

The Institute for Natural Resource Conservation
of the Christian-Albrechts-Universität zu Kiel

Quantification and mapping of
regulating and provisioning ecosystem services
in Schleswig-Holstein, Germany

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M.Sc. Sabine Bicking

born in Neuss

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Dean: Prof. Dr. Dr. Christian Henning

1. Examiner: Prof. Dr. Felix Müller

2. Examiner: Prof. Dr. Benjamin Burkhard

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Zusammenfassung

Die Dissertation befasst sich mit Aspekten des Ökosystemleistungskonzepts, in dem Ökosystemleistungen (ÖSL) grundsätzlich als Beiträge von Ökosystemstrukturen und –Funktionen zum menschlichen Wohlbefinden definiert werden. Es wird zwischen ÖSL-Potenzialen, -Flüssen und -Nachfragen unterschieden. Das Potenzial bezieht sich auf eine hypothetische, maximale Ernte oder Nutzung, wohingegen sich der bedarfsgesteuerte Fluss auf tatsächlich genutzte ÖSL bezieht. Das Konzept ermöglicht als transdisziplinärer Ansatz eine Analyse der Abhängigkeiten der menschlichen Gesellschaft von einer funktionsfähigen Natur. Diese Mensch-Umwelt Beziehungen lassen sich u.a. in der Landwirtschaft deutlich erkennen. Die räumliche Analyse von relevanten ÖSL kann entscheidend dazu beitragen, eine nachhaltige Landnutzung zu realisieren.

Der Schwerpunkt dieser Arbeit liegt auf der Bewertung und Kartierung der ÖSL „Pflanzenproduktion“ und „Nährstoffregulierung“ in landwirtschaftlich dominierten Regionen. Als Untersuchungsgebiete wurden Schleswig-Holstein, die Bornhöveder Seenkette und die Landschaft um Höxter und Eversen ausgewählt. Darüber hinaus setzt sich die Arbeit mit der Frage auseinander, wie Umweltbedingungen die räumliche Verteilung von Regulations- und Versorgungsleistungen beeinflussen.

Um die oben genannten Ziele zu erreichen, wurden einzelne Studien mit unterschiedlichen Quantifizierungs- und Kartierungsmethoden durchgeführt. Zuerst wurde das Nährstoffregulierungspotenzial nach dem ÖSL-Matrixansatz kartiert. Außerdem wurde der Stickstoffüberschuss als Indikator für die entsprechende ÖSL-Nachfrage berechnet. Die Studie ergab, dass die Nachfrage in der Regel das Potenzial übersteigt. Des Weiteren wurden Hotspot-Regionen räumlicher Diskrepanzen zwischen der ÖSL-Nachfrage und dem -Potential identifiziert. Anschließend wurde die rationalisierende Berechnung des Stickstoffüberschusses als Indikator für die ÖSL-Nachfrage verfeinert und durch die Integration von weiteren relevanten Informationen über landwirtschaftliche Praktiken ausgebaut. Die Berechnung belegt die mildernden Einflüsse von erweiterten Fruchtfolgen und anderen Nährstoffrückhaltemaßnahmen auf den Stickstoffüberschuss. Um das Potenzial der Nährstoffregulierung genauer einschätzen zu können, wurde ein bayessches Netz erstellt, das den ÖSL-Matrixansatz und weitere räumlich explizite Daten zu relevanten Umweltmerkmalen integriert. Auch hier zeigte die Studie ein ausgeprägtes regionales Muster. Schließlich wurden mit Hilfe von raumbezogenen Analysen ausgewählte Indikatoren der ökologischen Integrität und die Pflanzenproduktion analysiert und miteinander verglichen, um Aussagen zu deren Abhängigkeiten zu treffen. Der Einfluss von regional differenzierten Ausprägungen und Verteilungen von Attributen der ökologischen Integrität auf das Ökosystemleistungspotenzial ließ sich mit Hilfe dieser Analyse nachweisen.

Die Ergebnisse der Arbeit heben die Bedeutung von umfassenden ÖSL-Forschungsansätzen hervor, die ein ganzheitliches Verständnis von Ökosystemen als Teile komplexer sozial-ökologischer Systeme generieren können.

Summary

This doctoral thesis has been executed within the framework of the ecosystem service (ES) concept, which defines ES as the contributions of ecosystem structures and functions in combination with other inputs to human well-being. The concept differentiates between ES potentials, flows and demands. The potential relates to the hypothetical maximum yield, while the flow, driven by the demand, refers to ES that are actually used. The concept can be applied with the aim of assessing socio-ecological issues that arise from the interactions between human and environmental systems.

This thesis focused on the assessment of the ES crop production and nutrient regulation. The provision of food for satisfying basic human needs, along with the current situation surrounding nutrient use, specifically with regard to over-fertilization and consequent degradation of the environment, are key as foundations for sustainable land management. The objective of the thesis was to assess and map these ES in agriculturally-dominated landscapes. Therefore, Schleswig-Holstein, the Bornhöved Lakes District and the landscapes around Höxter and Eversen were selected as study areas. A further objective of the thesis was the investigation of ecosystem properties and conditions as a base for the capacity of ecosystems to provide ES.

In order to achieve the objectives outlined above, individual studies were conducted, applying different quantification and mapping methods. Firstly, the nutrient regulation potential was assessed applying by the ES matrix approach. In addition to this, a nitrogen surplus was calculated as an indicator for the respective ES demand. The study revealed that the demand generally exceeds the potential. Furthermore, hotspot regions for a spatial mismatch between ES demands and potentials were identified. In the subsequent study, the calculation of the nitrogen surplus as an indicator for the ES demand was refined with the integration of further relevant information on agricultural practices. The assessment revealed the mitigating influences of crop rotation and further nutrient retention measures on the nitrogen surplus. Furthermore, aiming to assess the potential of the ES nutrient regulation in more detail, a Bayesian Belief Network was established that integrated the ES matrix approach with further spatially explicit data on relevant environmental characteristics. Again, the study revealed a distinct regional pattern. Finally, an integrative assessment was performed with the aim of quantifying ecological integrity variables, the ES crop production and the spatial relationships between them. It can be concluded that the influences of ecosystem conditions and properties on the potential of an ecosystem to provide ES can be proven. Thus, regional differentiations arise.

The results of the thesis highlight the importance of holistic ES research approaches, as it is only through using these conceptions that an integral understanding of ecosystems as parts of complex social-ecological systems can be established.

List of abbreviations

a	year
BKG	Bundesamt für Kartographie und Geodäsie
CLC	CORINE land cover
CORINE	Coordination of information on the environment
DPSIR	Driver-Pressure-State-Impact-Response
dt.	deutsch
DüV	Düngeverordnung
EEA	European Environment Agency
EI	ecological integrity
ES	ecosystem service
ha	hectare
kg	kilogram
km	kilometer
LANUV	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen
LBEG	Landesamt für Bergbau, Energie und Geologie (Niedersachsen)
LLUR	Landesamt für Landwirtschaft, Umwelt und ländliche Räume (Schleswig-Holstein)
LULC	land use land cover
MAES	Mapping and Assessment of Ecosystems and their Services
MELUND	Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung des Landes Schleswig-Holstein
MELUR	Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (former name of MELUND)
mm	millimeter
N	nitrogen
NO ₃ ⁻	nitrate
NRW	Nordrhein-Westfalen
TEEB	The Economics of Ecosystems and Biodiversity
TEEB DE	The Economics of Ecosystems and Biodiversity Deutschland
UBA	Umweltbundesamt

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1

Introduction

This chapter provides a brief overview on the current situation (of quantification and mapping of regulating and provisioning ecosystem services) and introduces the conceptual framework of the thesis. Based upon that, the motivation and the objectives of the thesis are outlined.

