cation exchange capacity (CEC), which is the capacity of the soil to retain inorganic and organic positively charged compounds in the soil body, thus protecting the groundwater and the food chain against contamination. Also low clay + silt content is the limiting factor on 8.9% of the actually analyzed arable land. The resilience and performance is especially low in sandy soils in the north-east of Germany. The majority of German soils are slightly acidic, and a low pH is a limiting factor on 8.0% of the agricultural land analyzed in this study. Organic C as one of the most important soil properties is too low on 6.8% of the land area. The LUCAS soil sampling campaign did not take place on areas with an altitude higher than 1000 m. Therefore, the mountainous and alpine regions in the south with steep slopes were not considered in

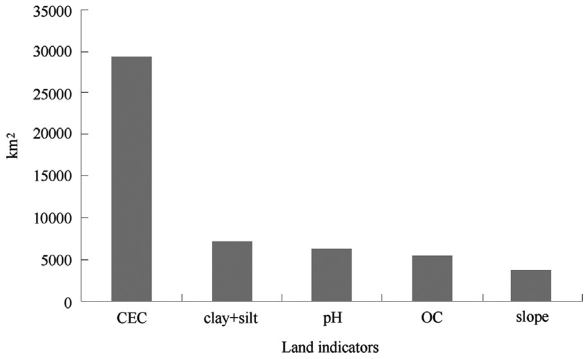

Fig. 2. Limiting indicators (in km^2 of analyzed arable land) for sustainable intensification in categories 1+2 in Germany.

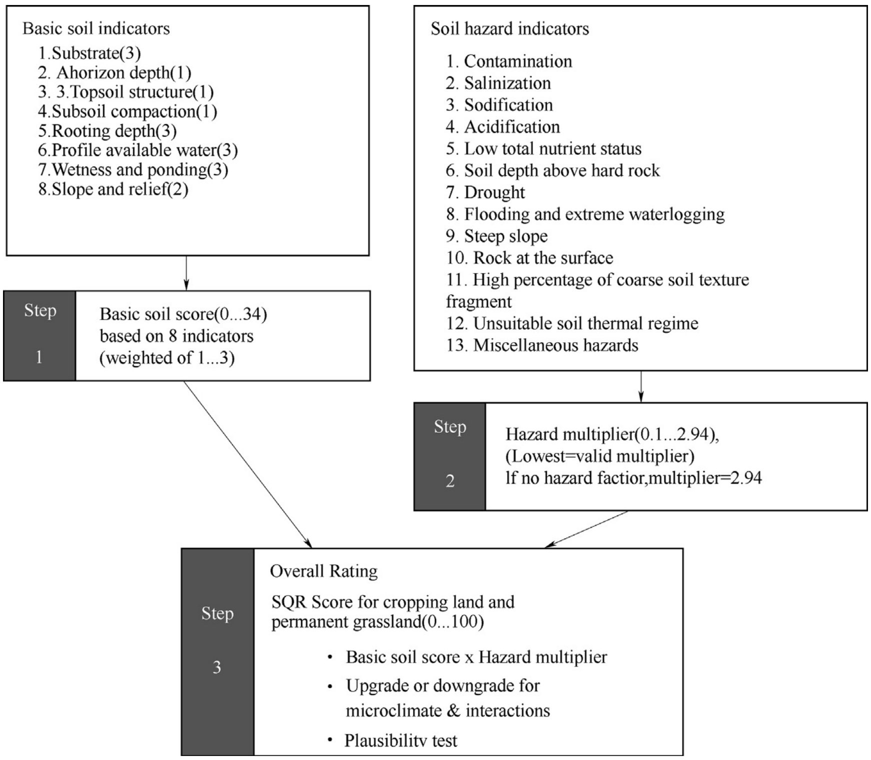

Fig. 3. Scheme of Muencheberg Soil Quality Rating assessing properties and limitations of soils for cropping and grazing (modified after Mueller et al., 2007, 2012).

this study. Even under these conditions, steep slopes are the limiting factor on 4.7% of the actually analyzed land in Germany.

