Development of an LCA-based approach for a regional assessment of the environmental impacts of nitrogen in crop production systems

Entwicklung einer LCA-basierten Methodik zur regionalen Bewertung der Umweltwirkungen von Stickstoff bei der Produktion landwirtschaftlicher Rohstoffe

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Dipl.-Ing. agr. Karoline Maria Wowra
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Erstreferentin: Prof. Dr. rer. nat. Liselotte Schebek
Korreferentin: Prof. Dr. Britta Schmalz

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Karoline Maria Wowra

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Korreferentin: Prof. Dr. Britta Schmalz

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> *“Remember, always, that everything you know, and everything everyone knows, is only a model. Get your model out there where it can be viewed. Invite others to challenge your assumptions and add their own.”*
>
> Donella H. Meadows, Thinking in Systems: A Primer

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ABSTRACT

Agricultural systems are dependent on nitrogen (N) inputs to achieve food security and, at the same time, put high pressure on environmental systems. Accordingly, global limits for N-cycles are already exceeded. However, the release of N compounds from agricultural cropping systems mainly impacts the regional level, for instance, by eutrophication or acidification of terrestrial systems. Therefore, avoiding the exceedance of regional boundaries is essential. Likewise, when assessing environmental impacts on agricultural cropping systems with Life Cycle Assessment (LCA), integration of regional N thresholds and, thus, regionalization plays a crucial role.

This thesis aims to provide an LCA-based approach to comprehensively assess N on a regional level by integrating N thresholds as reference values and regionalization in LCA. This thesis is a cumulative dissertation consisting of three peer-reviewed publications.

In the first publication, a comprehensive review following the LCA framework is presented by analyzing literature on regionalization approaches applied to agricultural cropping systems compared with general requirements of LCA and the scientific background of the N-cycle. Key factors are derived, formulating the basis for a targeted N assessment in LCA. The second publication presents the development of an approach for integrating regional N resilience as distance-to-target value in LCA. Therefore, regional carrying capacity based normalization references are derived for two N-related impact categories: terrestrial acidification and eutrophication. Additionally, regional background interventions comprising N-related emissions of non-crop production sectors are taken into account. Regional environmental interventions of cropping systems applying different yield scenarios are assessed for two regions. The newly developed approach is further developed within the third publication and applied to a case study including five NUTS-3 regions in Germany. The influence on regional N resilience is evaluated by assessing environmental interventions for four N management scenarios based on policy measures of the German Fertilizer Ordinance.

The case study demonstrates that environmental interventions and exceedance of N resilience are lowest in N scenarios applying catch crops for both impact categories assessed. Furthermore, regional differences in the exceedance of N resilience were observed.

Overall the analyses done within this thesis revealed that considering absolute sustainability references as regional N resilience in LCA is a valuable tool for agricultural decision-makers. This supports LCA practitioners by providing normalization references directly applicable for LCA and N-assessment of cropping systems. Additionally, it helps regional stakeholders to provide the possibility to evaluate and decide on the best options for N reduction strategies on the regional level and draw attention to vulnerable regions threatening N resilience. Finally, challenges, future research needs, and opportunities for application of the approach are outlined.

KURZFASSUNG

Landwirtschaftliche Produktionssysteme sind auf Stickstoffeinträge angewiesen, um die Versorgung mit Nahrungs- und Futtermitteln und somit die Ernährungssicherheit zu gewährleisten. Gleichzeitig üben sie jedoch großen Druck auf ökologische Systeme aus. Folglich sind planetare Grenzwerte für Stickstoffkreisläufe bereits überschritten. Die Freisetzung von Stickstoffverbindungen aus landwirtschaftlichen Anbausystemen wirkt sich jedoch hauptsächlich auf regionaler Ebene aus, z. B. durch Eutrophierung oder Versauerung von terrestrischen Ökosystemen. Daher ist es erforderlich, die Überschreitung regionaler Grenzen zu vermeiden. Auch bei der Bewertung der Umweltauswirkungen landwirtschaftlicher Anbausysteme mit Hilfe des Life Cycle Assessment (LCA) spielen regionale Stickstoffgrenzwerte und somit die Regionalisierung der LCA eine entscheidende Rolle.

Ziel der vorliegenden Arbeit ist daher, die Entwicklung eines LCA-basierten Ansatzes für eine umfassende Bewertung von Stickstoff (N) auf regionaler Ebene durch die Integration von Stickstoffgrenzwerten als Referenzwerte und Regionalisierung im LCA. Die vorliegende Arbeit ist eine kumulative Dissertation, die aus drei, von externen Experten (peer-reviewed), begutachteten Veröffentlichungen besteht.

In der ersten Veröffentlichung wird ein umfassender Überblick über den LCA-Rahmen gegeben, indem Literatur zu Regionalisierungsansätzen für landwirtschaftliche Anbausysteme vergleichend zu allgemeinen Anforderungen der LCA und dem wissenschaftlichen Hintergrund des Stickstoffkreislaufs analysiert werden. Es werden Schlüsselfaktoren abgeleitet, die die Grundlage für eine gezielte Stickstoff-Bewertung in Ökobilanzen bilden. In der zweiten Veröffentlichung wird ein Ansatz zur Integration der regionalen N-Belastbarkeit als Distance-to-target-Wert in die LCA entwickelt. Hierzu werden für zwei N-bezogene Wirkungskategorien (terrestrische Versauerung und terrestrische Eutrophierung), regionale, auf der Tragfähigkeit basierende, Normierungsreferenzen abgeleitet. Zusätzlich werden regionale Hintergrundbelastungen berücksichtigt, die N-bezogene Emissionen aus nicht-ackerbaulichen Produktionssektoren umfassen. Regionale Umwelteinflüsse von Anbausystemen mit unterschiedlichen Ertragsszenarien werden für zwei Regionen bewertet. Der neu entwickelte Ansatz wird in der dritten Veröffentlichung weiterentwickelt und auf eine Fallstudie angewendet, die fünf NUTS-3-Regionen in Deutschland umfasst. Der Einfluss auf die regionale Stickstoffresilienz wird durch die Bewertung von Umweltinterventionen für vier Stickstoffmanagement-Szenarien auf Grundlage von Maßnahmen der deutschen Düngemittelverordnung bewertet.

Die Fallstudie zeigt, dass die Umweltwirkungen und die Überschreitung der Stickstoff-Belastbarkeit in den Stickstoffszenarien mit Zwischenfruchtanbau für die untersuchten Wirkungskategorien am geringsten sind. Außerdem wurden regionale Unterschiede bei der Überschreitung der N-Belastbarkeit festgestellt.

Insgesamt zeigt die im Rahmen dieser Arbeit durchgeführte Analyse, dass die Berücksichtigung absoluter Nachhaltigkeitsreferenzen, wie der regionalen N-Resilienz, im Life Cycle Assessment ein wertvolles Instrument für landwirtschaftliche Entscheidungsträger zur Bewertung von Stickstoffmanagementstrategien für pflanzliche Produktionssysteme darstellt. Dies unterstützt LCA-Anwender durch die Bereitstellung von Normierungsreferenzen, die direkt zur Anwendung in der LCA zur Bewertung von Stickstoff in landwirtschaftlichen Anbausystemen anwendbar sind. Darüber hinaus wird regionalen Akteuren die Möglichkeit geboten, die für sie besten Optionen für Stickstoffreduktionsstrategien auf regionaler Ebene zu bewerten und die Aufmerksamkeit auf gefährdete Regionen zu richten, deren Stickstoffresilienz gefährdet ist.

Abschließend werden Herausforderungen und Anwendungsmöglichkeiten des Ansatzes diskutiert sowie der künftige Forschungsbedarf und weitere Möglichkeiten zur Übertragbarkeit skizziert.

PUBLICATIONS

I. NITROGEN IN LIFE CYCLE ASSESSMENT (LCA) OF AGRICULTURAL CROP PRODUCTION SYSTEMS: COMPARATIVE ANALYSIS OF REGIONALIZATION APPROACHES.

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II. REGIONAL NITROGEN RESILIENCE AS DISTANCE-TO-TARGET APPROACH IN LCA OF CROP PRODUCTION SYSTEMS

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III. EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF CROPPING SYSTEMS UNDER DIFFERENT NITROGEN MANAGEMENT SCENARIOS CONSIDERING REGIONAL NITROGEN RESILIENCE

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LIST OF ABBREVIATIONS

ACPS	Agricultural crop production systems
AE	Accumulated exceedance
AES	Absolute environmental sustainability
BI	Background intervention
C	Carbon
CF	Characterization factor
CM	Characterization method
EI	Environmental intervention
GWP	Global warming potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MEP	Marine eutrophication potential
N/N_r	Nitrogen, reactive nitrogen
N_2O	Di-nitrogen oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
NO_x	Nitrogen oxides
NR/ rNR	Normalization reference, regional normalization reference
NUTS	Nomenclature of Territorial Units for Statistics
P	Phosphorus
PB	Planetary Boundaries
PBM	Process based models
SO_2	Sulfur dioxide
SOC	Soil organic carbon
TAP	Terrestrial acidification potential
TEP	Terrestrial eutrophication potential
UBA	Umweltbundesamt

1 INTRODUCTION

1.1 OVERVIEW

The nitrogen (N) cycle is fundamental for all living organisms. N is abundant in the atmosphere occurring mainly in its molecular form as N_2. Although covering over 78% of the earth's atmosphere, most organisms cannot use this unreactive form (Vitousek et al., 2013). Only after N fixation and thus conversion to reactive N_r, N is taken up by organisms as, e.g., ammonium or nitrate (de Vries, 2021). In pre-industrial times, lightning and biological N fixation were the main pathways for conversion to reactive N_r (Galloway et al., 2003). Nowadays, anthropogenic N fixation has increased the creation of reactive N_r and more than doubled global N_r sources (Bodirsky et al., 2014; Vitousek et al., 2013). With help of the Haber-Bosch process, the production and use of synthetic fertilizers increased, also leading to a dramatic increase in agricultural productivity (Erisman et al., 2018). Thus, agriculture became a main contributor to anthropogenic N fixation through the synthesis of industrial N fertilizers and the cultivation of crops that support biological N fixation (Vitousek et al., 2013).

Accordingly, N is essential for reaching different sustainable development goals in view of food security and nutrient management (Kanter et al., 2016). Though, not all N is taken up by crops. About 80% of N, utilized for agricultural production in fertilizers and biological N fixation, is lost to the environment (Sutton et al., 2013). Losses of reactive N_r compounds in air, soil, or water have impacts on climate change or cause environmental implications such as eutrophication or acidification of ecosystems resulting in biodiversity losses or impacts on human health (de Vries, 2021).

Although crucial for humanity, agricultural production is putting high pressure on the earth system by the transgression of multiple planetary boundaries (PB), including N-cycles, globally and regionally (Campbell et al., 2017; Gerten et al., 2020). Therefore, the challenge for agricultural production is twofold: reducing N losses from agricultural production due to fertilizer use and maintaining N efficiency for food and feed production, especially in regions where N deficits exist. This requires improving N use efficiencies by improving crop and nutrient management strategies and thus developing and appropriately applying environmental policies (Lassaletta et al., 2014).

The PB concept quantifies limits for global N input to monitor and control N fixation resulting mainly from the agricultural sector (Rockström et al., 2009; Steffen et al., 2015). However, N losses result in impacts on different spatial and temporal scales, while N pollution from the agricultural sector is resulting in, for instance, eutrophication or acidification of terrestrial systems, and is mainly a regional problem (de Vries et al., 2013; Kahiluoto et al., 2015; Schulte-Uebbing et al., 2022; Steffen et al., 2015). Accordingly, assessing the impacts of agricultural cropping systems on N-cycles requires a detailed environmental assessment considering N boundaries. To account for the multidimensionality of the N problem, these assessments should be completed preferably on the regional level.

1.2 PROBLEM DEFINITION

Assessing environmental implications resulting from agricultural production systems and providing decision support in implementing policy strategies have long been studied using Life Cycle Assessment (LCA) (Bessou et al., 2013; Brentrup et al., 2004; Roy et al., 2009).

The results of an LCA are expressed in indicator scores for different impact categories, such as climate change, eutrophication, or ecotoxicity. Within a comparative LCA of two systems, the decision is made towards the alternative with less environmental impact expressed by results of impact categories. However, if several indicators are considered, the opposite effect may occur. In this case, a decision can only be made by argumentation or by analyzing the relevance of the environmental impacts by employing optional impact assessment components via normalization or weighting. Furthermore, LCA operates on a relative scale where the performance of a product is compared to alternative products or technologies, not considering absolute sustainability references as carrying capacities of the environment.

Conversely, due to the complexity of the N-cycle, LCA faces multiple challenges in assessing impacts resulting from agricultural crop production systems on the N-cycle:

- N affects the environment in numerous reactive forms (e.g., ammonia NH_3, nitrogen oxides NO_x, di-nitrogen oxide N_2O) that contribute to different environmental impacts depending on their temporal and spatial distribution, e.g., acidification, eutrophication on the regional or climate change on the global level.
- N emissions depend on regional biogeochemical and biogeographical conditions (soil conditions, N mineralization rate, temperature, or precipitation) and agricultural management practices (amount and type of fertilizer or tillage system).
- Eutrophication and acidification of terrestrial or aquatic ecosystems are primarily regional problems, as these environmental impacts are significantly influenced by regional conditions such as water and soil quality.
- Global N boundaries are already exceeded. Therefore, N thresholds and, thus, carrying capacities should be considered in the assessment of agricultural crop production systems, preferably on the regional level.

Accordingly, addressing these challenges, relevant requirements for a comprehensive assessment of N impacts in LCA resulting from agricultural crop production systems include regionalization and consideration of N thresholds on the regional level. Although methodological approaches for regionalized LCA applied to agricultural cropping systems already exist (Nitschelm et al., 2016; O'Keeffe et al., 2016), these may not necessarily reflect the listed challenges and the complex interaction of N compounds with the environment in LCA. Furthermore, for considering regional N thresholds and thus carrying capacity in LCA, concepts have to be identified suitable for integration in LCA as, for instance, regional reference values.

Consequently, this thesis investigates the requirements for a regional N assessment in LCA, considering regionalization of agricultural LCA and integration of carrying capacities for N on the regional level. Therefore, the main aim is to develop an approach linking these aspects in LCA and provide relevant requirements for a comprehensive N assessment.

Hence, the following research questions are raised:

1. How are regional nitrogen flows considered in LCA, and which methodological and practical recommendations can be drawn for a regional assessment of nitrogen in LCA?
2. How can nitrogen thresholds be integrated as reference values in LCA to assess the environmental performance of cropping systems considering regional nitrogen resiliencies?
3. How does the newly developed approach improve decision support in agricultural LCA for regional stakeholders in assessing nitrogen management measures for reducing regional nitrogen impacts?

The research questions are addressed and answered through three peer-reviewed publications presented in this thesis (chapters 2-4). The relation between the three publications is presented in chapter 5.

1.3 STRUCTURE OF THE THESIS

The overall structure of the thesis is displayed in Figure 1.1. The thesis is a cumulative research work based on three peer-reviewed publications. The introduction comprises an overview, problem definition, and the theoretical background of the topic. The theoretical background describes the method of LCA and the concept of absolute sustainability references as planetary boundaries and nitrogen thresholds for carrying capacity based assessments, building the basis of the developed approach. Chapters 2-4 contain the three research publications. By starting with a comprehensive review and identification of requirements to display N impacts in cropping systems on the regional level, the first publication is presented in chapter 2. The methodological basis, relevant steps, and data requirements for implementing regional N resilience within LCA are described in the second publication in chapter 3. The third publication evaluates and proves the developed approach by application to different N management scenarios in chapter 4. Chapter 5 summarizes and discusses the main findings, challenges, and recommendations from the developed approach and investigations. Finally, chapter 6 closes with a conclusion and outlook.