1 Introduction

1.1 Scientific and social motivation and corresponding objectives of the thesis

Socio-ecological issues, arising from the interactions between human and environmental systems, are currently highly relevant as social and environmental problems are deeply intertwined (Bossel 2000; Ash et al. 2010a). Essential aspects are the anthropogenically induced pressures on the environment. Even though the respective branches of research and development are advancing rapidly, the main issues involving the human-environment relation persist. More general scientific knowledge is required on this topic in order to support a roadmap for management and decision-making aiming for a sustainable future (Burkhard and Maes 2017a). The list of contemporary issues concerning the socio-ecological domain is long and in order to generate some profound research results, this thesis has a specific focus. The focal point of this thesis deals with different aspects related to land management and agricultural practices. Next to the aspect of crop production, the nutrient situation was considered. Through intensive agricultural practices that aim to increase crop production, the naturally closed nutrient cycle has been altered (Vitousek et al. 1997) and opened up (Tivy 1987; Chapin et al. 2002). In- and outputs of nutrients are out of balance and consequently, large areas suffer from either nutrient deficiency or nutrient surplus (Sutton et al. 2011b; Sutton et al. 2011a; Sutton et al. 2013; Özbek and Leip 2015). The surplus of nutrients in agricultural systems leads to high nutrient losses which pose a serious threat to the environment. Nitrogen and phosphate degrade the ground- and surface water quality and threaten biodiversity and the climate (Sutton et al. 2013; Kuhn 2017; Taube 2018). Enrichment of nutrients in water bodies leads to eutrophication (Welte and Timmermann 1985; Fu et al. 2012; Chislock et al. 2013; Dominati 2013; Jónsson et al. 2016; Jónsson and Davídsdóttir 2016). Due to the vast application of organic and mineral fertilizer to the agricultural grounds in the Federal Republic of Germany, the critical limit for the nitrogen concentration of 50 mg/l has been exceeded in a large share of the groundwater bodies (Court of Justice 2018; Umweltbundesamt 2018). The assessment of both issues, crop production and nutrient surplus, is highly relevant as a foundation for sustainable land management which is mandatory for securing the functionality and quality of our environment, most notably our soils and water bodies, our food and health.

All of the presented studies were executed applying the ecosystem service (ES) concept. Generally, ES are defined as the benefits people obtain from the ecosystem (De Groot et al. 2002; Burkhard et al. 2009; Ash et al. 2010b; Burkhard et al. 2012a; Syrbe and Grunewald 2017). One of the aims of ES analysis is the assessment of ecosystems to produce desired benefits. Therefore, they are applicable to support sustainable land management (Smith et al. 2013; Schröter et al. 2014b; Burkhard and Maes 2017a). In the last decades, the ES concept was developed as an interdisciplinary field of research within the domains of ecology, economy and social sciences. Early ES research dates back into the

1980s/1990s (De Groot et al. 2017). Since then, the ES concept has been further developed, gained popularity and got more and more established within the scientific as well as the political domain (Carpenter et al. 2009; Daily et al. 2009; De Groot et al. 2010a; Schröter et al. 2014a; Schröter et al. 2017). The political relevance has been highlighted by the fact that the European Union has asked its member States to map and assess the states of their ecosystems and the services they provide within the Biodiversity Strategy to 2020 (Maes et al. 2012). While the ES concept has been developed throughout the last decades, the definition of the concept evolved simultaneously. For instance in 1997, Daily (1997) defined ES as “[...] the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life”. Later, ES have for example been defined as “[...] contribution[s] which the biotic and abiotic components of ecosystems jointly and directly make to human well-being; an ‘end-product’ of nature” (Haines-Young and Potschin 2009) and as “[...] the direct and indirect contributions of ecosystems to human wellbeing” (TEEB 2010). For this thesis, the ES definition by Burkhard et al. (2012a) has been applied which states, that “ecosystem services are the contributions of ecosystem structure and function – in combination with other inputs – to human well-being”. Spatial ES analyses have been used in order to increase the understanding of the interrelations between human activities and the environment (Burkhard et al. 2012a; Schröter et al. 2014b; Burkhard and Maes 2017a). Within the ES concept, the ES potential, flow and demand can be distinguished. Thereby, the ES potential refers to the hypothetical maximum yield of selected ES (Burkhard et al. 2014). The ES flow describes ES that are actually used in a specific area and time, which in turn are driven by a certain demand for ES (Syrbe et al. 2017). Generally, the ES concept is an integrative concept, which considered ecosystems and human-environmental interactions (Burkhard 2017a; De Groot et al. 2017)

One of the main motivations of this thesis was to assess and map ES in agriculturally dominated landscapes. Therefore, Schleswig-Holstein, the Bornhöved Lakes District, Hötter and Eversen, all in Germany, were selected as study areas. More information on the study areas can be found in chapter 1.1. Agro-ecosystems, which are the focus of attention in this thesis, are highly dependent on several regulating ES in order to ensure high productivity in terms of provisioning ES. The emphasis lied on the ES assessment in Schleswig-Holstein and the Bornhöved Lakes District, whereby the influence of agricultural practices and land management on regulating and provisioning ES in the study areas were investigated. Next to the quantification and mapping of the individual ES, a further objective was the investigation of important environmental characteristics that influence the natural capacity of an ecosystem to provide ES. In particular, the spatial distribution of ecosystem properties and conditions, which are defined as the base for the capacity of an ecosystem to provide ES (Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017; Maes et al. 2018), were of interest. Therefore, ecosystem properties and conditions, such as soil texture and slope and ecological integrity (EI) variables, were

assessed in more detail. Whereby the EI of an ecosystem represents its general functions (Müller and Burkhard 2012; Schneiders and Müller 2017). Generally, there is a lack of knowledge on the influence of ecosystem conditions on the delivery of ES (Erhard et al. 2017). This thesis embraced this issue and, in doing so, contributes to the contemporary development of ecosystem research. The regional differences and the interlinkages between ecosystem properties, attributes of ecosystem condition and ES were considered. Further information on the definition of these concepts and their relevance for ecosystem research can be found in chapter 2.2. In summary, this thesis aimed to draw conclusions on the sustainability of land management with regard to agricultural practices and to improve knowledge on the interactions of ecosystem properties and conditions and the provision of ES.

1.2 Research questions and outline of thesis

The thesis was prepared as a cumulative dissertation, which incorporates four research papers. Within the targets outlined above, the dissertation aimed to answer the following main research question:

How do ecosystem properties and conditions influence the spatial distribution of regulating and provisioning ES?

The individual chapters (chapters 3-6), which correspond to the four individual research papers, focus on different aspects of the assessment. In order to achieve the general objectives described in chapter 1.1 and to answer the main research question, 12 sub questions were developed and were answered in the individual chapters. Table 1 summarizes the main research questions of each individual chapter.

Table 1: Research questions posed in chapters 3-6.

Chapter	Individual research questions
3	<ul style="list-style-type: none"> • Do nutrient regulation ES potentials and demands coincide in Schleswig-Holstein and the Bornhöved Lakes District? • Is it possible to statistically prove the influence of the ES nutrient regulation on the nutrient status of the ecosystems? • Does an assessment on a higher spatial resolution result in more valid outcomes?
4	<ul style="list-style-type: none"> • Does the calculated nutrient regulation ES demand in the case study area Eversen resemble the nutrient regulation ES demand on the scale of the municipalities in the county of Höxter? • Do the calculated nitrogen budgets depend on agricultural practices such as crop rotation, the establishment of flower strips and fellow land? • How can nitrate leaching and denitrification potentials be used in the assessment of the nutrient regulation ES?

5	<ul style="list-style-type: none"> • Does the inclusion of data on ecosystem properties and conditions for the assessment of the nutrient regulation ES potential result in a more scattered distribution of the ES potentials compared to the distribution based upon the ES matrix values provided by Burkhard et al. (2014)? • Does the assessment of the nutrient regulation ES potential indicate regional differences in Schleswig-Holstein? • Does the probability distribution of the nutrient regulation ES potential in the Bornhöved Lakes District resemble the distribution in Schleswig-Holstein?
6	<ul style="list-style-type: none"> • Does the spatial distribution of the assessed ecological integrity variables reveal a distinct regional pattern? • Does the spatial distribution of ES crop production reveal a distinct regional pattern? • What is the relation between the assessed ecological integrity variables and the crop production ES potential and flow?