4.3. Comparison with the Muencheberg Soil Quality Rating

The Muencheberg Soil Quality Rating (M-SQR) is an approach that includes indicators of inherent (soil substrate) and dynamic (soil structure) agricultural soil quality, as well as topography (slope) and climate (soil thermal and moisture regimes) to assess soil suitability for arable and grassland farming and crop yield potentials (Mueller, Schindler, Behrendt, Eulenstein, & Dannowski, 2007). Fig. 3 presents the scheme of the M-SQR. Basic soil indicators and their scores are based on a 5-ball scale ranked from best conditions (2) to worst (0) with possible

Table 3
Yield potential classes of arable land according to Muencheberg Soil Quality Rating in sustainable intensification land categories.

SI categories	Analyzed area (km^2)	Low yield potential M-SQR class 1+2+3 (%)	High yield potential M-SQR class 4+5 (%)
Not recommended for SI (SI categories 1+2)	57,234	57.7	42.3
Recommended for SI (SI categories 3+4)	43,177	27.1	72.9

increments of 0.5, or 0.25 in very sensitive cases. In a second step, the rating system uses hazard soil properties and indicators as multipliers for the basic soil score. This leads to a final score (SQR-score) ranging from 0 to 100 (classes of SQ < 20 = very poor, 20–40 = poor, 40–60 = moderate, 60–80 good, > 80 = very good). This method is widely accepted, and it was shown that it can operate consistently from the field up to global scale and create consistent soil functional maps anywhere in the world (Mueller et al., 2012). Therefore, the proposed agricultural yield potential gained with M-SQR (Mueller et al., 2007) was chosen and spatially overlapped with the land categories of SI.

A comparison of these two land evaluation schemes shows that the most suitable land for SI has also the highest natural agricultural yield potential. In Table 3 the actual analyzed land, which cannot be recommended for SI (category 1+2), consists of 57.7% of rather unproductive land according to the M-SQR (class 1+2+3). However, we found naturally productive land with M-SQR on 42.3% (15,358 km^2) of land in categories 1+2. The definition of suitability for SI is based on intrinsic soil quality parameters such as "performance" in the sense of productivity but also "resilience" against adverse ecological impacts. This shows that even on sites where high yields are possible, these cannot be produced sustainably under intensive agriculture. These sites are not resilient enough, and intensive agriculture can cause groundwater pollution and affect biodiversity negatively. This clearly shows that productive land is not automatically the best land for intensive agriculture. Therefore, decisions about intensification must seriously be considered under the concept of resilience and performance.

The land with a high performance (SQR), but low resilience (SI), should rather be used in an extensive way to avoid negative environmental effects. Land used for extensive agriculture (organic farming) counts only 6.4% of the total agricultural land in Germany (Umweltbundesamt, 2014). In view of the increasing demand for organically produced food in Germany these sites would be most suitable. As it is shown here, much more land has the potential for high yields but can only be recommended for a rather extensive agricultural use. On 43,177 km^2, where sustainable intensification can be recommended in Germany (category 3+4, Fig. 1), our results overlap with 72.8% of the most productive land (class 4+5 M-SQR). This clearly shows that the majority of the land recommended for SI also reflects the most productive land (Table 3).

5. Conclusions

Six intrinsic land characteristics (organic C, clay+silt, pH, CEC, soil depth and slope) were used to determine the resilience and performance of soils suitable for sustainable intensification (SI). According to these indicators, approximately 39% of the analyzed arable land in Germany could be recommended for SI. Almost half of the arable land was delineated and was not recommendable for intensification. As land and soil are heterogeneous natural resources, any decision with regard to intensification must also account for the local conditions. A comparison with the Muencheberg Soil Quality Rating showed, that on almost 73% of the land most suitable for SI also the highest natural agricultural yield potential is observed. However, fertile soils do not always allow a sustainable intensification.

This SI concept with only six indicators can be easily applied and should be considered to perform agricultural intensification environment friendly. The used LUCAS topsoil data are very promising, but a future soil survey should be extended to reach clear results.

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