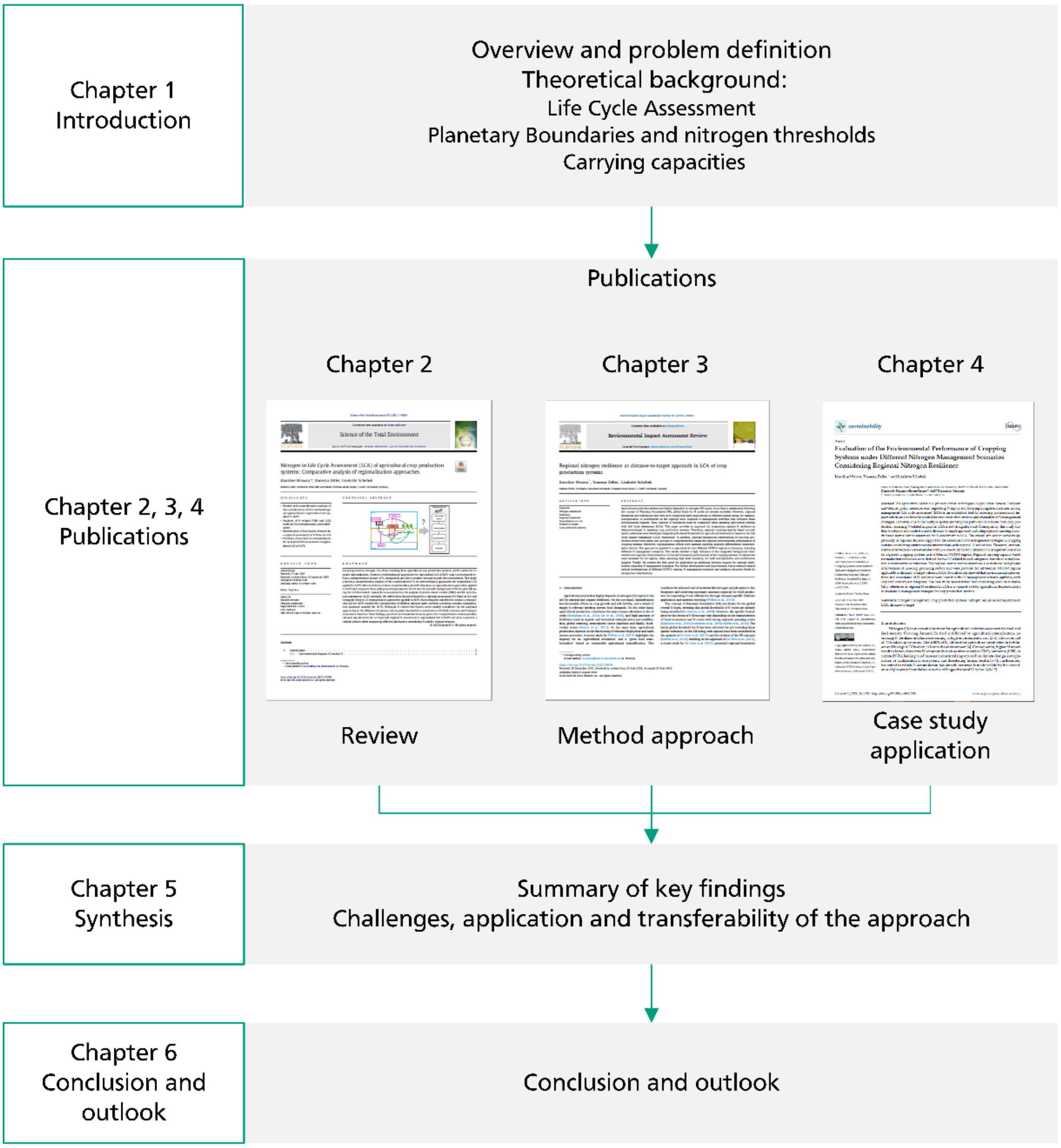

Figure 1.1: Structure of the thesis.

1.4 THEORETICAL BACKGROUND

The theoretical background of the chosen method concepts presents the basis for the newly developed approach. Herewith a brief overview of the method of LCA, the concept of planetary boundaries, and the development of regional N thresholds is presented. Furthermore, the concept of absolute sustainability references, such as carrying capacities, is introduced.

1.4.1 Life Cycle Assessment

Life Cycle Assessment (LCA) aims to analyze relevant environmental impacts caused by a product or service over its entire life cycle. This frequently used and internationally recognized method has already been largely standardized and defined in ISO standards 14040 and 14044 (ISO, 2006a, 2006b). According to these, the preparation of an LCA is carried out in four (iterative) steps: i) definition of the goal and scope of a study, ii) preparation of the life cycle inventory, iii) life cycle impact assessment, and iv) interpretation (Box 1).

Environmental implications are assessed based on the quantified emissions of a product system under study and are assigned to relevant impact categories depending on their environmental relevance. These elementary flows are then multiplied with a characterization factor (CF) relating to the relevant category indicator (e.g., N-eq.) of the chosen impact category (e.g., terrestrial eutrophication potential) (Box 2) (Hauschild and Huijbregts, 2015). The indicator scores calculated for all assigned elementary flows are then summed to the total impact score of a specific impact category. However, this does not display the magnitude of the impact or a comparison between different impact scores. Therefore, optional steps of the Life Cycle Impact Assessment (LCIA) phase, such as weighting or normalization, are suitable for interpreting impact assessment results. Furthermore, with distance-to-target approaches, impact results are weighted according to their distance from the current environmental situation to a defined target or reference value (Muhl et al., 2021). Targets may be based on environmental policy values (Muhl et al., 2021) or indicator concepts such as planetary boundaries (Bjørn and Hauschild, 2015).

Box 1: Phases of Life Cycle Assessment (LCA) according to ISO 14044/14040 (ISO, 2006a, 2006b)

I. Goal and scope

Within the first phase of LCA the goal and scope of the study is defined. The study's scope is defined by technical, spatial, and temporal system boundaries. Furthermore, the definition of a functional unit (FU), the respective reference flow, impact categories and impact assessment method is necessary (ISO, 2006a, 2006b).

II. Life Cycle Inventory (LCI)

The LCI collects information about relevant input and output flows. Inventory flows as used energy, resources, products, co-products and outputs as waste and emissions are quantified. A distinction is made between the foreground and the background system. The foreground system comprises processes of the product system specific to it, typically containing primary data, while in contrast the background system defines processes not specific to it containing secondary data as e.g. LCA databases like ecoinvent (Hauschild et al., 2018; ISO, 2006a, 2006b).

III. Life Cycle Impact Assessment (LCIA)

In the LCIA phase the environmental impacts are determined based on the LCI. For this purpose, impact categories such as eutrophication, acidification or global warming potential are selected in accordance to the goal and scope of the study and the associated characterization method and respectively LCIA method chosen. Characterization methods model the environmental cause-effect chain from the output flow of the life cycle inventory to the impact. Along the impact pathway impacts may be measured in the middle (mid-point indicator) or at the end (end-point indicator). The latter is also described as damage modelling relating to specific areas of protection as human health, natural environment and natural resources. Optional steps of the LCIA include normalization or weighting of results (Box 2) (Hauschild et al., 2018; ISO, 2006a, 2006b).

IV. Interpretation

The last phase serves for interpretation of LCI and LCIA results, building the basis for recommendations for decision makers (ISO, 2006a, 2006b).

Box 2: Glossary for relevant terms related to the Life Cycle Impact Assessment (LCIA)

Category indicator

A category indicator expresses the metrics of a specific impact (e.g. CO_2-eq. for global warming potential) and is based on a characterization model (Hauschild et al., 2018; Hauschild and Huijbregts, 2015).

Impact category

The impact category represents a class of environmental impacts to which elementary flows can be assigned, e.g. global warming potential or eutrophication potential (ISO, 2006a, 2006b).

Characterization methods/model

A characterization method (CM) calculates characterization factors of different elementary flows contributing to a specific impact category, e.g. terrestrial acidification (Roy et al., 2012a) (Humbert, 2009). Fate and transport of substances are estimated with CMs for different environmental compartments and on different spatial scales.

Characterization factor

The characterization factor (CF) is derived from a characterization method and expressed as the product of a fate factor and an optional exposure factor for midpoint characterization. Endpoint characterization includes the midpoint CF and an additional effect factor (de Haes et al., 2002).

Life Cycle Impact Assessment method

LCIA methods compile a set of different characterization methods/models for different impact categories in one LCIA method, e.g. IMPACT World+ (Bulle et al., 2019) or CML-IA (Guinée et al., 2002) (Humbert, 2009).

Normalization

The results of the different LCIA impact categories are reported in different metrics. As an optional step LCIA normalization serves to support LCA comparison by relating the LCIA results to a reference value. Typical reference values are geographical zones or population of a region, country, etc. (Hauschild et al., 2018; Hauschild and Huijbregts, 2015).

Weighting

The weighting step may serve to evaluate the importance of impacts in comparison between impact categories and therefore allowing prioritization. The weighting step requires prior the normalization step (Hauschild et al., 2018; Hauschild and Huijbregts, 2015).

1.4.2 The concept of planetary boundaries and regional nitrogen thresholds

The concept of planetary boundaries (PB) describes and identifies ecological stress limits of important earth system processes (Rockström et al., 2009; Steffen et al., 2015). It builds on a concept of defined global thresholds for essential earth system processes, beyond which the safe operating space for humanity is no longer guaranteed (Rockström et al., 2009). Exceeding these limits and thus leaving the safe operating space can result in sudden, sometimes irreversible damage to environment and society.

Nine biophysical systems and processes that regulate the state and resilience of the earth system using the comparatively stable interglacial Holocene (initiated 11,700 years ago) as the baseline have been defined, namely climate change, biodiversity, global nitrogen and phosphorus cycle, stratospheric ozone layer, land use change, water use, ocean acidification, aerosol pollution, and chemical pollution (Steffen et al., 2015). Four of these earth system processes were identified whose limits have already been exceeded; these included biodiversity loss, land-use change, climate change and exceedance of nitrogen and phosphorus input to the biosphere. In addition, a recent study by Wang-Erlandsson et al. (2022) also indicated the transgression of the planetary boundary for freshwater.

The initial global threshold for N has been criticized for not including spatial variations since N pollution is mainly a regional problem (de Vries et al., 2013). Therefore, a proposal to revise the concept on N was made in a study by de Vries et al. (2013). The authors proposed separate limits for the N components NH_3, NO_3^-, and N_2O and a restriction to agriculturally intensive regions due to the spatial variability of N losses. In addition, attention was drawn to the need for regional boundaries based on carrying capacity for N inputs to be aggregated into a global value. These aspects have been considered in the revision of the PB study by Steffen et al. (2015).

Building on the approach of de Vries et al. (2013), a recent study by de Vries et al. (2021) presented regional N boundaries for EU-27. However, in contrast to the N boundaries reflected by the PB concept, the authors also considered possible increases in N inputs to reach desired agricultural yields (de Vries et al., 2021). Therefore, the required N inputs to achieve target yields (based on the year 2010) for agricultural soils and N losses from agricultural systems in the EU-27 region were calculated. The authors analyzed N inputs to agricultural soils through mineral fertilizer, animal manure, bio solids, atmospheric deposition and biological N fixation.

Based on N inputs and N losses values for critical inputs and critical losses for different N limits were derived as: i) atmospheric N deposition levels to terrestrial ecosystems based on critical loads, ii) N concentrations in runoff to surface water to limit eutrophication and iii) NO_3^- concentration in leachate to groundwater to avoid human health impacts (de Vries et al., 2021; de Vries and Schulte-Uebbing, 2020).

The approach developed in this thesis applies the data on critical N losses provided by de Vires based on the methodological concepts by de Vries et al. (2021) and de Vries and Schulte-Uebbing (2020).

1.4.3 Absolute sustainability references and carrying capacities in Life Cycle Assessment

The exceedance of the PBs for biogeochemical flows due to nitrogen losses is a well-recognized problem (Gerten et al., 2020; Schulte-Uebbing et al., 2022). Setting thresholds to maximum N input is necessary to conserve the resilience of these critical earth system processes. Threshold concepts are therefore necessary to identify whether a system is sustainable also in absolute terms compared to its carrying capacity. The planetary boundary concept may be interpreted as carrying capacities of the earth system, monitoring sustainability from an absolute perspective by defining clear quantitative boundaries for what the earth can withstand (Bjørn et al., 2015). An “absolute perspective” involves comparing an environmental impact caused by anthropogenic intervention in relation to regional or global carrying capacities (Bjørn et al., 2015).

Although LCA provides the link between environmental interventions and impacts, it operates on a relative scale of sustainability where the performance of a product is compared to alternative products or technologies, not considering the environment's carrying capacity.

There is an increasing research interest in integrating the concept of "resilience" by including "carrying capacities" or PBs in LCA and thus assessing absolute environmental sustainability (AES). Methodological approaches for the integration of resilience or exposure limits in LCA and, thus, the inclusion of AES indicators have been published by several authors in recent years (Bjørn et al., 2020c; Bjørn et al., 2020d; Bjørn et al., 2020a; Bjørn et al., 2016; Bjørn and Hauschild, 2015; Ryberg et al., 2016; Sala et al., 2020; Sandin et al., 2015; Tuomisto et al., 2012; Vargas-Gonzalez et al., 2019; Wolff et al., 2017). The AES assessment evaluates an anthropogenic system's absolute environmental performance according to its assigned environmental carrying capacities (Bjørn et al., 2020a).

Defining absolute sustainability thresholds for LCA, Bjørn et al. (2020a) described carrying capacities as "[…] *the maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems* […]" (Bjørn et al., 2020a).

The developed approach in this thesis is built on the idea of integrating absolute sustainability reference as regional carrying capacities for N resilience in LCA (Bjørn et al., 2020a). The regional N resilience herewith displays the carrying capacity of a region defined as the maximum persistent impact the environmental compartments in a region, affected by these impacts, can sustain, maintaining their function and structure (Bjørn et al., 2015; Walker et al., 2004). With this, instead of analyzing LCA results in a comparative assessment of two systems in relative terms, the system is compared to an absolute reference as carrying capacity or, accordingly, N resilience of a specific region.

2 NITROGEN IN LIFE CYCLE ASSESSMENT (LCA) OF AGRICULTURAL CROP PRODUCTION SYSTEMS: COMPARATIVE ANALYSIS OF REGIONALIZATION APPROACHES

This chapter contains the following publication:

I. NITROGEN IN LIFE CYCLE ASSESSMENT (LCA) OF AGRICULTURAL CROP PRODUCTION SYSTEMS: COMPARATIVE ANALYSIS OF REGIONALIZATION APPROACHES.

Wowra, K., Zeller, V., Schebek, L.

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The publication Wowra et al. (2021) contains a comprehensive review of nitrogen in Life Cycle Assessment of agricultural crop production systems. The scientific background and relevant aspects specific to nitrogen in LCA are presented and analyzed. Particular focus is laid on implications on the regional level and, thus, the relevance of regionalization in LCA. The main outcome is the derivation of key parameters relevant to a comprehensive assessment of N impacts in LCA and recommendations for LCA practitioners. Furthermore, the study highlights the relevance of integrating regional impact categories in the assessment of cropping systems and the consideration of reference values for an improved interpretation of N-related impacts in the assessment of cropping systems in LCA.