In chapter 2, the focal background information to assess these research questions is outlined. The study areas relevant for this research are described and information on the concepts and definitions, which are essential for the assessment, are also presented. In addition to that, chapter 2 comprises a brief summary on the material and the respective methods used in the thesis. In the following chapters (chapters 3-6), the individual studies in the form of scientific papers are presented. The papers in chapters 3-5 focus on the contemporary issues with relation to the nitrogen situation in agriculturally-dominated landscapes. Therefore, they deal with the assessment of the regulating ES nutrient regulation. In chapter 3, the spatial distribution of the nutrient regulation ES potential and demand in the federal state of Schleswig-Holstein and the Bornhöved Lakes District are assessed. For assessing the nutrient regulation ES potential, the ES matrix approach, which distinguishes amongst others ES potentials for different land cover types, was applied. The focus of this chapter lies on the calculation of the nitrogen surplus, which was used to indicate the demand for the ES nutrient regulation. In chapter 4, the ES nutrient regulation was assessed in the county of Hötter. A nitrogen surplus, similar to the nitrogen surplus calculated in chapter 3, was compiled. This chapter also comprises a calculation of the nitrogen surplus on a local spatial scale in the case study area Eversen. Further relevant information on agricultural practices on the scale of individual fields was included. The subsequent chapter 5 also deals with the ES nutrient regulation in Schleswig-Holstein and the Bornhöved Lakes District. However, in the respective study, a Bayesian Belief Network approach was used in order to examine the heterogeneous supply of the ES. Chapter 6 focuses on the ES crop production, which is a

fundamental component of human well-being. The chapter comprises a more general ES and EI assessment of the federal State of Schleswig-Holstein related to the ES crop production. Through the integration of different methodologies, the relation between different EI variables and the ES potential and flow were assessed.

Altogether, two major issues, the provision of food for meeting basic human needs and the nutrient situation with regard to over-fertilization and consequent degradation of the environment, were considered in this thesis. Thus, the studies in the individual chapters provide insights into highly relevant aspects of land management by applying the ES concept. In addition, the thesis increases the understanding of the relation between EI and the delivery of ES and thereby contributes to the scientific development of ecosystem theory.

2

Background information

This chapter provides fundamental information in regard to this thesis and complements the introductory chapter. Firstly, the study areas are introduced. Thereafter, the conceptual framework and relevant definitions, mentioned above in the previous chapter, are described in more detail. Finally, an overview on the employed material and the applied methodologies is given.

2 Background information

2.1 Study areas

In the following section, the investigated study areas are described. Overall, studies were conducted in the federal state of Schleswig-Holstein (regional scale), in the case study area Bornhöved Lakes District (local scale), in the county of Höxter (regional scale) and in the case study area Eversen (local scale) (Figure 1).

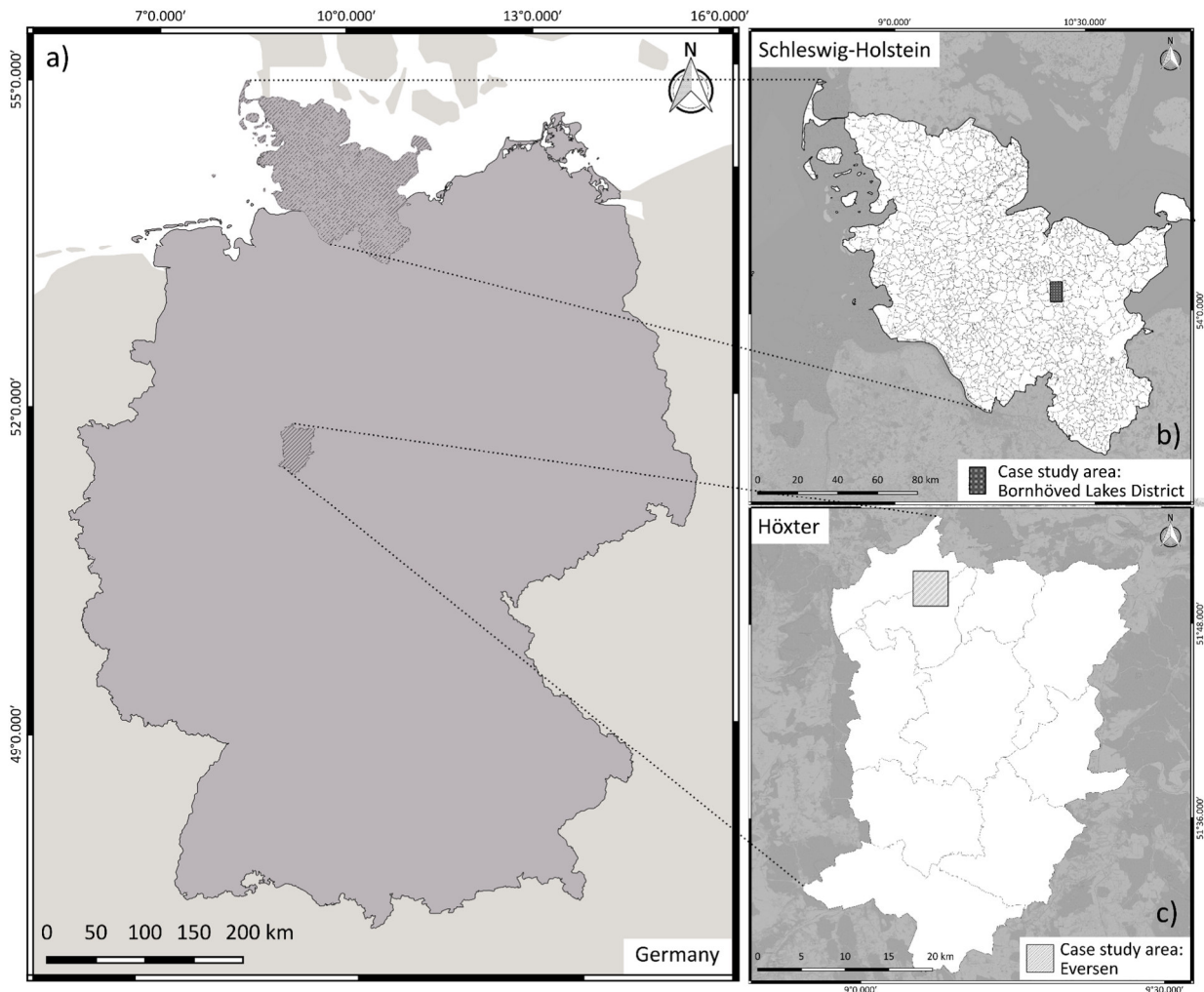


Figure 1: Study areas' locations: a) Schleswig-Holstein and Höxter in Germany, b) Bornhöved Lakes District in Schleswig-Holstein and c) Eversen within the county of Höxter.

All study areas were selected due to their landscape characteristics. Schleswig-Holstein, including the Bornhöved Lakes District, and Höxter are agriculturally dominated landscapes. Therefore, they are suitable to be investigated and compatible with the research objectives defined above. The implementation of the ES assessment in the different study areas and corresponding varying spatial extents, allowed further interpretation on the issue of spatial scale in the context of ES research. The somewhat stronger focus of the thesis lied on the ES assessment on the scale of Schleswig-Holstein.

This arose from the consistency of available datasets at that administrative level and in particular from the fact that the implementation of ES assessments at federal state level is highly relevant in the context of decision-making.

2.1.1 Schleswig-Holstein

Schleswig-Holstein is the northernmost German federal state with an overall extent of 15'802 km² (Statistische Ämter des Bundes und der Länder Deutschland 2018). The federal state is located between the North Sea and the Baltic Sea (Figure 1) and is characterized by maritime and humid climatic conditions. The annual mean temperature lies around 8°C and the annual precipitation average is around 840 mm (DWD Climate Data Center 2018). Schleswig-Holstein can be divided into three main landscape regions (Stewig 1982; Bähr and Kortum 1987): *Hügelland*, *Geest* and *Marsch* (Figure 2). The geological history of Schleswig-Holstein led to the diversity between these landscape regions. The strong impact of the last glacial period, the Pleistocene, on the geology and geomorphology can be detected in Schleswig-Holstein's landscapes. In particular the last two glaciations of the Pleistocene, the Saalian and the Weichselian glaciation, and their spatial extent played an important role in the creation and formation of today's landscapes including the regional diverging natural conditions (Schott 1956; Stewig 1982). During the Saalian glaciation, the glacier covered the area of what today makes up Schleswig-Holstein. The Geest can be divided into Vorgeest (also known as Niedere Geest) and Hohe Geest (LLUR 2012). The distinctive features of the Hohe Geest are the extensively degraded old moraines from the Saalian glaciation (LLUR 2012). The Weichselian glacier only covered the Eastern part, which corresponds to the landscape region Hügelland, nowadays. The Vorgeest is particularly characterized by its function as an outwash plain of the glacier during the Weichselian glaciation (LLUR 2012). As a consequence, the Geest region is featured by poorer and more sandy soils (Schott 1956; Bähr and Kortum 1987). Erosion also diminished the antecedent relief. The impact of the Weichselian glaciation can also be seen in the landscape of the Hügelland. Next to the rolling hills, which originate from the moraines, the landscape can be distinguished by the existence of many lakes and deep embayments (Schott 1956; Stewig 1982; Bähr and Kortum 1987). Another consequence of the geological history is the fertility of the soils in the *Hügelland* area. Contrary to the Hügelland and Geest, the *Marsch*, in the Western part of Schleswig-Holstein, originates from the Holocene. The youngest of the three landscape regions evolved from marine sediments (Stewig 1982; Hoffmann 2004). As consequence of the diverse geological histories of the three main landscape regions, many regional differences in natural conditions arose. Thus, the spatial distribution of various site-specific characteristics such as soil types, as implied above, correlates with the spatial distribution of the landscape regions.

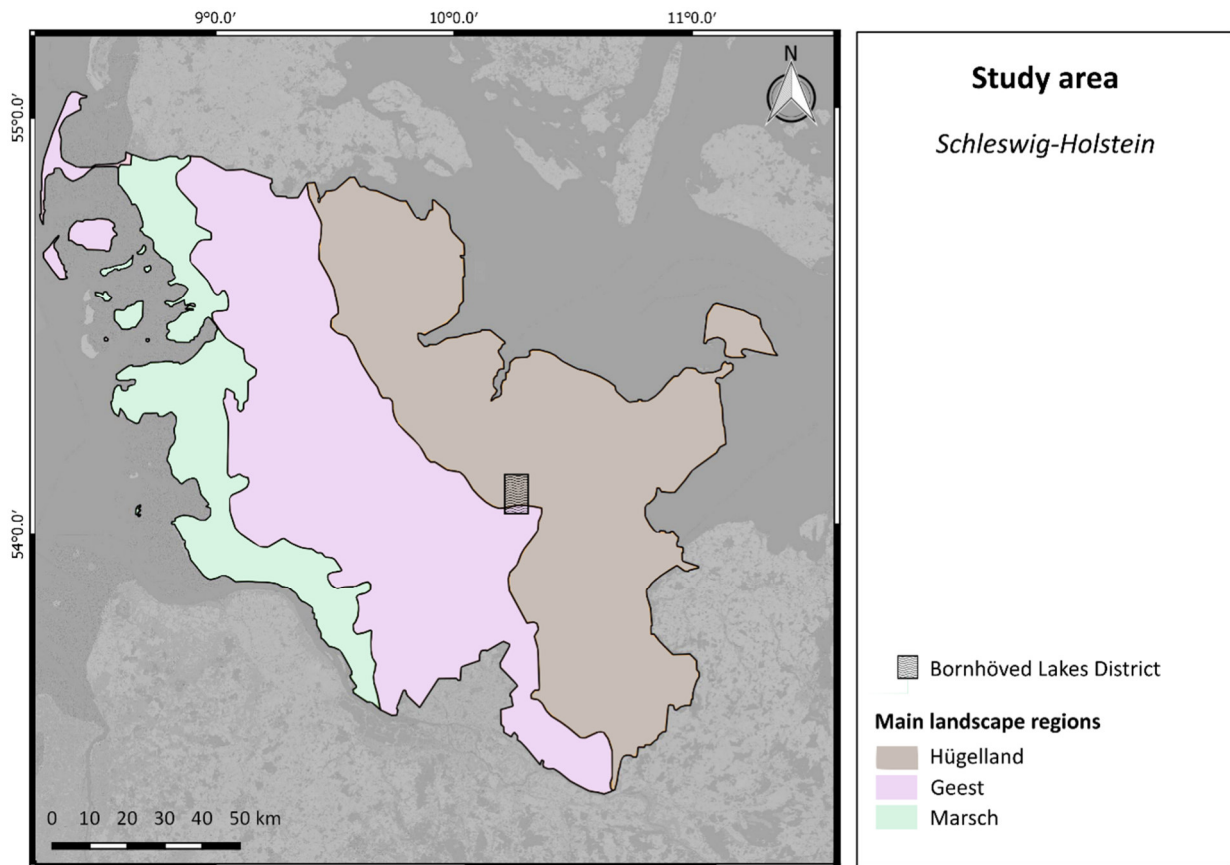


Figure 2: Spatial distribution of main landscape types in Schleswig-Holstein and the Bornhöved Lakes District.

2.1.2 Bornhöved Lakes District

This region, referred to as the Bornhöved Lakes District, is located within the federal state of Schleswig-Holstein (Figure 1 and 2). The area is located approximately 30 kilometers south of Schleswig-Holstein's state capital, the city of Kiel. This study area has been in the focus of several previous research and monitoring projects (Müller et al. 2006; Fränzle et al. 2008; Kandziora et al. 2013a). The spatial extent of the study area is 60 km² (Kandziora et al. 2013a; Kandziora et al. 2014). The Bornhöved Lakes District is located at the boundary between the two landscape regions Hügelland and Geest (Figure 2). Thus, the impact of the Weichselian glaciation as described above, can be observed in the landscape (Fränzle et al. 2008). The area of the Bornhöved Lakes District comprises six glacially formed lakes, which are surrounded by forests and agricultural areas. Fränzle et al. (2008) and Fohrer and Schmalz (2012) declared the area to be a representative landscape for Northern Germany.

2.1.3 Höxter

The county of Höxter is located in the federal state of North Rhine-Westphalia (NRW), Germany (Figure 1) is part of the natural regions Lippe Uplands (dt.: Lipper Bergland), Oberwälderland, Warburger Börde and Egge region (dt.: Egge). The annual mean temperature of the area lies around 9.9°C and the annual precipitation average around 918 mm (Deutscher Wetterdienst 2019). The county of Höxter belongs to 10 municipalities (Kreis Höxter 2018), including the municipality of Nieheim. A local farmer from the municipality of Nieheim who runs a family-owned business, supported the scientific research and served as a valuable source of information. He gave insight into his course of business, providing data on agricultural management and farming practices such as crop rotation and fertilizer application. His farmlands are located close to the village Eversen. Eversen has a population of 472 (Kreis Höxter 2018). For the sake of convenience, the case study area is called Eversen (Figure 1). In the area, which is situated between 135 and 231 m above sea level, the soil types Luvisol and Cambisol dominate the landscape. Agriculture is the primary land use in the area (Geologischer Dienst NRW 2016a; Geologischer Dienst NRW 2016b). The agricultural fields are fragmented by structural elements, such as hedgerows and trees, increasing the diversity and heterogeneity of the landscape (UIH Ingenieur- und Planungsbüro 2016). The prevailing geologic formations, lower and middle Keuper, originate from the Triassic period (Geologischer Dienst NRW 2016b). The agricultural grounds close to the town of Eversen are situated at the southern border of the Lippe Uplands (von Zezschwitz 2001). The Lippe Uplands, which belong to the German Central Uplands, have a spatial extent of approximately 1087 km² (Andres 1989; Bundesamt für Naturschutz 2012) and are characterized by strong variations in relief such as rounded peaks, steep ridges, hills and flat depressions. Within the natural region of the Lippe Uplands, the investigated agricultural grounds belong to the Steinheimer Börde, a fertile loess region (Andres 1989; UIH Ingenieur- und Planungsbüro 2016).

2.2 Concepts, definitions and methodologies

In the following section, the applied concepts in the domain of ecosystem research are discussed and the methodological approaches are outlined.

2.2.1 The concepts of ecosystem services and ecological integrity

As implied in the introduction, ecosystems are highly complex systems. This complexity provokes many challenges for ecosystem service research. Ecosystems consist of many different components, which are interlinked and cooperate with each other (Jorgensen 2012). On each hierarchical level within an ecosystem, high diversity can be encountered. Synergies, trade-offs and feedbacks are interwoven throughout the whole system and result in emergent properties. Therefore, ecosystems are a good example for systems which must be assessed using a holistic approach (Jorgensen 2012).

As a consequence, ecosystem research always needs to account for these circumstances and usually aims to abstract reality in order to obtain a feasible object of research which can be assessed. Thereby, one needs to find an appropriate balance between reasonable levels of abstraction and simplification and loss of reality. In addition to these challenges, ecosystem research is entwined with social and economic sciences. The enormous anthropogenic influence on the environment and all ecosystems cannot be ignored (TEEB DE 2012): Land take, accompanied by soil sealing and deforestation, agricultural practices leading to erosion and eutrophication and the combustion of fossil fuels, entailing anthropogenic climate change - just to name a few. Through these influences, the self-organizing capacity of corresponding ecosystems is impaired (Müller and Kroll 2011) and thereby the degree of freedom for natural development processes is diminished.