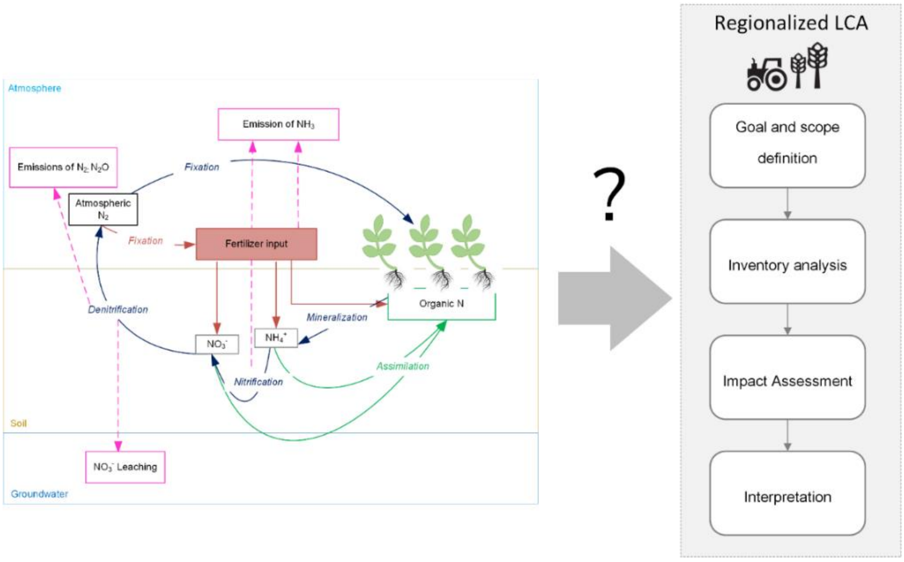

Figure 2.1. Graphical abstract review study Wowra et al. (2021).

ABSTRACT

Assessing reactive nitrogen (N_r) flows resulting from agricultural crop production systems (ACPS) with LCA requires regionalization. However, methodological approaches for regionalized LCA of ACPS may not necessarily reflect a comprehensive picture of N_r compounds and their complex interaction with the environment. This study presents a comprehensive analysis of the consideration of N_r in methodological approaches for regionalized LCA applied to ACPS. We conducted a review comprehending scientific literature on regionalization approaches applied to ACPS and compared these with general requirements of LCA and the scientific background of the N-cycle following the LCA framework. Special focus was placed on the analysis of process-based models (PBM) and life cycle impact assessment (LCIA) methods. We derived key factors relevant for a regional assessment of N flows in LCA and compared these to 23 regionalization approaches applied to ACPS. Main obstacles identified to conduct a regionalized LCA for ACPS involved the consideration of different regional scales and thus a missing common regionalization approach suitable for ACPS. Although, N related key-factors were mainly considered by the analyzed approaches in the different LCA phases, critical points involved the consideration of N field emissions and N impact assessment. Based on these findings, practical recommendations were given. Our comprehensive review provides relevant requirements for an improved regional N assessment in regionalized LCA of ACPS and aims to present a realistic picture when comparing different alternatives considering N specific regional impacts.

Keywords: Reactive Nitrogen; Nitrogen assessment; Regionalization in LCA; LCIA methods; agricultural crop production systems

3 REGIONAL NITROGEN RESILIENCE AS DISTANCE-TO-TARGET APPROACH IN LCA OF CROP PRODUCTION SYSTEMS

This chapter contains the publication:

II. REGIONAL NITROGEN RESILIENCE AS DISTANCE-TO-TARGET APPROACH IN LCA OF CROP PRODUCTION SYSTEMS

Wowra, K., Zeller, V., Schebek, L.

Environmental Impact Assessment Review 2022, Volume 97, 106869

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Based on the identified requirements for the consideration of N assessment in LCA in the first publication Wowra et al. (2021), the second publication Wowra et al. (2022b), provides the core of the thesis and the development of the distance-to-target approach. The study describes the development of the method, necessary data, and steps for the final application in LCA. The focus lies notably on the derivation of regional normalization references, which are the basis for the distance-to-target approach. The normalization references are based on values for critical N-losses on the regional level. The first proof of concept is presented for two NUTS-3 regions in Germany, Celle and Kassel for rapeseed production and three yield scenarios. Furthermore, the derived regional references are compared to already developed European references. To show sensitivity towards impact assessment and spatial differentiation, two different LCIA methods are applied.

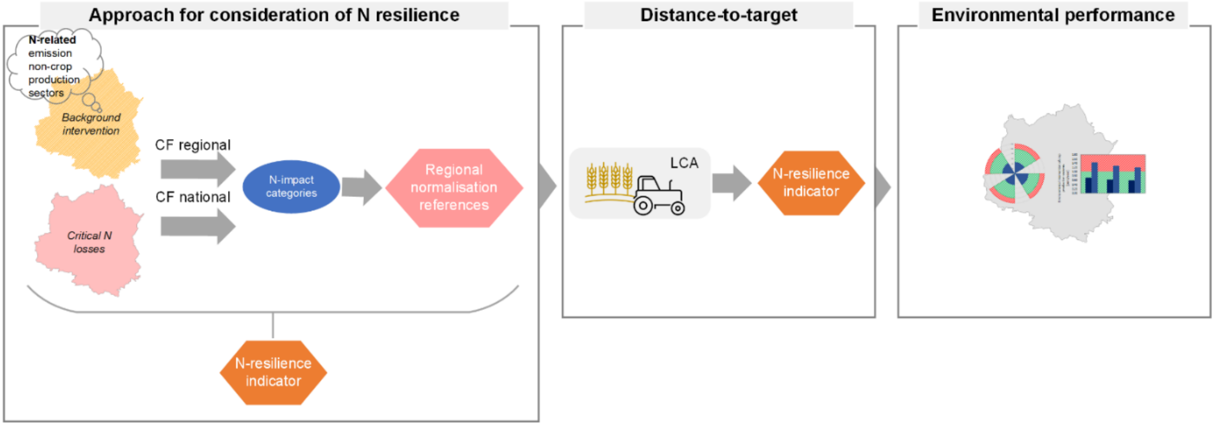

Figure 3.1. Graphical abstract study on approach development Wowra et al. (2022b).

ABSTRACT

Agricultural production systems are highly dependent on nitrogen (N) inputs. According to assessments following the concept of Planetary Boundaries (PB), global limits for N-cycles are already exceeded. However, regional thresholds and resiliencies may vary as N compounds have implications on different spatial scales, for instance, eutrophication or acidification on the regional level. Regional N management activities may influence these environmental impacts. Thus, regional N resiliencies must be considered when assessing agricultural systems with Life Cycle Assessment (LCA). This paper provides an approach for integrating regional N resilience as distance-to-target in assessing crop production systems. Therefore, regional carrying capacity based normalization references were developed, integrating N-related thresholds for agricultural intervention based on the Life Cycle Impact Assessment (LCIA) framework. In addition, regional background interventions of non-crop production sectors were taken into account to comprehensively assess the regional environmental performances of cropping systems. Moreover, regionalization effects were assessed applying spatially differentiated characterization factors. The approach is applied to a case study for two different NUTS-3 regions in Germany, including different N management scenarios. The results showed a high influence of the integrated background intervention and regional characterization on the environmental performances of the cropping systems. N resiliencies were exceeded for all regions, when assuming high yield scenarios, for both eutrophication and acidification impacts. Finally, we present the first proof for application as additional decision support for regional stakeholders regarding N management strategies. For further development and improvement, future research should include investigations of different NUTS-3 regions, N management scenarios and emission reduction levels for background interventions

Keywords: Nitrogen assessment; Resilience; Regional thresholds; Normalization in LCA; Distance-to-target; Crop production systems

4 EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF CROPPING SYSTEMS UNDER DIFFERENT NITROGEN MANAGEMENT SCENARIOS CONSIDERING REGIONAL NITROGEN RESILIENCE

This chapter contains the publication:

III. EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF CROPPING SYSTEMS UNDER DIFFERENT NITROGEN MANAGEMENT SCENARIOS CONSIDERING REGIONAL NITROGEN RESILIENCE

Wowra, K., Zeller, V., Schebek, L.

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The third publication Wowra et al. (2022a), provides the proof of concept of the distance-to-target-approach introduced in Wowra et al. (2022b). The study aims to prove the applicability as decision support in agricultural LCA within five case study regions and four different N management scenarios. Furthermore, regional normalization references for all German NUTS-3 regions are derived for the two N-related impact categories, terrestrial acidification potential, and terrestrial eutrophication potential.

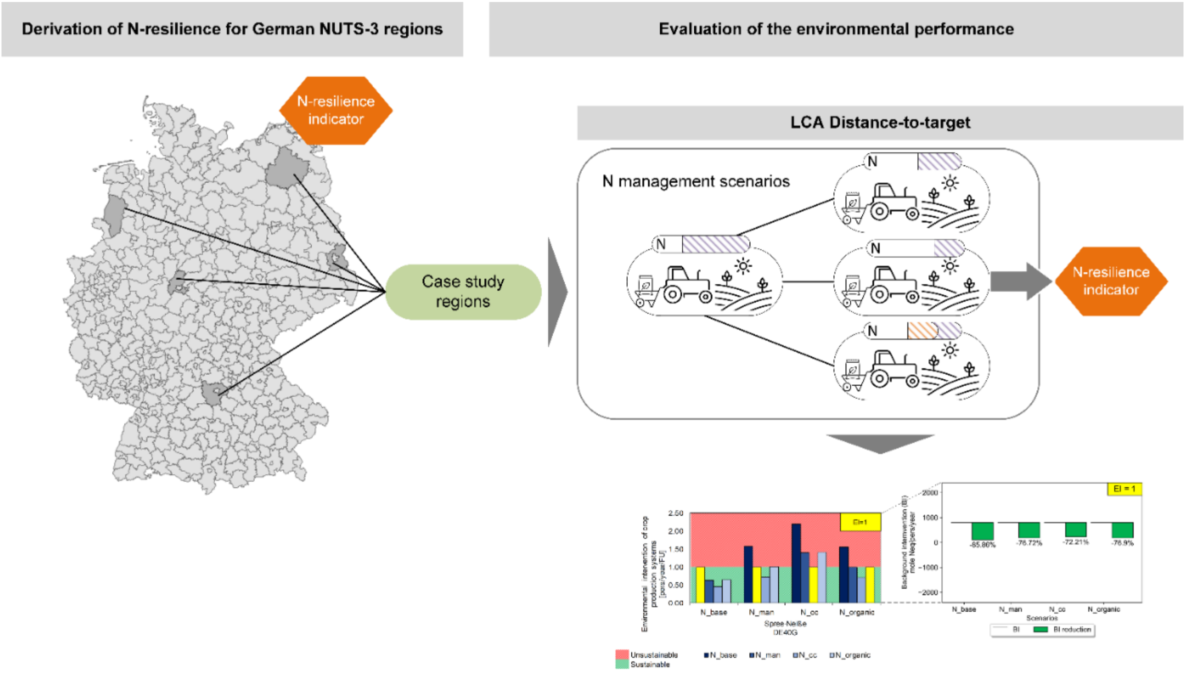


Figure 4.1. Graphical abstract case study Wowra et al. (2022a).

ABSTRACT

The agricultural sector is a primary driver of nitrogen (N) pollution. Several European and German policy measures exist regulating N inputs and fostering mitigation measures in crop management. Life cycle assessment (LCA) is an established tool for assessing environmental impacts which are also broadly applied for crop production systems and evaluation of N management strategies. However, due to the multiple spatial and temporal pathways of N losses from crop production, assessing N-related impacts in LCA is not straightforward. Consequently, this study further developed and applied a novel distance-to-target approach including regional carrying capacity based normalization references for N assessment in LCA. The overall aim was to prove its applicability as regional decision support for the assessment of N management strategies in cropping systems considering environmental interventions with regional N resiliencies. Therefore, environmental interventions were evaluated within a case study for four different N management scenarios for rapeseed cropping systems in five German NUTS-3 regions. Regional carrying capacity based normalization references were derived for two N-related impact categories: terrestrial eutrophication and terrestrial acidification. The regional normalization references also included background interventions of non-crop producing sectors and were provided for all German NUTS-3 regions applicable as distance-to-target values in LCA. Overall results showed that environmental interventions and exceedance of N resilience were lowest in the N management scenario applying catch crops for both impact categories. The case study demonstrated that considering absolute sustainability references as regional N resilience in LCA is a valuable tool for agricultural decision-makers to evaluate N management strategies for crop production systems.

Keywords: Nitrogen management; Crop production systems; Nitrogen resilience; Normalization in LCA; Distance-to-target

4.1 INTRODUCTION

Nitrogen (N) is an essential nutrient for agricultural activities necessary for food and feed security. Growing demand for food is followed by agricultural intensification, increasing N fertilizer and land use coming at high environmental costs (Chen et al., 2014; Erisman et al., 2013; Foley et al., 2011). However, not all N is taken up by crops. About 80% of N, utilized for agricultural production in fertilizers and biological N fixation, is lost to the environment (Sutton et al., 2013). Consequently, higher N inputs result in losses of reactive N compounds such as nitrous oxides (N_2O), ammonia (NH_3) or nitrate (NO_3^-), leading to adverse environmental impacts such as climate change, eutrophication or acidification of ecosystems and threatening human health (Bodirsky et al., 2014; Bouwman et al., 2013; Tian et al., 2020). Furthermore, the extent to which N accumulation has already occurred is made visible by the exceedance of planetary boundaries biogeochemical N-cycles (de Vries et al., 2013; Erisman et al., 2015; Rockström et al., 2009; Salomon et al., 2016; Steffen et al., 2015; Sutton et al., 2013).

Since N fertilizers are one of the largest N inputs resulting from agricultural activities, sustainable N management aiming to reduce N inputs and increase N use efficiencies is vital (Sutton et al., 2013). In practice, N management strategies such as improving N fertilizer timing and placement, matching N fertilizer application rate to crop requirements, or using catch crops and reduced tillage may reduce N losses (Döhler et al., 2011; Schütze and Geupel, 2011). Multiple policies and strategies have been introduced at the European and the German level to implement these measures. A central part of the European Green Deal is the Farm to Fork Strategy, which aims to reduce 50% nutrient losses like N and P, leading to fertilizer reductions of 20% by 2030. In Germany, the Fertilizer Ordinance (in German Düngeverordnung - DüV), as a key agricultural and environmental policy instrument, aims to reduce and regulate the use of mineral and organic fertilizers on farms and thus the input of N emissions from agricultural production systems to terrestrial and aquatic ecosystems (BMEL, 2021). However, recommendations about suitable N management strategies to achieve necessary reduction targets depend on regional conditions as different N mineralization (Nmin) rates, yield requirements or other biogeographical aspects (Olfs et al., 2005). Hence, identifying the impact of N management strategies of cropping systems requires a detailed assessment on the regional level to address the effects of the diverse environmental impacts.

A well-established method for determining the environmental impacts of crop production systems and decision support is Life Cycle Assessment (LCA). LCA serves as a support tool for implementing policy strategies such as the Farm to Fork strategy (Sala et al., 2021) and can provide an added value in evaluating and monitoring N reduction measures as, e.g. proposed by the German Fertilizer Ordinance. However, assessing the impacts of N losses resulting from agricultural production systems and considering different management strategies is not straightforward due to the multiple spatial and temporal N pathways.

The relevance of regionalization in LCA to cover N-related impacts such as eutrophication and acidification of terrestrial and freshwater systems is widely acknowledged (Patouillard et al., 2018; Potting et al., 1998; Yang and Heijungs, 2017) and well established in standard Life Cycle Impact Assessment (LCIA) methods (Norris, 2002; Potting et al., 1998; Roy et al., 2014; Roy et al., 2013; Roy et al., 2012a; Seppälä et al., 2006). Hence, it also plays a crucial role in agricultural LCA. However, standard LCA allows for a comparative assessment of alternative crop management systems, for example, but it does not express sustainability in absolute terms (Bjørn et al., 2020b). Therefore, the environmental performance of cropping systems in relation to absolute boundaries, such as carrying capacities, is not covered (Wowra et al., 2021).

Approaches studying absolute environmental sustainability (AES) in LCA exist with the planetary boundary concept, where a reference is integrated with, e.g., characterization factors (CF) (Bjørn et al., 2020c; Bjørn et al., 2020b; Ryberg et al., 2018; Ryberg et al., 2016) or applied as normalization reference (NR) (Bjørn and Hauschild, 2015). Normalization is an optional part of the Life Cycle Impact Assessment (LCIA) and is defined as "calculating the magnitude of category indicator results relative to reference information" (ISO, 2006b). Therefore, it can play a valuable role in facilitating the interpretation and communication of results to decision-makers (Pizzol et al., 2017). Furthermore, the integration of normalization references based on carrying capacities for ecological thresholds may improve the assessment of, for instance, management strategies of cropping systems by an interpretation in absolute terms.