In order to fully understand an ecosystem, one also needs to consider the respective pressures on the system (TEEB DE 2012). Thus, research on the interactions between humans and the environment is indispensable. The ES concept meets the requirements formulated above concerning ecosystem research. The approach considers the whole ecosystem as such, concurrently with the individual components of the system. Thereby, the ES concept corresponds to a holistic approach in the domain of ecosystem research. In addition to that, the concept is anthropocentric, enabling a comprehensive view on the human-nature interactions (National Academy of Sciences 2013; Fürst 2015). Thus, the ES concept facilitates an assessment of the link between humans and the environment, which is highly relevant for decision-making (Ash et al. 2010b; Schröter et al. 2014a; Schröter et al. 2016). Generally, ES can be divided into three main ES categories; provisioning, regulating and cultural ES (Kandziora et al. 2013b; Burkhard et al. 2014; Sohel et al. 2015; Stoll et al. 2015; Haines-Young and Potschin 2017; Schneiders and Müller 2017). Provisioning ES refer to the direct products which ecosystems provide for humans (De Groot et al. 2010b; Haines-Young and Potschin-Young 2010; Kandziora et al. 2013b; Haines-Young and Potschin 2017), such as crops and freshwater. Regulating ES correspond to the

benefits people obtain due to the ecosystem's regulation of natural processes such as nutrient regulation (Kandziora et al. 2013b; Haines-Young and Potschin 2017). Cultural ES include the intangible benefits that humans obtain from ecosystems, e.g. as non-material inspirational and educational experience (De Groot et al. 2010b; Kandziora et al. 2013b; Haines-Young and Potschin 2017). The ES from the different categories can be linked to a respective set of components in regard to human well-being (TEEB DE 2012; Kandziora et al. 2013b; Maes et al. 2018). Throughout the development of the ES concept, different ES classification systems were created. The following classification (Table 2), identifying ES and corresponding ES categories, was used as a foundation for this thesis.

Table 2: Classification of ES (based on Müller et al., in prep.; Kandziora, Burkhard and Müller, 2013b; Burkhard et al., 2014).

Provisioning ES	Regulating ES	Cultural ES
Crops	Global climate regulation	Recreation & tourism
Biomass for energy	Local climate regulation	Landscape aesthetics & inspiration
Fodder	Air quality regulation	Knowledge systems
Livestock (domestic)	Groundwater recharge, water flow	Cultural heritage
Timber	Flood protection	Regional identity
Fiber	Nutrient regulation	Natural heritage
Wood fuel	Water purification	
Wild food	Erosion regulation (wind & water)	
Fish and seafood	Pollination	
Beach wrack, flotsam	Pest and disease control	
Freshwater		
Abiotic energy		
Minerals		

The individual ES can be linked to different aspects of human well-being either directly or indirectly (McMichael et al. 2005; Maes et al. 2017; Potschin and Haines-Young 2017). An example for a direct link would be the provision of food for satisfying the human well-being constituent basic material for good life. Other ES such as air quality regulation and flood protection relate more indirectly to human security and health (Haines-Young and Potschin 2010; Erhard et al. 2017). Cultural ES link to human well-being components such as public health and psychological experiences (Kopperoinen et al., 2017). They are usually harder to tie to environmental parameters (Dunford et al. 2017a) and are strongly related to human perceptions, attitudes and beliefs (Kopperoinen et al. 2017). Their general detachment from environmental parameters is the reason for the exclusion of the category from this thesis.

The provision of ES depends on the properties and conditions of a respective ecosystem (Figure 3). Therefore, an evaluation of these aspects is highly relevant for a comprehensive ES assessment (Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017). Ecosystem properties are defined as the biophysical structures and processes of an ecosystem (Burkhard and Maes 2017b; Syrbe et al. 2017) (Figure 3). Ecosystem structures can be divided into biotic and abiotic components (Schneiders and Müller 2017). The abiotic structural components, for instance soil properties and geological factors, determine the living conditions of the biota whereas the biotic components are involved with active life processes (Schneiders and Müller 2017). Ecosystem processes can be defined as the dynamics or pools and flows in an ecosystem. They are dedicated to energy, water, carbon and nutrients (Schneiders and Müller 2017).

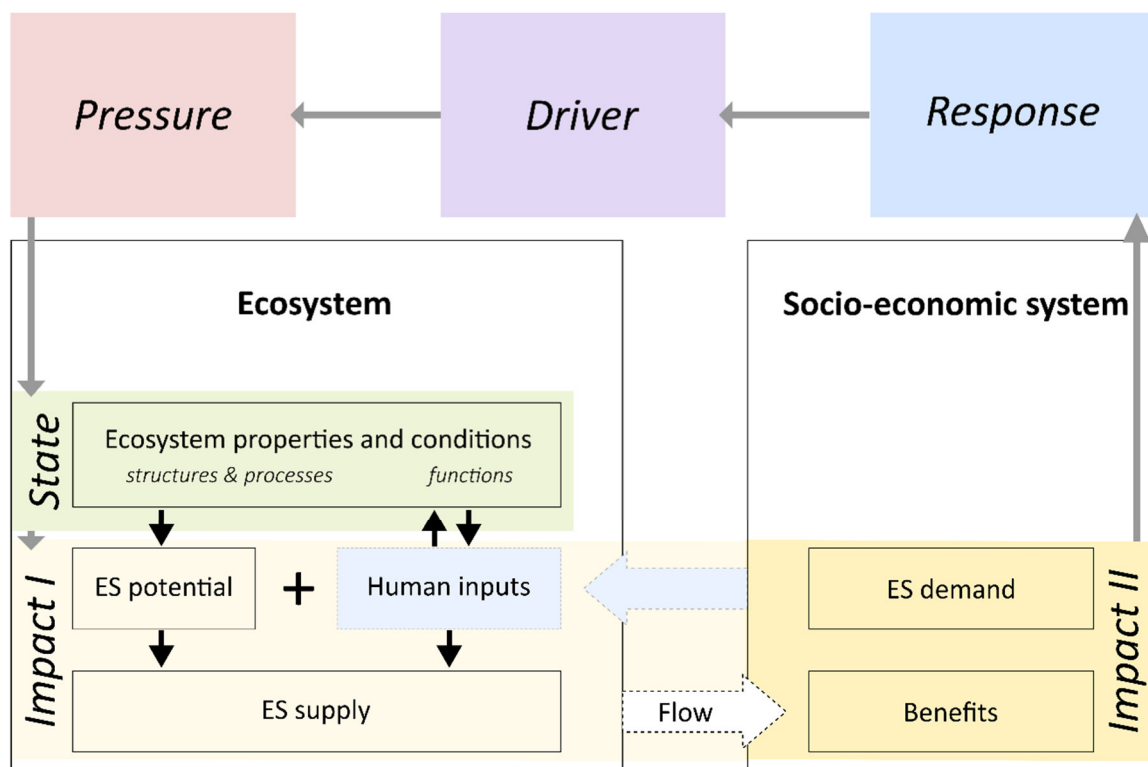


Figure 3: Overview on the ES concept, including an embedment into the DPSIR concept (after Haines-Young and Potschin 2010; Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017).

The ecosystem condition or ecosystem state (Maes et al. 2014) is often associated with the EI (Syrbe et al. 2017). The EI of an ecosystem describes its general functions (Müller and Burkhard 2012; Schneiders and Müller 2017) (Figure 3). The ecosystem condition is determined by the physical, chemical and biological condition and quality of an ecosystem (Maes et al. 2014; Erhard et al. 2017; Maes et al. 2018). Thus, the ecosystem condition is for instance determined by climate, geology, soil properties and elevation (Erhard et al. 2017). The concept of EI aims to preserve the processes and structures within an ecosystem which are fundamental for the ecosystems capacity to maintain self-

organization over time (Kay and Schneider 1992; Müller 2005; Müller and Kroll 2011). Integer ecosystems have the capacity to remain in their self-organizational states in case they are being influenced by disturbances or gradual changes (Kay and Schneider 1992; Kay and Schneider 1995). Through an assessment of the degree of self-organization of an ecosystem, the ecological integrity can be measured or indicated (Kay and Schneider 1995; Müller 2005). For illustration purposes, two ecological indicators, which are highly relevant for this thesis, are described below (Müller and Nielsen 2000; Müller and Kroll 2011).

- Exergy capture: Exergy measures the energy fraction that can be transformed into mechanical work. Thus, exergy capture is the capability of a system to enhance the input of usable energy. In ecosystems, the exergy is captured from solar radiation, H₂O and CO₂ through the construction of biomass and structures.
- Reduction of nutrient loss: Nutrient loss refers to the irreversible deletion of elements from the system. It is the result of gradient dissipation, in ecosystems for instance by mineralization.

As illustrated in Figure 3, the ecosystem properties and conditions are the foundation of the ES potential. In combination with human inputs, the ES supply is formed which - driven by the ES demand – becomes the ES flow (Syrbe et al. 2017). In order to guarantee an integrated assessment, the consolidated knowledge from ecosystem theory should be applied (Müller and Kroll 2011). By including both EI and ES in the assessments, consolidated findings on the linkages between the environmental and human systems can be obtained, which should be the base for decision-making. The inclusion of further information on ecosystem properties (Syrbe et al. 2017), such as slope inclination and climatic conditions, delivers a complete assessment (Figure 3).

The ES concept can be embedded into the DPSIR approach (Driver-Pressure-State-Impact-Response; (Burkhard and Müller, 2008; van Oudenhoven *et al.*, 2012; Mattas, Voudouris and Panagopoulos, 2014; Maes *et al.*, 2016; Erhard *et al.*, 2017; Figure 3). The DPSIR approach aims to structure and organize the multiple human-environmental interactions (Müller and Burkhard 2012). The individual aspects of the approach are connected by causal relations. Generally, the approach is used to identify the consequences of certain drivers, which can be any kind of anthropogenic activity that has an environmental effect (Mattas et al. 2014; Erhard et al. 2017). The following example (Figure 4) clarifies the DPSIR approach and illustrates the possibility to embed the ES concept into the DPSIR framework (Figure 3): Contemporary anthropogenic drivers are amongst others, industry, intensive agriculture and energy consumption. With regard to the objectives and general topic of this thesis, intensive agriculture was selected as a driver. Intensive agriculture produces certain pressures on the environment, amongst which fertilization plays a very important role. This pressure affects the state of an ecosystem (Maes et al. 2018). In this case, the state corresponds to high concentration values of

NO₃⁻. With regard to the ES concept, the state of an ecosystem corresponds to the ecosystem properties and conditions. This state possesses a certain impact, which can be identified as changes in the natural and human system (Müller and Burkhard 2012) and which can be linked to the provision and demand of ES. With reference to the example in Figure 4, the ES nutrient regulation is influenced by the state. As a consequence of the impact, the society may respond to the changes, for instance through the development or adjustments of agricultural policies.

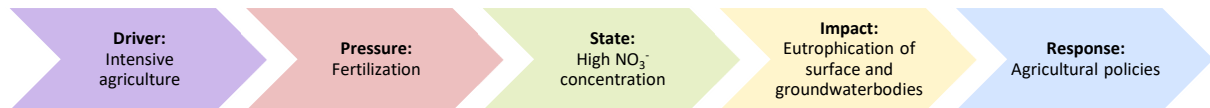


Figure 4: Schematic abstraction of DPSIR framework on the topic of intensive agriculture.

The possibility to embed the ES concept into the DPSIR framework highlights the effectiveness to assess interlinkages between anthropogenic pressures and the environment by means of ES assessments. It proves how the ES concept supports the abstraction and simplification of the human-environmental system and provides solutions for application in practice. Besides, the inclusion of the ES concept into the DPSIR approach highlights the role of the state of an ecosystem (Erhard et al. 2017). This thesis has quantified several ES and EI variables. As the thesis aims to assess the spatial distribution and respective regional differences of the assessed variables, the creation of spatially explicit and quantitative maps was an integral part of the different studies. The spatial representation of results from ecological assessments has become more and more important for planning and management purposes (Kienast et al. 2009; Swetnam et al. 2011; Burkhard et al. 2012a; Schröter et al. 2014b; Burkhard and Maes 2017a). ES maps, for instance, have been identified as useful visualization tools (Burkhard and Maes, 2017a), powerful for organizing and communicating complex data (Maes, 2017). In particular, in the context of decision-making, these maps can support sustainable land management strategies (Burkhard and Maes, 2017a).

2.2.2 Materials and methods

The following section gives a brief overview on the general assessment and mapping methods and respective software applied and subsequently on the datasets used for the assessments.

Generally, the thesis includes both quantification of ES and EI variables and their mapping, for which statistical and GIS software has been essential. For the statistical evaluation and analysis, Excel v16.0 and R 3.5.2 were used. For all matters related to spatial assessments and mapping, the software ArcMap 10.5.1 by ESRI and the open source software QGIS 2.18.24 were utilized. In addition, for the assessment described in chapter 4, a Bayesian Belief Network was developed, using the software

GeNIe 2.2 Academic by BayesFusion, LLC. Besides, literature research was essential for each study in this thesis.

Different types of input datasets were essential for the assessments. Geodata, especially land use/land cover, was used as a basis for the assessment of ES. The Coordination of information on the environment (CORINE) Land Cover dataset, which was provided by the Service Centre of the Federal Government for Geo-Information and Geodesy (<http://www.geodatenzentrum.de/>), served as a primary source for land use/land cover information. The Service Centre of the Federal Government for Geo-Information and Geodesy belongs to the Federal Agency for Cartography and Geodesy (dt.: Bundesamt für Kartographie und Geodäsie, BKG). The CORINE Land Cover inventory, initiated in 1985 by the European Union, has been coordinated by the European Environmental Agency (EEA 1995; Glaser 2012). It is based on remote sensing data and differentiates between a nomenclature of 44 land use and land cover classes. The dataset was developed for the years 1990, 2000, 2006, 2012 and 2018. The CORINE dataset from 2012 was used for this thesis. Next to the CORINE LULC dataset, further geodata, such as administrative boundaries and a digital terrain model, was provided by the Service Centre of the Federal Government for Geo-Information and Geodesy.

Another valuable source for geodata was the State Agency for Agriculture, Environment and Rural Areas (dt.: Landesamt für Landwirtschaft, Umwelt und ländliche Räume, LLUR) and the State Agency for Nature, Environment and Consumer Protection (dt.: Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, LANUV). They provided data on environmental characteristics such as soil texture and other soil properties. The dataset from the LLUR on soil properties included, amongst others, information on nitrate leaching potential and field capacity. Furthermore, the LLUR provided datasets on the installation of biogas power plants and the spatial distribution of the risk of wind and water erosion. Data on atmospheric nitrogen deposition was provided by the German Environment Agency (dt.: Umweltbundesamt, UBA). The spatially explicit data was complemented with statistical datasets from regional statistical offices. In particular the agricultural census 2010 by the Statistical Agency North (dt.: Statistikamt Nord) and the agricultural census 2016 from the Central Statistical and IT Services Provider of NRW (dt.: Landesbetrieb Information und Technik NRW) was consulted intensively. In this context, the commitment of a local farmer and his family to cooperate in this study has to be highlighted. They provided information on land management and agricultural practices on their family-run farm, including crop rotation and fertilizer application. For the intensive literature research, scientific literature, grey literature and the German Fertilizer Law and Ordinance were reviewed. They provided the base for the development of the research design and were essential during the implementation process. During the process,

relevant information was adopted from the respective literature items. In addition to that, the literature was consulted for matter of comparison and for the discussion of the results.

More detailed information on the applied methodologies and the respective input datasets can be found in the individual chapters (chapters 3-6).

3

Assessing the nutrient regulation ES demand and potential in Schleswig-Holstein

Publication title: Mapping of nutrient regulating ecosystem service supply and demand on different scales in Schleswig-Holstein, Germany

Bicking, S., B. Burkhard, M. Kruse and F. Müller
One Ecosystem 2018
DOI: 10.3897/oneeco.3.e22509

In this paper, the nutrient regulation ES potential and demand were assessed for the area of the federal state of Schleswig-Holstein. The nutrient regulation ES potential was estimated by applying the ES matrix approach, which integrates expert-evaluation and land use/land cover information. Furthermore, a methodology was developed in order to quantify the demand for the ES nutrient regulation. A calculation of nutrient in- and output parameters was performed in order to evaluate the nutrient surplus. The calculation was executed on the scale of the municipalities of the federal state and allocated onto land use/land cover distribution in the case study area Bornhöved Lakes District. The resulting nutrient surpluses were compared to the spatial distribution of the nitrate leaching potential.