In a recent study by Wowra et al. (2022b), the authors developed an approach to determine regional carrying capacity based normalization references for N assessment in LCA. The references are applied as distance-to-target values to assess the impacts of crop production systems on regional N resilience, contributing to terrestrial acidification and terrestrial eutrophication impacts. The regional N resilience herewith displays the carrying capacity of a region defined as the maximum persistent impact that the environmental compartments in a region, affected by these impacts, can sustain while maintaining their function and structure (Bjørn et al., 2015; Walker et al., 2004). The study by Wowra et al. (2022b) revealed that the environmental performance of cropping systems in terms of N resilience might differ regionally and concluded that it is necessary to also consider current N-related background interventions of non-crop producing sectors. However, the study did not evaluate the influence of different N management strategies based on policy measures and their impacts on regional N resilience.

Consequently, this study aims to evaluate different N management scenarios affecting N resilience by further developing and applying regional carrying capacity based normalization references as distance-to-target values in LCA. The scenarios are based on policy measurements of the German Fertilizer Ordinance applied to rapeseed cropping systems for five case study regions. Furthermore, for all German regions on NUTS-3 level (smallest regional division in Eurostat's Nomenclature of Territorial Units for Statistics), values for regional normalization references and background interventions of non-crop producing sectors contributing to acidification and eutrophication impacts were derived. The overall aim of the study is to evaluate the applicability of a newly developed approach for assessing policy reduction measures and N management strategies by considering regional N resilience in LCA. Therefore, regional differences in N management options and reduction potentials for minimizing impacts on regional N resilience will be identified.

Herewith, the improved decision support for agricultural stakeholders on the regional level for a wide range of research questions in the evaluation of cropping systems shall be proven.

4.2 MATERIALS AND METHODS

The study's main goal was to comprehensively assess the environmental intervention considering regional N resilience of rapeseed production systems in five different case study regions. Therefore, the environmental performance for four N management scenarios was assessed by combining LCA and a recently developed distance-to-target approach (Wowra et al., 2022b). An attributional LCA is applied following ISO 14040/44 (ISO, 2006a, 2006b). The study focused on regional N-related impacts of terrestrial acidification potential (TAP) and terrestrial eutrophication potential (TEP). The distance-to-target approach applies regional carrying capacity based normalization references (rNR) for N-related impact categories and considers background interventions (BI) of non-crop producing sectors in NUTS-3 regions. For the application of the approach, three steps have to be undertaken: first, the calculation of N-related background interventions of non-crop producing sectors; secondly, the definition of N-related thresholds; and based on these, in a third step, the derivation of carrying capacity based normalization references. A detailed description of each step, background data, and data sources is provided by Wowra et al. (2022b). The subsequent sections briefly describe the steps required for assessing the environmental performance of the cropping systems with the distance-to-target approach, the case study design, and each life cycle phase.

4.2.1 Distance-to-target approach for assessing the environmental performance

The relevant steps for assessing the environmental performance and derivation of the relevant parameters are the following:

1. **Calculation of background interventions (BI).**

   Based on data for air pollutant emissions of the German Environment Agency (Umweltbundesamt) (Schneider et al., 2016), background interventions of non-crop production sectors are calculated for N emissions contributing to acidification and eutrophication impacts. The background interventions are aggregated on a NUTS-3 level and derived for TAP and TEP impact categories.

2. **Definition of regional N-related thresholds.**

   The calculation of regional thresholds is based on data for critical N losses for German NUTS-3 regions provided by De Vries based on de Vries and Schulte-Uebbing (2020) and de Vries et al. (2021). The thresholds are derived from values for the critical loss of NH_3 emissions leading to critical N deposition, depending on the ecosystem's critical load (de Vries et al., 2021). These values are used as thresholds for TAP and TEP mid-point impact categories.

3. **Derivation of regional carrying capacity based normalization reference (rNR).**

   The regional normalization references (rNR) are based on the derived regional N-related thresholds. According to an equal per capita sharing principle, the threshold for a specific NUTS-3 region *j* and impact category *i* is related to the number of persons (pers) *P* living in the region *j* as described in equation (1).

$$rNR_{i,j} = \frac{Threshold_{i,j}}{P_j} \quad (1)$$

The indicator rNR does not consider background interventions related to non-crop producing sectors in a specific region. Therefore, the background intervention BI of an impact i in a region j is subtracted from the rNR as shown in equation (2),

$$rNR_{BI_{i,j}} = rNR_{i,j} - BI_{i,j} \quad (2)$$

where, the indicator rNRBI is defined as the regional normalization reference of a specific region j, contributing to an impact category i and considering the background intervention (BI) of non-crop producing sectors expressed in pers/year.

4. **Assessment of the environmental performance.**

After completing steps 1 to 3, the environmental performance is assessed for the defined scenarios of the crop production system using the indicator rNR_{BI}. This is applied as a distance-to-target value to an impact I resulting from an LCIA category i. Thus, the environmental performance is described as the environmental intervention (EI) namely, the specific personal share (in pers/year) of a cropping system's impact I to the N resilience (rNR_{BI}) in a region j contributing to an impact category I – as shown in equation (3). If the EI results in a value above 1, the EI of the environmental performance of the respective cropping system is assessed as "unsustainable" since it exceeds regional N resilience.

$$EI = \frac{I_i}{rNR_{BI_{i,j}}} \quad (3)$$

All parameters are derived for each NUTS-3 region in Germany and include an impact characterization focusing on TAP and TEP impacts. To assess the TAP, we applied the IMPACT World+ (Bulle et al., 2019) method using characterization factors (CF) on regional levels. For TEP, we applied the Environmental Footprint (EF) method (reference package 2.0) (Fazio et al., 2018; Sala et al., 2019) using CF on the national level since no finer scale of CF is available.

4.2.2 Case Study Regions

The case study regions are related to German NUTS-3 regions. First, background interventions of non-crop producing sectors were derived for all German NUTS-3 regions contributing to terrestrial eutrophication and terrestrial acidification impacts. Five case study regions were selected based on the following criteria:

i. NUTS-3 region with the highest background intervention affecting TAP;

ii. NUTS-3 region with the highest background intervention affecting TEP;

iii. NUTS-3 region with the largest share of agricultural area.

iv. In addition, for comparability, two regions were selected, representing average population and agricultural area.

Accordingly, the following regions were further assessed:

1. Emsland (DE949), located in Lower Saxony, North West Germany;

2. Mecklenburgische Seenplatte (DE80J) located in Mecklenburg-Western Pomerania, North-East Germany;

3. Kassel (DE734), located in Hesse, Mid-West-Germany;

4. Spree-Neiße (DE40G), located in Brandenburg, East-Germany and

5. Ansbach (DE256), located in Bavaria, South Germany.

Table 4.1 shows the main characteristics of the regions and the related criteria.

Table 4.1. Case study regions and biogeographical characteristics.

Name and NUTS identification	Emsland (DE949)	Mecklenburgische Seenplatte (DE80J)	Kassel (DE734)	Spree-Neiße (DE40G)	Ansbach (DE256)
Region	Lower Saxony	Mecklenburg-Western Pomerania	Hesse	Brandenburg	Bavaria
Population (amount)[a)]	325,657	259,130	236,633	114,429	183,949
Total land area (in ha)	288,366	549,560	129,333	165,698	197,133
Agricultural area (in ha)[b)]	174,440	316,597	57,704	57,942	111,284
Soil characteristics[c]	Para-brown earths, Pseudogley characterized by periodically stagnated surface water, Soils are mainly sand to loamy sands, poor to moderate in nutrients, well-drained	Pseudogley and Para-brown earths with loamy sands to sandy loam structure, moderate nutrient demand	Para-brown earths, Podzolic brown earths, with clay slit to slit clay textures, good water and nutrient capacity	Podzolic brown earths, parabrown earths, with mainly sand to loamy sand structure, dry and excessively drained, acidic and nutrient-poor	Podzol-brown earths with slit-clay to clay sand texture, moderate nutrients, well-drained
Clay amount (in%)[c)]	0 – 8	5 – 12; 8 – 17	17 – 30; 8 – 17	0 – 8	25 – 45; 8 – 17
Precipitation (average in mm)[d)]	~782	~530	~622	~603	~625
Related criteria selection	iii	ii	iv	i	iv

[a)](DeStatis, 2018b); [b)](DeStatis, 2018a); [c)](Düwel et al., 2007); [d)](Wetterkontor.de, 2020)

4.2.3 Goal, scope and functional unit

Figure 4.2 shows the considered system boundary comprising all relevant process steps of the fore- and background system from cradle-to-farm-gate. The system included the agricultural production of rapeseed until its provision as raw material. The analysis focused on the vegetation period of rapeseed production, assuming winter barley as the previous crop, including catch-crop cultivation (if applied), sowing of rapeseed, and the harvest, but not including further crop rotations. The functional unit (FU) describes the management of 1 hectare of arable land indicated for rapeseed within a NUTS-3 region. Data for background processes were based on the ecoinvent database v.3.5 (cut-off) (ecoinvent association, 2018).

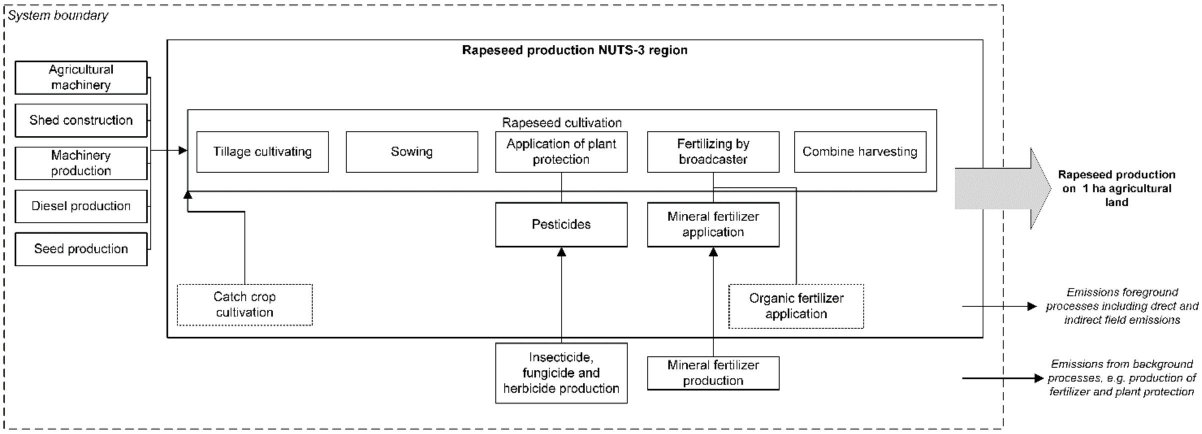


Figure 4.2. System boundary and considered processes for LCA of rapeseed production systems for a NUTS-3 region. The dotted lines show optional process steps depending on the scenario considered.

4.2.4 Life Cycle Inventory and assumptions

4.2.4.1 Nitrogen management scenarios and effects of nitrogen reducing management

One of the most important measures to reduce N emissions within the German Fertilizer Ordinance is a binding N demand analysis to determine fertilization requirements (BMEL, 2021; LLH, 2021a). According to a defined procedure, farmers must calculate the specific N requirement depending on parameters influencing the requirement of the respective cultivated crop.

For the case study assessment, four different N management or reduction scenarios were defined on the basis of neglecting or considering the N demand analysis and applying different N mitigation options:

N-base scenario: This scenario does not include an N demand analysis, and potential yields are based on general recommendations of the German fertilizer ordinance.

N-management: In this scenario, the fertilizer amount is determined according to the N demand analysis, and the considered yields are based on the region's three-year average. Furthermore, soil humus content is considered, and no further N mitigation options are included.

N-catch crop: The calculated fertilizer amount is determined according to the N demand analysis, and considered yields are based on the region's three-year average. The cultivation of a catch crop as an N reduction option is assumed.

N-organic: This scenario applies the same measurement as the N-catch crop. In addition, it is assumed that the crop production system proportionally replaces its mineral fertilizer quantity by importing organic fertilizers (liquid manure). Thus, it also accounts for the organic fertilizer application of the previous year.

As further N reduction management, we considered specific characteristics such as low tillage soil cultivation technique for all scenarios and N reducing application technique for manure. We included data based on regional agricultural statistics for each region to derive values for yields, N mineralization (Nmin) in soil, and applied fertilizer types. Table 4.2 lists all relevant scenario parameters and considered values of the respective regions.

4.2.4.2 Consideration of direct and indirect emissions

We applied an emission factor based approach to quantify direct and indirect field emissions, including data on the regional NUTS-3 level where possible. N_2O emissions were estimated according to the Tier 1 approach of the Intergovernmental Panel on Climate Change (IPCC, 2006) as proposed in Nemecek et al. (2016). In addition, we calculated the amount of leached N that leads to indirect N_2O emissions (Rösemann et al., 2021). Losses of ammonia (NH_3) from mineral nitrogen (Audsley et al., 1997) fertilizers were calculated according to the Tier 2 approach and emission factors provided by the EEA (2019). We calculated emissions for mineral fertilizers considering: calcium ammonium nitrate (CAN), urea ammonia nitrate (UAN) and urea. Furthermore, NMVOC emissions were calculated based on the Tier 2 methodology described in (EEA, 2019). Nutrient losses via leaching were considered for nitrate (NO_3^-) (Emmenegger et al., 2009) and leaching and run-off of phosphorus (P_2O_5) (Nemecek et al., 2007). According to the Guidance for the development of Product Environmental Footprint Category Rules provided by European Commission (2017), emissions of pesticides, fungicides, and insecticides were estimated. We also calculated nitrogen and phosphor emissions from manure application for the N-organic scenario. We assumed the application with a trailing shoe and an immediate (<4 hours) incorporation of manure (Rösemann et al., 2021).

4.2.5 Life Cycle Impact Assessment

The life cycle impact assessment was carried out using the LCIA methods Environmental Footprint method (reference package 2.0) (Fazio et al., 2018; Sala et al., 2019) and IMPACT World+ (Bulle et al., 2019). Regional CFs were applied for TAP calculated with IMPACT World+.

4.2.6 Sensitivity and uncertainty analysis

Sensitivity and uncertainty analysis of the developed normalization references, chosen LCIA methods, and life cycle inventory (LCI) input parameters were done to test the influence of the assumptions made (Rosenbaum et al., 2018). Therefore, the uncertainty of the developed indicator rNR_{BI} was assessed across all NUTS-3 regions with a quantitative uncertainty approach. Furthermore, to account for the sensitivity of spatial variability for the TAP category, regional normalization references and background interventions were additionally calculated with the national CF of IMPACT World+ and the EF method (reference package 2.0) (Fazio et al., 2018; Sala et al., 2019).

Uncertainty analysis of LCI input parameters was done to evaluate statistical significance. However, a complete statistical significance analysis could not be conducted since uncertainty of all parameters is unknown. Therefore, only the most sensitive input parameters for agricultural LCI calculation, namely Nmin values and agricultural yields, were taken into account due to their high spatial variability and dependency on biogeographical conditions (Nemecek et al., 2005). Both parameters define fertilization requirements. Monte Carlo simulations were carried out to account for these uncertainties, including 1000 iterations for all scenarios and regions and two LCIA methods. Since yield variabilities are already considered in the different scenarios, only the parameter Nmin was varied. We considered a standard deviation of 10% and log-normal distribution. Results of the sensitivity and uncertainty analysis are provided in detail in the supplementary material Appendix I SM2.

Table 4.2. Scenario parameters and calculated values for LCI for the NUTS-3 regions, Ansbach, Spree-Neiße, Kassel, Mecklenburgische Seenplatte and Emsland. Unless N-base, all scenarios are based on a N demand analysis. (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario; Nmin = N-mineralization in soil; CAN = Calcium ammonia nitrate; UAN = urea ammonium nitrate).