Research Article

Mapping of nutrient regulating ecosystem service supply and demand on different scales in Schleswig-Holstein, Germany

Sabine Bicking^{‡,§}, Benjamin Burkhard^{‡,|}, Marion Kruse[§], Felix Müller[§]

[‡] Leibniz Universität Hannover, Hannover, Germany

[§] CAU Kiel, Kiel, Germany

[|] Leibniz Centre for Agricultural Landscape Research ZALF, Müncheberg, Germany

Corresponding author: Sabine Bicking (sbicking@ecology.uni-kiel.de), Benjamin Burkhard (burkhard@phygeo.uni-hannover.de), Marion Kruse (mkruse@ecology.uni-kiel.de), Felix Müller (fmueller@ecology.uni-kiel.de)

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Abstract

This study deals with one of the regulating ecosystem services, nutrient regulation. In order to guarantee sustainable land management, it is of great relevance to gain spatial information on this ecosystem service. Unsustainable land management with regard to nutrient regulation may, for example, result in eutrophication which has been identified as a major threat for the environmental state of our water bodies. In the first step of research, the potential supplies and demands of/for nutrient regulation were assessed and mapped at two different spatial scales: The German federal state of Schleswig-Holstein (regional scale) and the Bornhöved Lakes District (local scale). The assessment was undertaken for nitrogen, as an exemplary nutrient. Subsequently, potential supply and demand, combined with the nitrate leaching potential and the groundwater nitrate concentration, were incorporated into a correlation analysis. The data was statistically analysed with varying pre-processing and spatial resolutions. The statistical analysis reveals that large scale data with low resolution leads to more uncertain results. Decreasing the spatial scale and increasing the resolution of the data through a spatially more explicit assessment, leads to

more explicit results. It is striking that the study reveals a spatial mismatch between the potential supply and demand for the ecosystem service nutrient regulation, which denotes unsustainable land management in the study areas.

Keywords

Bornhöved Lakes District, eutrophication, fertiliser application, nitrogen budget, groundwater nitrate concentration, nutrient status, correlation analysis, local scale, regional scale

Introduction

The availability of nutrients is essential for living organisms such as plants, animals and bacteria. With regard to agricultural production, nutrients are applied to agricultural grounds in order to guarantee high yields (Vitousek et al. 2009, Power 2010, Tilman 1999, Tivy 1987). The increasing demand for agricultural products has led to increasing fertilisation (Tilman 1999, Tivy 1987). Unfortunately, it is common practice that, through fertilisation, the amount of nutrients available in the soil exceeds the actual requirements of the crop (Tilman 1999) which leads to over-fertilisation (Vitousek et al. 2009, Tivy 1987). The consequence of a persistent surplus of nutrients results in degradation of the environment (Chapin et al. 2002, Fenn et al. 1998). More precisely, the excess of nutrients on agricultural land leads to increasing nutrient losses from the soil and consequently enrichment of nutrients in groundwater, lakes, rivers and eventually the ocean (Chapin et al. 2002, Vitousek et al. 1997, Tivy 1987). Therefore, the eutrophication of ecosystems has been recognised as a severe issue by society as well as research, whereby agriculture has been defined as the major diffuse source of nutrient inputs into the environment (Trepel 2016, TEEB 2015, Taube et al. 2013, Larsson and Granstedt 2010, HELCOM 2004). On the political level of the European Union, there are different directives aiming to decrease nutrient inputs, such as the Nitrate Directive (European Council 1991), Water Framework Directive (European Parliament and Council of the European Union 2000) and Groundwater Directive (European Parliament and Council of the European Union 2006). In 2016, the European Commission took legal action against Germany for failing to take stronger measures to combat water pollution by nitrates as data on nitrate concentration in ground and surface waters were worsening (European Commission 2016).

Sustainable management of nitrogen is of great importance for agroecosystems, as insufficient nitrogen inputs will decrease crop production while an excess input will pollute the environment (Withers et al. 2014, Tilman 1999). According to the LLUR (2014)¹ in Schleswig-Holstein, the groundwater bodies of more than 7500 km² have a poor chemical status in the main aquifer, primarily due to nitrate pollution. This area equals approximately half of the federal state's spatial extent. In order to combat eutrophication efficiently and to improve the status of the environment, it is necessary to generate (spatially) explicit data on nutrient inputs (Selman and Greenhalgh 2009, Ondersteijn 2002, European Council

1991). Much of recent literature deals with nutrient oversupply and its consequences for the environment (e.g. Taube et al. 2015, Wendland et al. 2014, Withers et al. 2014, Larsson and Granstedt 2010, Tilman 1999).

Spatial ecosystem service analyses can be used to increase the understanding of the interrelations between human activities, e.g. land management and the environment. Therefore, the European Union has asked all its member states to map and assess the states of their ecosystems and the services they provide within the Biodiversity Strategy to 2020² (Maes et al. 2012). Ecosystem service analyses are qualified to support sustainable land management (Smith et al. 2012), as the capacity of ecosystems to produce desired benefits is assessed.

The underlying concept commonly differentiates amongst 3 categories of ecosystem services: regulating, provisioning and cultural services. All these ecosystem services contribute to human well-being (i.e. Burkhard and Maes 2017, Burkhard et al. 2012b, de Groot et al. 2010, Kandziara et al. 2013, Landuyt et al. 2012, Millennium Ecosystem Assessment 2005). In this study, the concept of ecosystem services is applied to the topic of nutrient regulation. Recent ecosystem service research, with regard to nitrogen, identifies nitrate leaching into fresh waters as the consequence of "...overloading the regulating service [...] naturally provided by soils of all habitats..." (Jones et al. 2014, p. 81). In the context of this research, nutrient budgets were calculated by using nutrient nitrogen as an example. A statistical evaluation was undertaken whereby the data on the potential supply and demand for nutrient regulation was combined with data on the nitrate leaching potential and the groundwater nitrate concentration.

Following the problems described above, the objectives and corresponding research questions of the study are:

1. Assessing the potential supply and demand of nutrient regulation in the study areas. Do potential supplies and demands of/for nutrient regulation coincide in Schleswig-Holstein and the Bornhöved Lakes District?
2. Testing the statistical relation between the nitrogen budget, nutrient regulation potential, nitrate leaching potential and the actual nutrient status of the study areas. Is it possible to statistically prove the influence of the ecosystem service nutrient regulation on the nutrient status?
3. Giving useful advice on the usability of the different methodologies and scales assessed. Does higher resolution data result in more valid outcomes?

This study is part of the EU-funded Horizon 2020 Support and Coordination Action ESMEALDA³. Within this project, various methods for mapping and assessment of ecosystems and their services have been identified. Selected methods are tested in case studies which are representative for different biomes, spatial scales, ecosystem types and services as well as policy questions across Europe. Our methods and case study is part of the testing and contributes to the implementation of the EU Biodiversity Strategy to 2020.

In the following chapter, background information is given on the topic of ecosystem services. Thereafter, the two study areas are described. Chapter 3 outlines the methods which were applied in this study. Furthermore, relevant datasets are specified. In Chapters 4 and 5, the results of the study are presented and discussed, respectively. Conclusions are drawn in Chapter 6, based on the objectives defined in the introduction.

Background information

The following section, gives information on the applied ecosystem service concept, nutrient regulation and the study areas.

The ecosystem service concept and nutrient regulation

Research on ecosystem services has been prospering in recent years. The fast evolution in this field of science results in divergences with regard to definitions and terminologies. Ecosystem services have been defined by de Groot et al. (2010) as direct and indirect contributions to human well-being that originate from ecosystems. Burkhard et al. (2012b) (p. 2) defined ecosystem services as “the contributions of ecosystem structure and function - in combination with other inputs - to human well-being”. Fig. 1 depicts the interrelations and dependencies between the ecosystem and human benefits through ecosystem services within a defined system. The supply of ecosystem services is strongly dependent on ecosystem properties and conditions (Fig. 1). Ecosystem service supply can be specified as potentials (or capacities) and flows (Syrbe et al. 2017, Burkhard et al. 2014, Schröter et al. 2014; see Table 1).