	Ansbach				Spree-Neiße				Kassel				Mecklenburgische Seenplatte				Emsland			
	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org
Yield potential	high	3-year average middle f)			high	3-year average middle h)			high	3-year average middle j)			high	3-year average middle l)			high	3-year average middle n)		
Yield rapeseed [tha^{-1}]	4	3.55	3.55	3.55	4	1.74	1.74	1.74	4	3.29	3.29	3.29	4	4.04	4.04	4.04	4	3.21	3.21	3.21
Yield dependent N demand [a] [kg Nha^{-1}]	200	187	187	187	200	132	132	132	200	179	179	179	200	201	201	201	200	176	176	176
Nmin [kg NO_{3}- Nha^{-1}]	44 [g]				18 [i]				32 [k]				7 [m]				35 [o]			
N demand [-Nmin kg Nha^{-1}]	156	143	143	143	182	114	114	114	168	147	147	147	193	194	194	194	165	141	141	141
Catch crop [minus 40 kg Nha^{-1}][b]	-	-	✓	✓	-	-	✓	✓	-	-	✓	✓	-	-	✓	✓	-	-	✓	✓
Organic fertilizer previous year [minus 5.4 kg Nha^{-1}]	-	-	-	✓	-	-	-	✓	-	-	-	✓	-	-	-	✓	-	-	-	✓
Humus amount more than 4% [minus 20 kg Nha^{-1}][c]	-	✓	✓	✓	-	-	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	✓

Continuation Table 4.2. Scenario parameters and calculated values for LCI base for the NUTS-3 regions, Ansbach, Spree-Neiße, Kassel, Mecklenburgische Seenplatte and Emsland. Unless N-base, all scenarios are based on a N demand analysis. (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario; Nmin = N-mineralization in soil; CAN = Calcium ammonia nitrate; UAN = urea ammonium nitrate).

	Ansbach				Spree-Neiße				Kassel				Mecklenburgische Seenplatte				Emsland			
	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org	N base	N man	N cc	N org
Fertilization																				
N-requirement for fertilization [kg Nha^{-1}]	156	123	83	77.6	182	114	74	68.6	168	127	87	81.6	193	194	154	148	165	141	101	95.6
Fertilization																				
Mineral fertilizer [kg Nha^{-1}]d)																				
CAN	76	60	41	22	91	57	37	18	146	110	76	43	33	34	26	20	49	42	30	19
UAN	3	3	2	1	46	28	19	9	7	6	3	2	17	17	14	10	31	27	19	12
Urea	77	60	40	22	45	29	18	9	15	11	8	4	143	143	114	86	85	72	52	32
Liquid manure [kg Nha^{-1}]e)				32.4				32.4				32.4				32.4				32.4
Mineral N [kg N ha^{-1}]	156	123	83	45.2	182	114	74	36.2	168	127	87	49	193	194	154	116	165	141	101	63.2

a) according to Fertilizer Ordinance 4 t ha^{-1}(BMEL, 2021); b) yield share legumes > 20-40% (LLH, 2021a); c) humus amount based on (Düwel et al., 2007); d) ratio for each region based on (DeStatis, 2020); e) application of 15m^{3}, 3.6 kg total N (LLH, 2021a); f) (BLS, 2021); g) (LfL, 2021); h) (SBB, 2021); i) (LELF, 2021); j) (HSL, 2021); k) (LLH, 2021b); l) (Laiv-mv, 2021); m) (LMS Agrarberatung GmbH, 2021); n) (LSN, 2021); o) (LWK Niedersachsen, 2021)

4.3 RESULTS AND DISCUSSION

4.3.1 Current background interventions and regional normalization references

Figure 4.3 shows the background intervention for all German NUTS-3 regions for the impact categories TAP and TEP of non-crop producing sectors displaying their share in relation to the highest interventions. The main share of the regions is distributed within lower background interventions for TAP impacts, whereas for TEP, the regions' background interventions are mainly distributed within a share of more than 25% of the highest background intervention. Emissions contributing to the N-related background interventions of non-crop producing sectors are NO_x emissions from the public energy sector or transportation and NH_3 emissions from the livestock sector. Both compounds cause acidification and eutrophication impacts. Regions with the highest background intervention contributing to TEP are located in the northwestern part of Germany. The reason is the high importance of the livestock sector in these regions. Consequently, their NH_3 emissions contribute considerably to the background interventions (Schneider et al., 2016). The region with the highest background intervention contributing to TAP and TEP is Spree-Neiße, located in the eastern part of Germany. Here, in contrast, the high background intervention results from NO_x emissions from the public power sector due to the location of a large-scale lignite power plant (Bundesnetzagentur, 2021).

Based on evaluations of the background interventions, the case study regions were chosen as described in section 4.2.2. The results of the derivation of regional normalization references (rNR), background interventions (BI) and the resulting regional normalization references considering BI (rNR_{BI}) are listed in the supplementary material Appendix I SM1. The values for the five case study regions are shown in Figure 4.3. The uncertainty analysis revealed that rNR and BI values are similar for most regions, meaning rNR_{BI} is predominantly positive and nearly evenly distributed around zero (see supplementary material Appendix I SM2). However, if the rNR is lower than current background interventions, rNR_{BI} may result in negative values, as in the case of Emsland and Spree-Neiße for eutrophication impacts. The same holds for Spree-Neiße for acidification impacts. In fact, if background interventions of the non-crop producing sectors are considered, the calculated regional rNR_{BI} values vary between minus 25% to more than minus 600% (Figure 4.3). This underpins the relevance of considering N-related background interventions in developing regional carrying capacity based normalization references. Likewise, based on this information, possible reduction levels and strategies for regions with high background interventions may be elaborated.

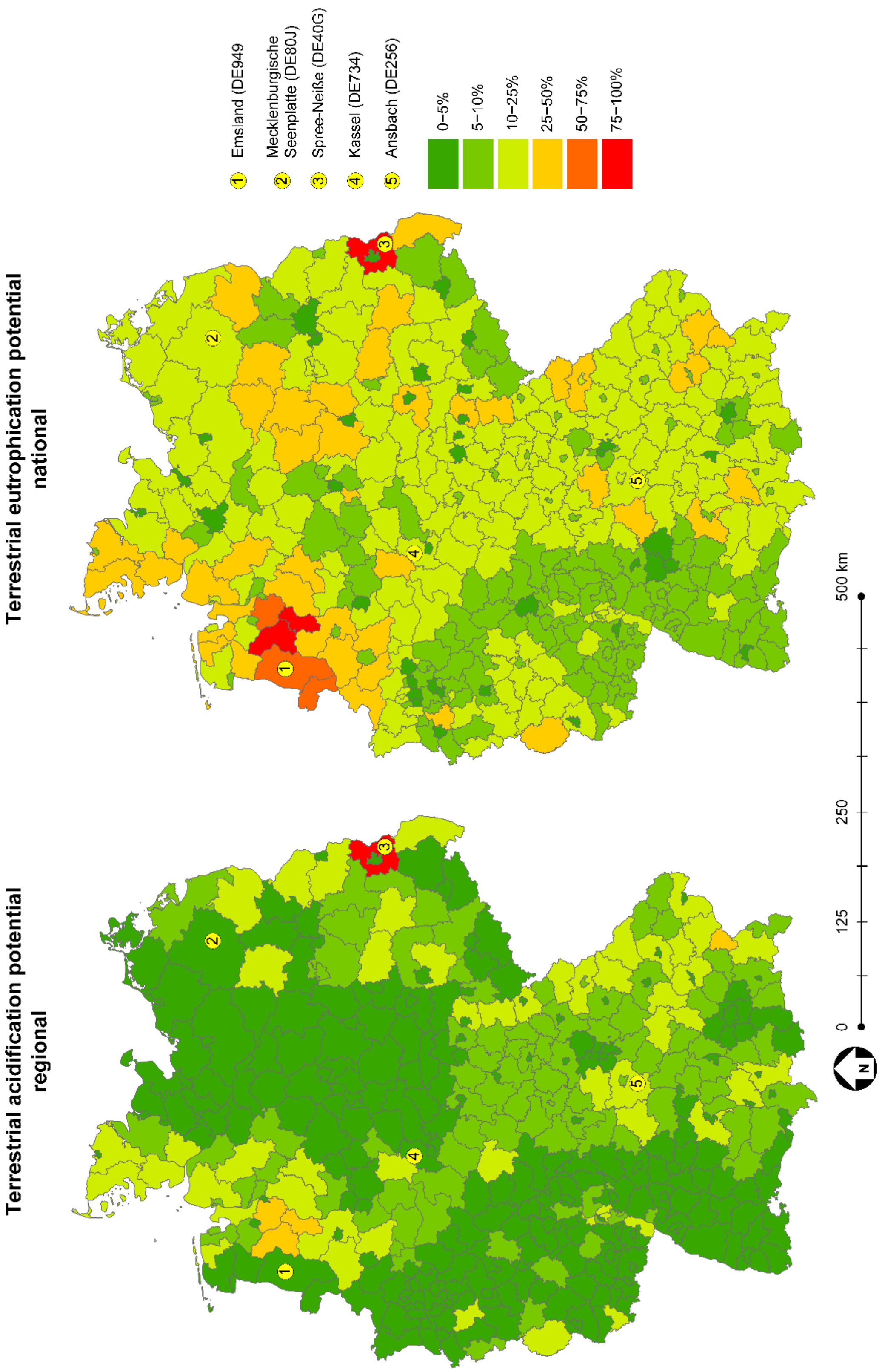
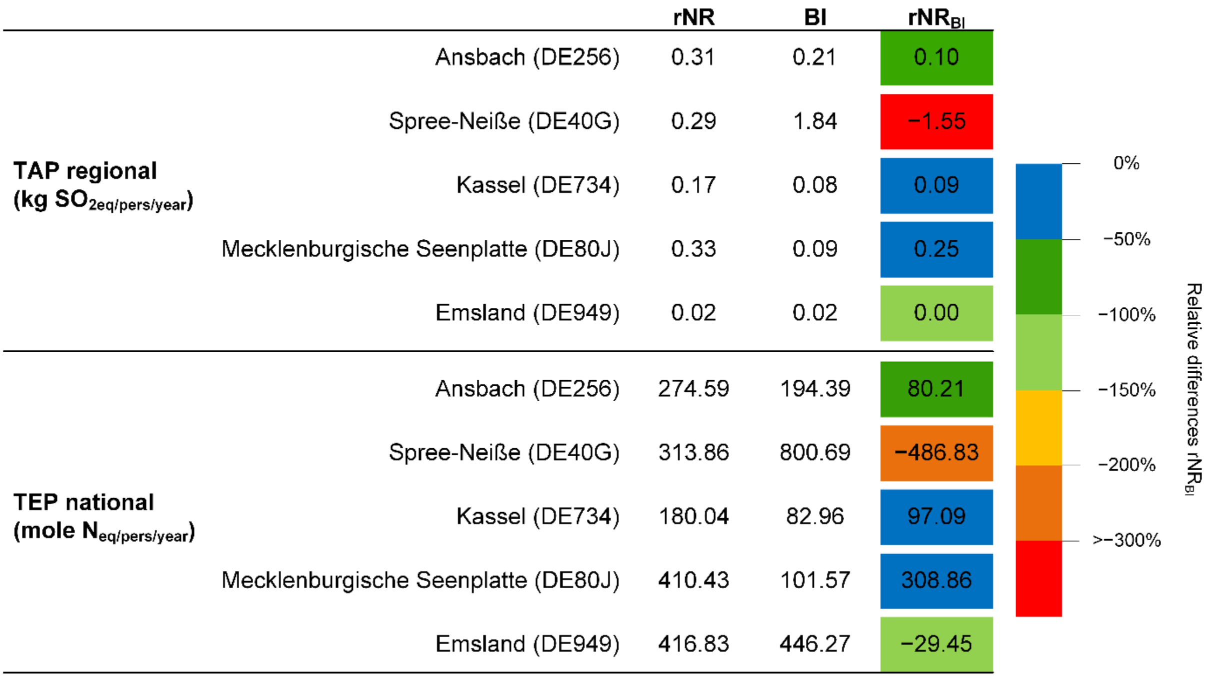


Figure 4.3. Background intervention in Germany for the impact categories terrestrial acidification potential, regional and terrestrial eutrophication potential, national. The intervention of NUTS-3 regions is shown as a share of distribution from low to high.



		rNR	BI	rNR_{BI}
TAP regional (**kg $SO_{2eq/pers/year}$**)	Ansbach (DE256)	0.31	0.21	0.10
	Spree-Neiße (DE40G)	0.29	1.84	−1.55
	Kassel (DE734)	0.17	0.08	0.09
	Mecklenburgische Seenplatte (DE80J)	0.33	0.09	0.25
	Emsland (DE949)	0.02	0.02	0.00
TEP national (**mole $N_{eq/pers/year}$**)	Ansbach (DE256)	274.59	194.39	80.21
	Spree-Neiße (DE40G)	313.86	800.69	−486.83
	Kassel (DE734)	180.04	82.96	97.09
	Mecklenburgische Seenplatte (DE80J)	410.43	101.57	308.86
	Emsland (DE949)	416.83	446.27	−29.45

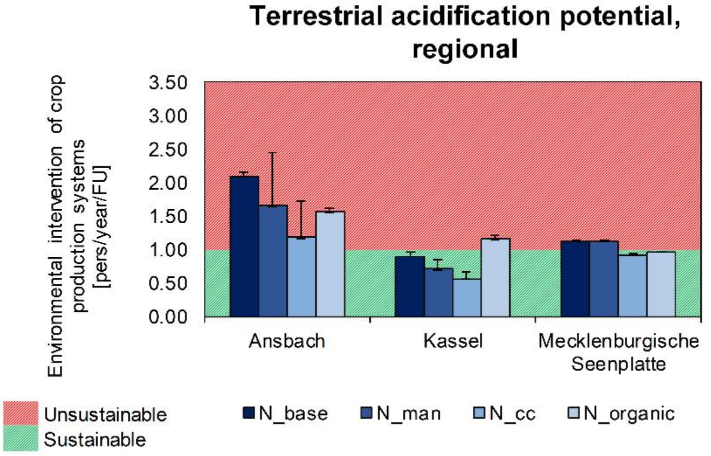
Figure 4.4. Regional normalization reference (rNR), background intervention (BI) and regional normalization references considering background interventions (rNR_{BI}) for the five case study regions for terrestrial acidification potential, TAP and terrestrial eutrophication potential, TEP. Relative differences from rNR for the resulting rNR_{BI} are shown in color.

4.3.2 Environmental performance of rapeseed production systems

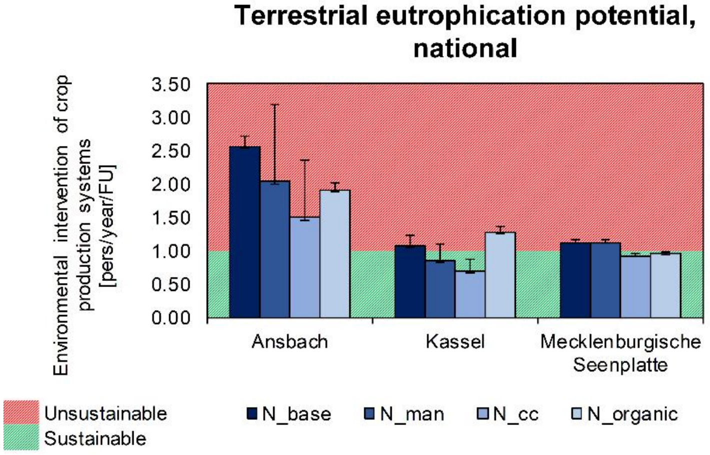
4.3.2.1 Regional differences in nitrogen management scenarios

The results of the environmental performance analysis of the N management scenarios for TAP and TEP impacts are presented in Figure 4.5 for the three case study regions, Ansbach, Kassel and Mecklenburgische Seenplatte and in Figure 4.6 for the other two regions Spree-Neiße and Emsland. As indicated in Figure 4.4, Spree-Neiße and Emsland showed higher background intervention than normalization references. Therefore, separate analyses including reduction of background interventions, have been carried out.

Comparing the three case studies in Ansbach, Kassel and Mecklenburgische Seenplatte, Kassel showed the lowest environmental intervention and Ansbach the highest (Figure 4.5). In all N-base scenarios, environmental interventions (EI) exceeded regional N resilience for TEP impacts, whereas for TAP impacts, this was only the case for Ansbach and Mecklenburgische Seenplatte. We generally observed a decrease in EI from the N-base to the N-catch crop scenario for all N scenarios. The highest decrease appeared for the Ansbach region, with a more than 40% reduction of EI from the N-base to the N-catch crop scenario. Due to the application of catch crops, lower mineral fertilizer amounts are necessary, leading to lower environmental intervention.



(a)



(b)

Figure 4.5. Environmental performance expressed as environmental intervention (EI, as annual personal share per functional unit, FU) of the case study regions Ansbach, Kassel and Mecklenburgische Seenplatte for (a) terrestrial acidification potential, regional and (b) terrestrial eutrophication potential, national. Results are displayed for the different N-management scenarios (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario). Error bars represent 95% probability range based on Monte Carlo analysis (see supplementary material Appendix I SM2).

For all three regions depicted in Figure 4.5, the lowest reduction of EI compared to the N-base scenario is observed for the N-management scenario. This lies notably in the fact that only the basic measurements of implementing and calculating fertilizer requirements according to the Fertilizer Ordinance were applied, and no further measurements were considered. Only for the region Kassel the N-base scenario remain under current background interventions in the sustainable area, resulting from high yields in the region and low background interventions (Figure 4.5). The region Mecklenburgische Seenplatte showed a minor influence amongst the different management scenarios, with a reduction of only 18% between the N-base and the N-catch crop scenario compared to the other regions, and no reduction from N-base to N-management. High yield assumptions based on a three-year average were the main reason. Moreover, although in Mecklenburgische Seenplatte, N-input assumptions were also highest amongst the regions due to high yields and low assumed Nmin in the soil, the environmental interventions only slightly exceeded regional N resilience, e.g., in the base scenario with EI=1.1

pers/year. A primary reason for this was, as in the case of Kassel, the low background interventions in this region (Figure 4.4). The uncertainty analysis of the LCI inventory revealed that the differences between all scenarios and regions based on the 95% confidence interval were deemed significant. The highest uncertainty was observed for the Ansbach region as displayed in the larger 95% probability range in Figures 4a and 4b (see Appendix I supplementary material SM2).

We assumed the background intervention for the non-agricultural sectors to remain static. However, background interventions are higher for some regions than the calculated rNR. This means that none of the agricultural management scenarios would perform environmentally friendly without reduction from these sectors in view of regional N resiliencies. Therefore, to achieve an equal share amongst the non-crop and the crop-producing sectors, we likewise assessed the necessary reductions in non-crop producing sectors by setting the EI = 1. The environmental performance assuming environmental interventions resulting in EI = 1 are shown in Figure 4.6 (a,b) for the Spree-Neiße region, and in Figure 4.7 (a,b) for Emsland. We highlighted these regions for demonstration due to their negative rNR_{BI} values. Results of the necessary reduction levels for the remaining regions are displayed in the supplementary material Appendix I SM1.

None of the scenarios in the Spree-Neiße and Emsland regions exceeded the regional N resilience for either impact categories if the target EI = 1 was set for N-base. The highest necessary reduction (−173%) of background interventions resulting from non-crop producing sectors is for Emsland for TAP impacts. The lowest reduction (−43%) of background intervention is displayed for TEP impacts in the region Emsland, if the minimum set of EI = 1 for the N-catch crop scenario is fulfilled. The N-catch crop scenario showed the best overall performance compared to the other regions. By contrast, in the Emsland region the N-organic scenario revealed the lowest environmental intervention in the case of TAP impacts (Figure 4.7a). In this case, a reduction of up to 26% was achieved by applying the N-organic scenario. When comparing all N-scenarios within the Spree-Neiße region, it can be noted that the reductions in environmental interventions were highest between the N-base and the other scenarios. For instance, EI leading to TEP impacts decreased by 55% and for TAP by 54% from N-base to N-catch crop (Figure 4.6 (a,b)). Since the three-year average yield was lowest for Spree-Neiße, applying demand specific N fertilization based on the N demand analysis resulted in the highest reduction of environmental intervention. Thus, the application of region specific N measures was thereby demonstrated to reduce EI.

In general terms, the cultivation of catch crops is the most recommended option for reducing overall N impacts in all regions, with the highest reduction potential of more than 40% in Ansbach (Figure 4.5) and Spree-Neiße (Figure 4.6) compared to the base scenario. Using catch crops significantly impacts N availability in soil, reducing the necessary mineral N fertilizer amount. Several LCA studies analyzing crop production systems have also reported the positive impact of catch crops reducing environmental intervention (Câmara-Salim et al., 2021; Knudsen et al., 2014; Nemecek et al., 2011a; Nemecek et al., 2011b). Although catch crop cultivation was also assumed in the N-organic scenario, and the amount of mineral fertilizer applied was the lowest amongst all management scenarios, this option was observed to be the best solely for the region Emsland, given TAP impacts (Figure 4.7a). In Kassel, for instance, the N-organic scenario performed worst. This lies notably in the combination of low background interventions, high Nmin amounts, medium yield potential, and lower N fertilizer requirements compared to the other regions. Furthermore, the share of urea fertilizer in mineral N fertilizer application in Kassel was lower than in other regions. Urea has a higher emission factor than other N fertilizers (Rösemann et al., 2021). Therefore, the NH_3 emission from organic fertilizer application caused higher environmental interventions in the N-organic scenario in Kassel than in the other N scenarios, where the overall impact was lower due to fewer NH_3 emissions.

A pattern between the regions can be observed comparing TAP and TEP results. TEP impact results were nearly similar (Mecklenburgische Seenplatte and Spree-Neiße) or slightly higher (Ansbach, Kassel and Emsland) than TAP for EI. This is due to the fact that the same critical N-thresholds for deriving regional normalization references were assumed for both impact categories (Wowra et al., 2022b). The thresholds are derived from values for the critical loss of NH_3 emissions leading to critical N deposition, depending on the ecosystem's critical load (de Vries et al., 2021).

The assessed environmental interventions result from background intervention, regional parameters such as yields and fertilizer input, and impact characterization. For instance, although N inputs were lower in Ansbach compared to other regions, the EI was higher. This is explained by the combination of high background intervention and the calculated normalization references, resulting in a low rNR_{BI}. The smaller rNR and rNR_{BI} values arise within LCIA normalization in higher environmental intervention.

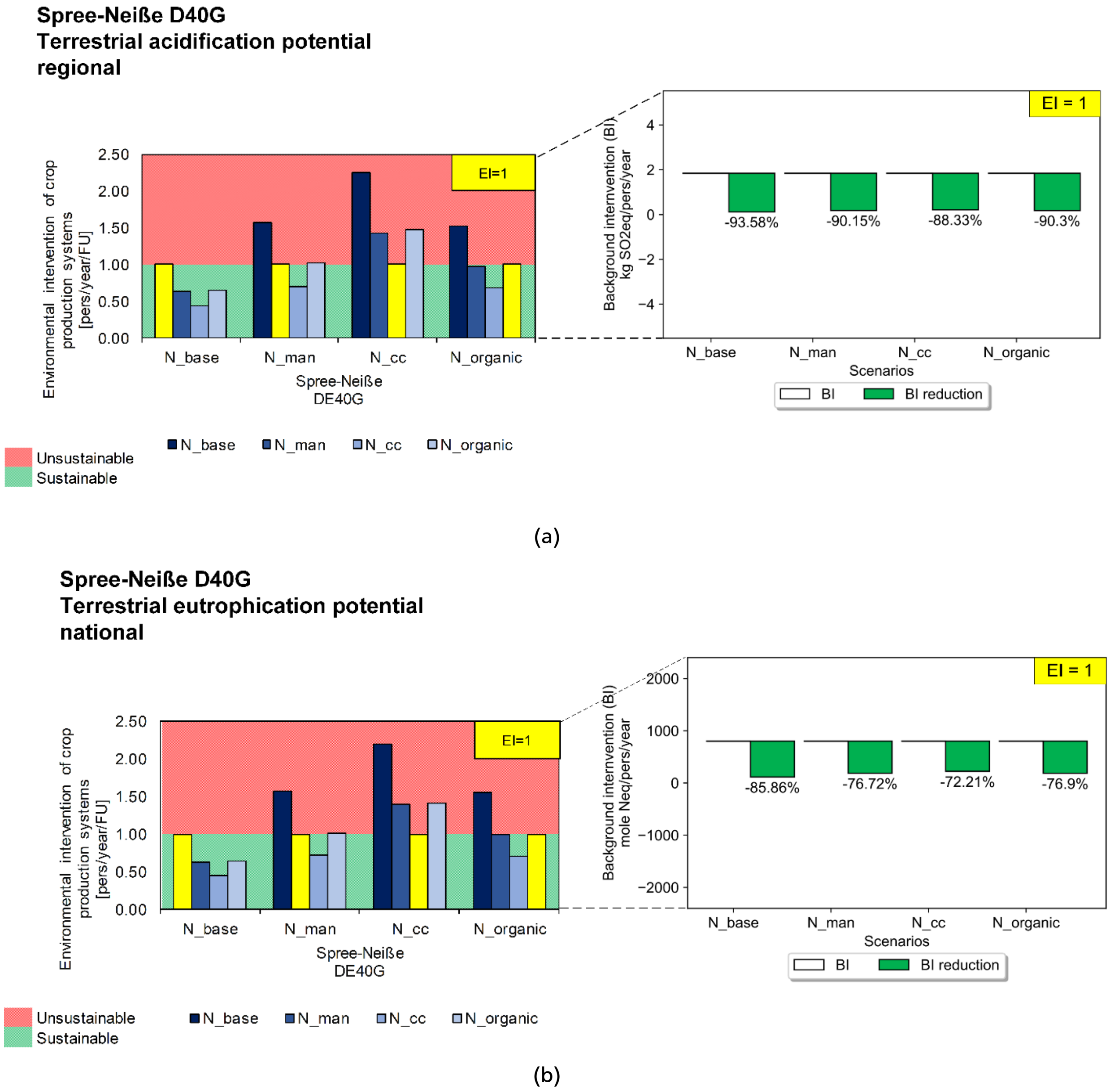
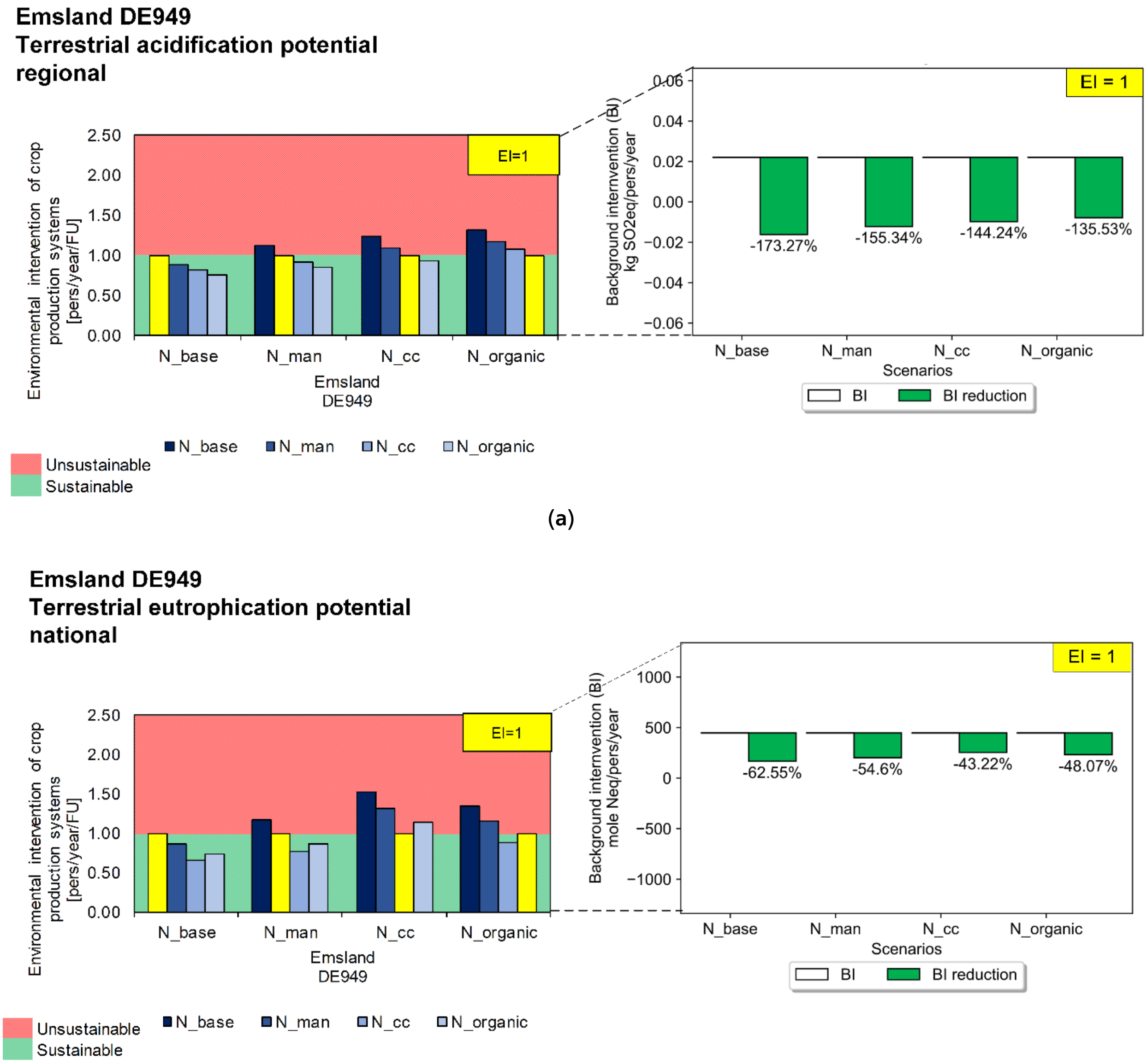


Figure 4.6. Environmental performance expressed as environmental intervention (EI, as annual personal share per functional unit, FU) for the case study region Spree-Neiße for (a) terrestrial acidification potential, regional and (b) terrestrial eutrophication potential, national. Results are displayed for the different N-management scenarios (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario). For each scenario, the necessary reduction of background interventions (BI) is displayed (in %) if EI = 1.



(a)

(b)

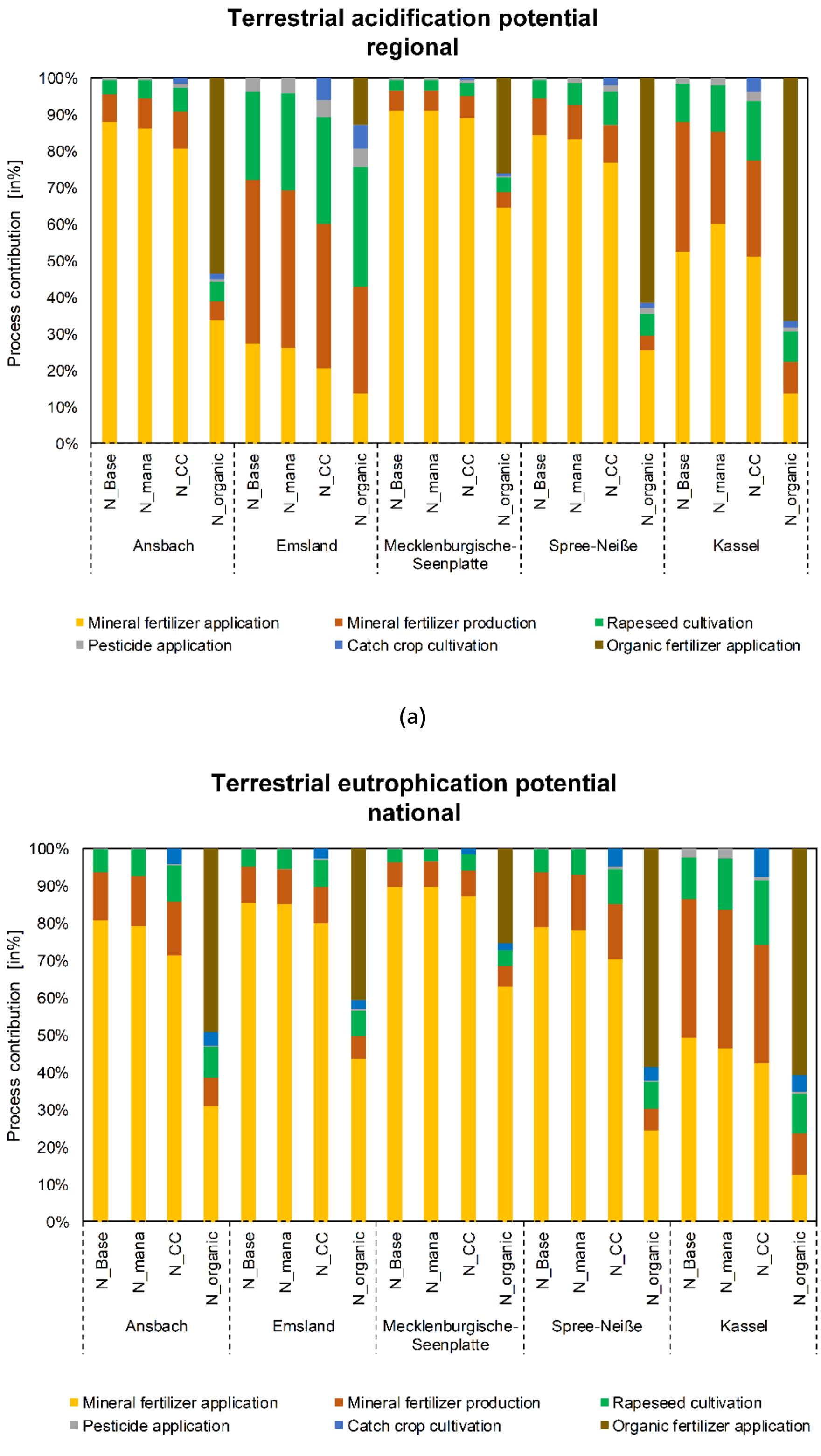
Figure 4.7. Environmental performance expressed as environmental intervention (EI, as annual personal share per functional unit, FU) for the case study region Emsland for (a) terrestrial acidification potential, regional and (b) terrestrial eutrophication potential, national. Results are displayed for the different N-management scenarios (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario). For each scenario, the necessary reduction of background interventions (BI) is displayed (in %) if EI = 1.

4.3.2.2 Contribution of agricultural processes in N-management scenarios

Figure 4.8 displays the contribution of agricultural activities to each scenario and, thus, environmental intervention to the depicted impact categories TAP and TEP. In both impact categories, fertilizer application, including field emission, contributed mainly to TAP and TEP impacts. These results correspond with previous studies showing that due to large amounts of mineral fertilizer applications, field emissions are the main contributor to TAP (Bacenetti et al., 2014; González-García et al., 2021; Noya et al., 2015) and TEP impacts on rapeseed production systems (Mousavi-Avval et al., 2017). Furthermore, all regions, besides Kassel, have a share of more than 25% urea in mineral fertilizer use (see Table 4.2). As indicated earlier, urea has the highest emission factor corresponding to NH_3 emissions. Therefore, for both TAP and TEP combined impacts, Kassel showed the lowest emission contributions from mineral fertilizer application.

Regional differences could be observed for Emsland, where impacts from mineral fertilizer application were lowest compared to the other regions for TAP impacts. This is by reason of, firstly, a lower fertilizer application and, secondly, the use of regional CFs, which in Emsland resulted in a reduced impact of the field emissions. In this case, the choice of spatial level influenced the results, as also shown by the sensitivity results (Appendix I SM2).

An interesting observation can also be made by looking at contributions from organic fertilizer applications. Here regional differences are most visible. For instance, Kassel's highest contribution was observed with 66% and the lowest for Emsland with merely 13% for TAP. Moreover, in Kassel, organic fertilizer application contributed most (61%) in Kassel to TEP, whereas Mecklenburgische Seenplatte showed a minor contribution within the organic scenario reaching only 26%. The main reason for this is the lower amount of mineral fertilizer and the higher NH_3 emissions from organic fertilizers for Kassel. The direct emissions from mineral fertilizer application and production were reduced within the organic fertilizer scenario (Câmara-Salim et al., 2021). However, it has to be noted that this was mainly influenced by the fertilizer type applied (Basosi et al., 2014).



(a)

(b)

Figure 4.8. Process contribution analysis of rape seed production system for all N-management scenarios (Nbase = N-base scenario; Nman = N-management scenario, Ncc = N-catch crop scenario, Norg = N-organic scenario) and regions for terrestrial acidification potential, regional and terrestrial eutrophication potential, national.

4.3.3 Recommendation for decision makers and added value for decision support

Recommendations on which mitigation measures are most suitable may vary across regions due to regional dependent parameters such as Nmin amounts, yields, other bio-geographical parameters or agricultural inputs. For instance, although the N-organic scenario showed high reduction potential in other regions, it had the lowest environmental performance in Kassel and exceeded the regional N resilience. As a result, the N-organic scenario would not be recommended as the best option for Kassel to reduce regional impacts on N. The impacts of introducing mitigation measures on N resilience were also apparent in the Ansbach and Spree-Neiße regions. Both regions showed high reduction potentials compared to the N-base scenario when applying N reduction strategies. This demonstrates the ability of the approach to serve policymakers on the federal level to evaluate and compare different regions and elaborate the most suitable N management measures or reduction strategies for a region, based on regional requirements. Furthermore, the approach herewith serves decision-makers in improving the environmental performance of regional cropping systems in consideration of N resilience.

Beyond this, the applied methodology adds value for stakeholders from LCA by making it possible to analyze N mitigation measures that take into account different targets on environmental interventions affecting regional N resilience. For example, in the case of achieving an equal share amongst background emissions, we showed the necessary reduction also from non-crop producing sectors, if environmental interventions given regional N resilience remain in a sustainable area (EI = 1). On this basis, recommendations for reducing N impacts for policymakers on the regional and federal levels are given to achieve environmental sustainability targets.

Furthermore, an added value is provided by improving the communication of LCIA results to non-LCA practitioners, for instance, farmers. The regional normalization references are based on the LCIA frameworks and are compatible with frequently used LCIA methods and can thus complement existing approaches, e.g., European references based on the LCIA concept. Finally, by applying the indicator rNR_{BI}, LCIA results might be easily translated into single indicators, allowing a simplified presentation of the environmental intervention of cropping systems and management strategies. In the light of this, consulting companies for farmers, agricultural authorities responsible for monitoring sustainable fertilizer use and N management strategies, and other stakeholders may be guided in decision support and consultancy.

4.3.4 Limitations and improvement of the approach

Although the case study proved the applicability of regional normalization references as a distance-to-target approach for regional N resilience, several areas require further research. First, the approach focused on regional N impacts and, therefore, on only two N-related impact categories, TAP and TEP. Further research should elaborate on integrating and combining existing normalization references based on absolute references for other impact categories also, aiming to improve the overall impact assessment and to avoid possible burden shifting. Second, it has to be noted that we considered background interventions of non-crop producing sectors only. In order to evaluate the impacts of each contributing sector, a scenario analysis is recommended to assess the resilience considering single sectors, such as the livestock sector, or combinations of sectors. Moreover, the case study showed sensitive results when regional CF had been applied, as in the case of, e.g., Emsland. The choice of LCIA method and spatial level may influence the results given a regional assessment considering N resilience (see Supplementary Materials Appendix I SM2). The practitioner should therefore base the choice of LCIA method and spatial level on data requirements and regional focus of the study. Likewise, scenario analysis and parameter sensitivity should be considered. For instance, the uncertainty analysis of LCI data and variation of the parameter Nmin showed variability of the impact results (see Supplementary Materials Appendix I SM2). The amount of fertilizer applied and, thus, resulting emissions are highly dependent on the considered Nmin. Therefore, the sensitivity of Nmin should be taken into account in the uncertainty analysis of agricultural LCA due to its spatial variability and dependency.

4.4 CONCLUSIONS

In order to reduce human alteration of global and regional N cycles and enable the transition to sustainable agriculture, it is crucial to develop appropriate measurement tools and monitor environmental impacts for deriving necessary targets, trajectories and relevant policy measures (Leach et al., 2012).

The study proved the applicability of considering regional N resilience in LCA to evaluate N management scenarios based on policy measurements. Therefore, it provides improved guidance for evaluation and decision support for regional stakeholders on N management strategies. Overall, the LCA results confirmed the reduction of N impacts by applying policy measures such as the N demand analysis. Moreover, the study revealed the necessity to account for regional differences in an overall N assessment for recommendations of N management options. We displayed necessary reduction levels for background interventions from non-crop producing sectors. With this, we showed that cropping systems would not remain sustainable for any N management option, given regional N resilience, without additional reduction in other sectors, especially in regions with high background interventions. Furthermore, the study is the first to provide regional carrying capacity based normalization references considering background interventions (rNR_{BI}) for the impact categories of terrestrial acidification and terrestrial eutrophication potential for all German NUTS-3 regions.

Finally, this work highlights the need to consider absolute sustainability metrics such as regional N resilience to stress the importance of regional impacts such as terrestrial acidification and eutrophication in assessing crop production systems as an additional tool and an alternative for standard LCA interpretation. However, further research is needed to explore the approach for different countries and regions and complement existing methods that focus on the global or European level.

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5 SYNTHESIS

The previous chapter 2, 3 and 4 presented the three publications of the thesis. In the following, the first section of the synthesis summarizes the key findings addressing the raised research questions. The second section discusses main challenges, application, and transferability of the developed approach.

5.1 SUMMARY OF KEY FINDINGS

1. How are regional nitrogen flows considered in LCA, and which methodological and practical recommendations can be drawn for a regional assessment of nitrogen in LCA?

The review presented in chapter 2 included a scientific analysis compiling background information of the N-cycle and LCA conditions to identify the specific requirements for N assessment within each LCA phase. Regionalization in LCA of agricultural production systems plays a crucial role in N assessment. Therefore, within a comparative analysis, the identified key factors were matched with regionalization approaches along the four LCA phases. By this, a detailed overview of N compounds and pathways most relevant for assessing impacts resulting from agricultural cropping systems was built.

By analyzing and comparing existing methodological approaches, differences in the level of regionalization, the definition of a region, data requirements, and consideration of biogeochemical conditions or agricultural management practices were found. The release of reactive N compounds is mainly influenced by biogeochemical conditions such as climate (temperature, precipitation), soil conditions (type and structure, O_2 capacity SOC (soil organic carbon) content, pH, N-surplus), and agricultural management practices. The application of process based models or emission factor based approaches may display biogeochemical conditions. Although applying process based models could highly improve the quantification of N pathways and emissions, the necessity of expert knowledge and a high amount of spatial differentiated data make these not applicable and not recommended for an LCA practitioner. By means of this, emission factor based approaches are more suitable for LCA practice and more frequently applied.

Furthermore, the analysis of the different LCIA methods showed that LCIA methods consider different N pathways and compounds. The most relevant impact categories for a regional N assessment are terrestrial eutrophication (TEP) and acidification (TAP), as well as marine eutrophication (MEP). These impact categories include relevant N compounds resulting from N release due to agricultural production systems. The analysis revealed that an LCIA method covering these aspects would include all relevant impact categories and provide regionalized characterization factors (CF). However, none of the analyzed LCIA methods was found to cover all these aspects. Therefore, it is recommended to combine two LCIA methods to analyze the effects of neglected emission pathways. For instance, by combining the LCIA method IMPACT World+ (Bulle et al., 2019), which covers the relevant N impact category TAP and provides CFs on the regional level with the LCIA method Accumulated Exceedance (AE) (Seppälä et al., 2006). The latter provides CF for terrestrial eutrophication, only on the national level. Both methods have been applied for the further development of the approach. IMPACT World+ for calculation of regional TAP impacts and AE for TEP impacts, as part of the Environmental Footprint (EF) method (reference package 2.0) (Fazio et al., 2018; Sala et al., 2019).

Furthermore, integrating N boundaries in the optional phase of LCIA as regional normalization references may improve decision support. The review revealed that although studies described the relevance of the integration of reference values (Nitschelm et al., 2016) or carrying capacities (Cosme and Niero, 2017), none focused explicitly on regional N references.

Finally, the review provided a comprehensive overview and understanding of the requirements of N for a regional assessment in LCA for all LCA phases. With this, it built the relevant scientific basis and knowledge for developing an LCA-based approach for a regional assessment of the environmental impacts of N from crop production systems.

2. How can nitrogen thresholds be integrated as reference values in LCA to assess the environmental performance of cropping systems considering regional nitrogen resiliencies?

The review study revealed that the integration of regional N-related reference values in the optional phase of LCIA could improve interpretation in view of absolute impacts affecting regional N-cycles and be necessary for a comprehensive regional N assessment.

However, standard LCA represents the implication caused by a system in relative terms, not in absolute terms. The latter requires the integration of reference values in LCA normalization to interpret implications against carrying capacities or environmental resiliencies and therefore assess the overall sustainability (Bjørn et al., 2020a).

So far, two different application routes have been identified in the literature for integrating absolute sustainability references in LCA (Bjørn et al., 2020a). The first route is a planetary boundary (PB) based application, which includes the development of novel LCIA methods that address environmental indicators covering earth system processes of the PB framework (Bjørn et al., 2020c; Butz et al., 2018; Doka, 2015; Ryberg et al., 2018; Ryberg et al., 2016). The second application route is LCIA-based, mainly defined by LCIA impact categories based on the LCIA framework (Bjørn et al., 2016; Bjørn and Hauschild, 2015; Sala et al., 2020; Wolff et al., 2017). Some of these methods (Bjørn et al., 2016) integrate carrying capacities in LCIA characterization and thus adapt characterization factors. Other apply carrying capacity based normalization references built on the LCIA framework (Bjørn and Hauschild, 2015; Sala et al., 2020). The advantage of using normalization references is that these are based on established impact mechanisms of the LCIA framework, grounded on well-known characterization models, and indicator results can be interpreted accordingly. However, as indicated in chapter 2, none of the named approaches provides normalization references considering N resilience on the regional level.

In order to assess the environmental performance of cropping systems and their interference with regional N resilience, regional carrying capacity based normalization references were developed and applied as distance-to-target values. The regional normalization references were derived for N-related impact categories and were based on N-related thresholds (critical N-losses) from agricultural production, avoiding exceedance of N concentrations in environmental compartments (de Vries et al., 2021). Furthermore, the influence of N-related background interventions of non-crop producing sectors was considered by including data on background emissions (Schneider et al., 2016) for each NUTS-3 region.

An indicator was introduced evaluating the environmental performance as environmental intervention (EI). EI results from the impact a cropping system contributed to terrestrial acidification or terrestrial eutrophication in a specific region considering its regional carrying capacity, which is expressed as regional normalization reference (rNR).

As identified within the review, two different LCIA methods were applied to assess the sensitivity of the regional assessment. The EF (Environmental Footprint) method (Fazio et al., 2018; Sala et al., 2019) and IMPACT World+ (Bulle et al., 2019). CFs on the national level were applied for both methods for TAP and TEP impacts and included CF on the regional level for TAP only for IMPACT World+.

The approach was applied to three NUTS-3 regions and three yield potential scenarios within a first proof of application. Hereby was shown that the developed approach is applicable to the assessment of the environmental performance of cropping systems. Furthermore, it is replicable and compatible with frequently applied LCIA methods. According to the analysis in chapter 3, further research development and improvement of the approach were identified, given application to different NUTS-3 regions and integration of N management scenarios. Additionally, the analysis of background interventions was identified as essential to assess reduction potentials for a fair distribution of environmental burdens between N-related sectors, avoiding exceedance of regional N resiliencies. The findings from the first proof of concept were integrated with investigations within the third publication (chapter 4), including consideration of background interventions and evaluating their impacts. Furthermore, the approach was further developed and applied to regions with different background loads evaluating different N management scenarios.

3. How does the newly developed approach improve decision support in agricultural LCA for regional stakeholders in assessing nitrogen management measures for reducing regional nitrogen impacts?

The main advantage of transferring LCA results to normalized indicator results is the improvement for decision makers in understanding and relating the environmental assessment (Hauschild and Huijbregts, 2015). The provided indicator EI, for environmental intervention, offers decision makers the possibility to easily interpret the interventions of cropping systems in a region under study in view of the exceedance of regional N resilience. Therefore, hotspots as to transgression of regional N resilience and possible mitigation strategies may be identified. The results of the case study analyses in chapter 3 and chapter 4 showed that considering regional N resilience would consequently lead to different suggestions and decisions concerning agricultural management strategies.

The third publication, summarized in chapter 4, aimed to prove the applicability of the developed distance-to-target approach for improved decision support for regional stakeholders. The approach was applied to a case study including four different N management scenarios of rapeseed cropping systems in five different NUTS-3 regions. The scenarios were based on policy measures, including an N demand analysis based on the German Fertilizer Ordinance.

Overall, the LCA results confirmed the reduction of N impacts by applying policy measures such as the N demand analysis. Comparing the results on the environmental performance of the different cropping systems under study, regional differences were identified. The N-organic scenario showed high reduction potentials in all regions under study, except for Kassel, where it had the lowest environmental performance and exceeded regional N resilience. Thus, the N-organic scenario would not be recommended as the best option for reducing regional impacts on N. The impacts of introducing mitigation measures on N resilience were also highly visible looking at the regions Ansbach and Spree-Neiße. Both regions showed high reduction potentials compared to the base scenario when applying N reduction strategies. Taking these results into account demonstrates the approach's ability to serve policymakers on the federal level to evaluate and compare different regions and elaborate on the most suitable N management measures or reduction strategies for a region based on regional requirements. This allows regional decision makers to identify priorities regarding N management strategies and therefore improve the environmental performance of regional cropping systems while considering N resilience.

Furthermore, different targets for environmental interventions affecting regional N resilience were evaluated. Aiming to achieve an equal share amongst background emissions, the necessary reduction also from non-crop producing sectors, if environmental interventions in view of regional N resilience remain in a sustainable area (EI = 1) for the different scenarios, was investigated. With this, recommendations for reducing N impacts for policymakers on the regional and federal levels were given, achieving environmental sustainability targets given specific N measures.

Hence, it was proved that addressing regional impacts and carrying capacities serve as additional and simplified decision support in agricultural LCA and play a crucial role in a comprehensive N assessment.

Overall the approach addresses key factors relevant to a regional N assessment and interpretation of impacts identified within the review (chapter 2). Furthermore, an added value is provided by improving the communication of LCIA results to non-LCA practitioners, for instance, farmers. The regional normalization references are based on the LCIA framework and compatible with frequently applied LCIA methods and can thus complement existing LCIA-based approaches, e.g., based on European references. Finally, by applying the indicator rNR_{BI}, LCIA results might be easily translated into single indicators, allowing a simplified presentation of the environmental intervention of cropping systems and management strategies. This was proven within the case study presented in chapter 4. Furthermore, rNR and rNR_{BI} indicators were derived for all NUTS-3 regions in Germany. Thus, with the newly developed approach, stakeholders, e.g., consulting companies for farmers or agricultural authorities responsible for monitoring sustainable fertilizer use and N management strategies, may be guided in decision support and consultancy.

5.2 CHALLENGES, APPLICATION, AND TRANSFERABILITY OF THE APPROACH

Variability of nitrogen compounds and focus on regional impacts

N losses result in impacts on different temporal and spatial levels. The results of the scientific background analysis of the N-cycle in chapter 2 described the N-cycle and the different N compounds showing pathways and the spatial variance coming with these compounds. The thesis focus was on assessing impacts resulting from losses of agricultural crop production systems and, herewith fertilizer inputs. The analysis identified terrestrial acidification, terrestrial eutrophication, and marine eutrophication as the main LCIA categories affected by N flows on the regional scale. However, for the development of the further approach, only terrestrial acidification potential (TAP) and terrestrial eutrophication potential (TEP) were included. The data used for the calculation of background interventions by Schneider et al. (2016) comprises only air-born emissions. However, to assess background interventions for N emission in surface waters, data on N emission loads to surface waters on the regional level would be necessary. Since these data were unavailable, the focus was on impacts affecting terrestrial compartments due to N deposition. Nevertheless, based on the provided steps described in chapter 3, regional carrying capacity based normalization references may also be developed including other compartments, if data availability is given.

Notwithstanding, the approach is compatible with other normalization references covering impact categories on other spatial levels (Bjørn and Hauschild, 2015; Sala et al., 2020). Further research should elaborate on integrating and combining existing normalization references based on absolute references for other impact categories, improving the overall impact assessment and avoiding possible burden shifting.

Regional reference

The review in chapter 2 revealed different definitions for regional scales in regionalized LCA studies. The definitions vary from political regions on a country or sub-country level to geographical catchments or territories, including different ecological or political regions (see chapter 2). Furthermore, the complexity of having the same regional reference for LCI and LCIA was stressed. Therefore, NUTS-3 regions and, herewith, political boundaries to assess regional N resilience were chosen for the development of the approach. To provide maximum consistency, using the NUTS-3 reference is in line with the data applied for the critical N losses by de Vries et al. (2021) and other studies referring to political boundaries when analyzing regionalization and N-related impacts (Ding et al., 2021; Morais et al., 2017).

Moreover, it was assumed that all N-related emissions contributing to TAP and TEP impacts, e.g., NH_3 emitted in a NUTS-3 region, will also be deposited in the region. This assumption is also in line with the assumption made by de Vries et al. (2021). This likewise included the considered N compounds for the background intervention. Furthermore, it was assumed that the compounds emitted in a NUTS-3 region would cause impacts in the same NUTS-3 region since TEP and TAP impacts are considered to have effects on the regional level. However, on the regional level, only characterization factors for terrestrial acidification were available for the LCIA method IMPACT World+, based on the characterization method of Roy et al. (2012a), Roy et al. (2012b) and Roy et al. (2014). Therefore, these were allocated to the respective NUTS-3 regions under study. For TEP, no characterization factors beneath the country level were available. Consequently, the spatial level in LCI and LCIA was different for TEP. Therefore, applying spatially differentiated CF also for TEP would improve the adapted approach.

Generally, setting thresholds as to ecological regions, e.g., watersheds, would better reflect trans-regional emissions and improve the results. However, regional agricultural data is mainly available on the NUTS-3 or NUTS-2 level. Thus, in the case of decision making, the NUTS level is most suitable to choose as regional decision-makers evaluate or take N mitigation actions mainly on this level (Nitschelm et al., 2018).

Choice of Life Cycle Impact Assessment method

Different LCIA methods and the respective characterization models were analyzed regarding the most relevant N pathways and N compounds for a regional N assessment. As described in chapter 2, the most recommended method was IMPACT World+ (Bulle et al., 2019); however not including TEP impacts. Therefore, this LCIA method was included in the development and complemented with the EF method to cover also TEP impacts. In the EF method, the TEP category is covered based on the characterization method Accumulated Exceedance (AE) (Seppälä et al., 2006).

Regional CFs were available only for assessing TAP impacts with IMPACT World+. The EF method covers TEP impacts with CF on the national level only. To analyze the impacts of the LCIA method choice, additional analyses to investigate sensitivities were made.

The results of the environmental interventions calculated with the different LCIA methods are displayed and discussed in chapters 3 and 4. The choice of LCIA method and spatial level may influence the results given a regional assessment considering N resilience (see Appendix I, SM2). Uncertainty is therefore linked to the applied CFs for deriving the indicator BI (background intervention) and the rNR (regional normalization reference). The results showed alterations when applying spatial differentiated CFs provided by IMPACT World+ in the case of TAP. However, the LCIA method IMPACT World+ provides a more accurate picture of the emission flows contributions to regional impacts with reduced uncertainty instead of using globally default CFs (Bulle et al., 2019).

As indicated earlier, uncertainty also remains for TEP since a direct comparison of TAP and TEP could not be done due to the lack of regional CFs for TEP. Furthermore, uncertainty is linked to interpreting results for regional environmental performance since the CFs of TEP and the calculated regional N resiliencies refer to different spatial scales.

Hence, the choice of LCIA method is a challenge for an LCA practitioner. In addition, some LCIA methods do not cover all impact categories or are based on different characterization methods for the same impact category. The practitioner should therefore base the choice of LCIA method and spatial level on data requirements, availability, and the regional focus of the study.

Consideration of background interventions

The method development and the results of chapter 3 showed the influence of background interventions of non-crop producing sectors. In order to get the whole picture of interventions influencing regional N resilience, these were included in the distance-to-target approach. However, it was assumed that the regional background intervention is constant. Since for some regions background interventions (BI) were higher than the regional normalization references (rNR) cropping systems would not remain sustainable for any N management option, in view of regional N resilience, without an additional reduction of background intervention. The case study analysis showed (chapter 4) the impact of reduction potentials of the non-crop producing sectors. To achieve an equal share amongst the non-crop and the crop-producing sectors, the necessary reductions of non-crop producing sectors should be taken into account. Further investigations may also focus on analyzing the influence of different reduction targets aiming to implement specific mitigation measures or analyzing the contributions of single sectors or sector combinations.

The background interventions were assessed based on data for air emissions contributing to TAP and TEP impacts from the related sectors (Schneider et al., 2016). Hence, N compounds were included contributing to eutrophication and acidification impacts. Since in particular SO_2 emissions are mainly contributing to TAP impacts, these were also included in the background interventions (Bouwman et al., 2002). This was done since neglecting this emission compound would have decreased the background load of the relevant emissions contributing to TAP, and thus comparability to TEP background interventions would not have been given.

Integration as normalization reference and choice of sharing principle

As indicated in chapter 3 there are different ways of integrating absolute references in LCA. The basis of the developed approach included an LCIA-based application (Bjørn et al., 2020a) by integrating carrying capacity based normalization references according to the approach proposed by Bjørn and Hauschild (2015). However, the share of a system under study to its carrying capacity can be calculated by applying different sharing principles, for instance, via a grand fathering principle (share proportional to an impact of a reference year), to the added economic value, land area or equal per capita (Bjørn et al., 2020a). Since the impacts were evaluated according to rapeseed production on one hectare, the possessed land area as sharing principle could have also been a suitable option.

Nevertheless, the per capita sharing principle was chosen since the compatibility with other approaches (Bjørn and Hauschild, 2015; Sala et al., 2020) applying the same allocation principles is given. Secondly, critical N-losses resulting from crop production and background interventions from non-crop producing sectors were considered for carrying capacity assessment in the developed approach. Since both are not directly related to land area, the per capita sharing principle was identified as the most suitable. Nevertheless, adapting the approach to other sharing principles or combinations may be of interest for future investigations.

Transferability and applicability for LCA practitioners in agricultural Life Cycle Assessment

The approach was developed based on derived regional normalization references for German NUTS-3 regions. Therefore, it can be applied to assess agricultural crop production systems in German regions. The transferability is given by providing all relevant steps and necessary data for application, as described in chapter 3. Data on critical losses and background intervention are necessary to apply the approach to different countries. Herewith further adjustment is needed.

The regional normalization references are based on the LCIA framework and compatible with frequently used LCIA methods and can thus complement existing approaches, e.g., for European references based on the LCIA concept, applying the same allocation principles. Thus, it can complement or replace TEP and TAP categories. Finally, by applying the indicator rNR_{BI}, LCIA results might be easily translated into single indicators, allowing a simplified presentation of the environmental intervention of cropping systems and management strategies.

6 CONCLUSION AND OUTLOOK

In this thesis, a novel, LCA-based distance-to-target approach was developed that links regional nitrogen thresholds with LCA by applying these as regional carrying capacity based normalization references for an improved regional assessment of environmental impacts of nitrogen in crop production systems.

Three main research questions were raised and answered, addressing the development of the LCA-based approach for a regional assessment of environmental impacts in crop production systems considering regional nitrogen resilience.

This thesis investigated relevant requirements for assessing nitrogen releases of crop production systems with LCA. The analysis identified nitrogen requirements for a regional assessment translating these into a newly developed approach for LCA. A comprehensive overview of the requirements of LCA, including the scientific background of the nitrogen cycle for each LCA phase, completed this. Analyzing process based models and Life Cycle Impact Assessment methods reflecting nitrogen pathways gave a detailed overview and basis for a targeted nitrogen assessment. This information was included to derive an approach serving for a comprehensive assessment of regional nitrogen impacts, considering threshold values as critical nitrogen losses and nitrogen-related background interventions. Based on these, regional carrying capacity based normalization references were derived for all NUTS-3 regions in Germany, directly applicable for the impact categories terrestrial acidification and eutrophication potential in LCA.

The thesis showed that with the developed approach, research questions regarding regional vulnerabilities of nitrogen could be addressed more specifically. The approach herewith **supports two types of decision makers**. **Firstly**, decision makers on the policy level are supported in view of the evaluation and choice of nitrogen management strategies and implementation of nitrogen reduction strategies. The approach delivers not only recommendations as to the most suitable reduction strategy for crop production systems in a region but also advises stakeholders in view of changes in a region's nitrogen carrying capacity and therefore serves as a warning system given the precautionary principle. **Secondly**, LCA practitioners, by providing indicators which can be directly applied within LCA for assessment of terrestrial eutrophication and terrestrial acidification impacts on the regional level. The approach provides an added value for the environmental assessment of cropping systems by interpreting results on a relative level and considering absolute levels of environmental intervention, such as regional nitrogen resilience. A main advantage is the direct applicability in LCA and the simplified interpretation by translation in personal share equivalence.

The main challenges include the choice of LCIA method, level of regional reference, and choice of sharing principle. Furthermore, a main limitation is that the approach is currently developed for Germany only. However, the newly developed approach provides all necessary steps for transferability to other countries. Possibilities for further development and investigations addressing the named challenges are therefore given.

The developed approach contributes as a relevant part to the research field of regional nitrogen assessment in LCA. Within the case study assessments, it was demonstrated that the developed distance-to-target approach serves as improved decision support for regional stakeholders when assessing nitrogen mitigation measures and is also applicable to other cropping systems.

Especially for relevant policy decisions, the integration of absolute indicators is necessary. Finally, the provided approach showed the application of regional nitrogen thresholds as reference values in LCA and application for evaluation of policy strategies. Therefore, it can also be seen as a relevant contribution to developing an integrative nitrogen reduction strategy on the national level.

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APPENDIX

Appendix I. Supplementary material: Evaluation of the environmental performance of cropping systems under different nitrogen management scenarios considering regional nitrogen resilience

Supporting information can be downloaded at

https://doi.org/10.48328/tudatalib-1119

SM1: Results of background intervention (BI), regional normalization reference (rNR), regional normalization reference considering BI (rNRBI), results of environmental interventions (EI) for all regions and scenarios including sensitivity of LCIA methods, analysis of reduction of background interventions for all regions and scenarios including sensitivity for LCIA methods, LCA results contribution analysis, LCIA results of all impact categories, regions and scenarios.

SM2: Results of sensitivity and uncertainty analysis.