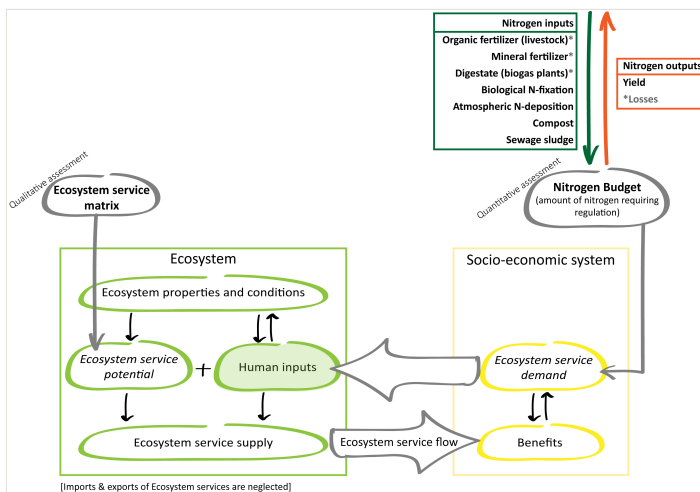


Figure 1.

Ecosystem service mapping framework (based on Syrbe et al. 2017; aspects presented in *italic* were assessed in this study).

Table 1.

Definitions used within the approach.

Ecosystem service potential

Ecosystem service potentials are related to the hypothetical maximum yield of selected ecosystem services (Burkhard et al. 2012a), which are commensurate with the theoretical capacity of an ecosystem to provide a service (Wiggering et al. 2016, Bastian et al. 2012). After von Haaren et al. (2014), the ecosystem service potential can be described as 'offered ecosystem service'. In other words, an ecosystem service potential is the overall available service of a certain ecosystem, but the potential service does not need to be utilised (Bastian et al. 2013). This definition depicts the ecosystem service as stock (Burkhard et al. 2014).

Ecosystem service flow

The ecosystem service flow describes the utilised service in a specific area and within a defined period of time (Syrbe et al. 2017, Burkhard et al. 2014, von Haaren et al. 2014). Thus, the flow measures the effective extraction (Syrbe et al. 2017, Bastian et al. 2012). The ecosystem service flow includes effects derived from additional anthropogenic inputs (Syrbe et al. 2017, Burkhard et al. 2014).

Ecosystem service demand

Burkhard et al. (2012a) (p. 18) define the demand for ecosystem services as the "[...] sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period." They state that "[...] up to now, demands are assessed not considering where ecosystem services actually are provided" (Burkhard et al. 2012a, p. 18). Syrbe et al. (2017) define the ecosystem service demand as the need for an ecosystem service by society as a whole, particular stakeholder groups or individuals, thus linking the ecosystem service to particular beneficiaries. They identify the risk that sometimes beneficiaries might not be aware of their demand for a certain ecosystem service, particularly with regard to some regulating ecosystem services.

The beneficiaries of the ecosystem service nutrient regulation are diverse. At first sight, it is obvious that society as such is a beneficiary as it strives for a clean environment (Villamagna et al. 2013). With regard to directives and regulations arising from national as well as European legislation, politics can also be defined as a beneficiary for the assessed ecosystem service, which can eventually also be allocated to society as such. Following the approach of Power (2010), agriculture as such simultaneously provides and consumes ecosystem services. In order to provide high yields amongst others, the agricultural system, also known as the agroecosystem, requires the ecosystem service nutrient regulation (Burkhard et al. 2012a, Power 2010). These different applicable perspectives on the beneficiaries of the ecosystem service nutrient regulation emphasise the importance of the service and, as a consequence, underline the demand for its evaluation.

Nutrient regulation

Nutrient regulation is the ability of an ecosystem to recycle nutrients (Burkhard et al. 2014) and is of significant relevance regarding land management. According to Tivy (1987), unmanaged ecosystems are thought to reach a 'steady-state' with regard to the nutrient pool. Losses, as well as inputs, of nutrients are small and in balance (Chapin et al. 2002, Hedin et al. 1995, Tivy 1987). Thus, the nutrient cycle is almost closed (Chapin et al. 2002). However, intense agricultural usage has greatly changed the natural nutrient cycle (Vitousek et al. 1997). Due to fertiliser use and high production yields, the nutrient cycle has been artificially opened up (Chapin et al. 2002, Tivy 1987). As a result, affected areas suffer from the consequences of either nutrient deficiency or oversupply. In order to

guarantee human health and food security, society strives to prevent these circumstances. Nutrient regulation or retention should combat either nutrient deficiency or nutrient oversupply in order to secure a sustainable nutrient cycle (Tivy 1987). Therefore society has a demand for the ecosystem service nutrient regulation. Nutrient regulation varies for different ecosystems. In particular, natural ecosystems such as forests and grassland have a high potential for nutrient regulation (Fu et al. 2012, Burkhard et al. 2014). Besides LULC, other factors are of relevance for determining the potential of nutrient regulation, such as the slope (Fu et al. 2012) and climatic conditions. In our study, next to the assessment of the nutrient regulation potential, we focus on a spatially explicit quantification of the demand for the ecosystem service nutrient regulation.

Study Areas

The following section describes the two study areas: the federal state of Schleswig-Holstein and the Bornhöved Lakes District, both located in northern Germany. We selected these two study areas of different spatial extent in order to allow for some comparisons with regard to the issue of scale. In the first step, we assessed both case study areas with the exact same data and spatial resolution. Thus, in that case, the results of the Bornhöved Lakes District are simply an extract of the results for the federal state of Schleswig-Holstein. In the second step, we used a higher spatial resolution to assess the situation in the Bornhöved Lakes District.

Schleswig-Holstein

Schleswig-Holstein is the northernmost federal state of the Federal Republic of Germany (Fig. 2). The federal state has an area of 15,803 km² (*Statistikamt Nord*⁴). To the west and east, Schleswig-Holstein is surrounded by the North Sea and the Baltic Sea, respectively. Thus, the climatic conditions in the federal state are maritime and humid with an annual mean temperature of approximately 8°C and precipitation averages of around 840 mm (Climate Data Center 2017). Its geological as well as geomorphological conditions are highly influenced by the final two glaciations of the last glacial period (Pleistocene) (Schott 1956). Both the Saalian and the Weichselian glaciation formed the current landscapes and led to the differentiation within the federal state (Schott 1956). The current landscapes can be divided roughly into three main regions (Bähr and Kortum 1987, Stewig 1982): *Hügelland*⁵ in the eastern part, *Geest* concentrated in the centre and *Marsch* in the western part of Schleswig-Holstein (Fig. 2).

In particular, the varying expansions of the glaciers during the two glaciation periods resulted in the current conditions (Schott 1956, Stewig 1982). The glacial influence can still be recognised in the area of the *Hügelland*, as the rolling hills formed by the moraines and small lakes as well as deep embayments prevail in the landscape (Bähr and Kortum 1987, Stewig 1982, Schott 1956). Contrary to the fertile soils of the *Marsch* and *Hügelland*, the *Geest* is characterised by sandy soils, as the area embodies the outwash plains of the Weichselian glaciation (Bähr and Kortum 1987, Schott 1956). In conjunction with additional erosion, a landscape evolved featuring only little relief. Unlike these two landscape forms,

the *Marsch* can be attributed to the Holocene and is thus the youngest of the three landscape types (Hoffmann 2004, Stewig 1982). The *Marsch* area is a low lying area where drainage predominates the landscape (Hoffmann 2004). The federal state is divided into administrative units. These are important in the context of decision-making as well as data availability. The most relevant administrative units for this study are municipalities (Fig. 3), which are the smallest administrative units.

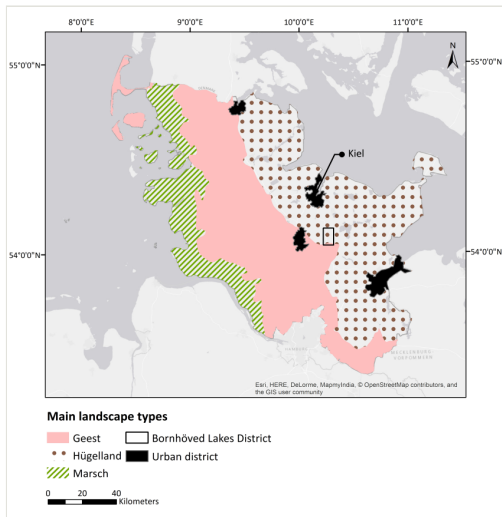


Figure 2.

Schleswig-Holstein study area, showing the differentiation between main landscape types (based on data from LLUR 2017⁶).

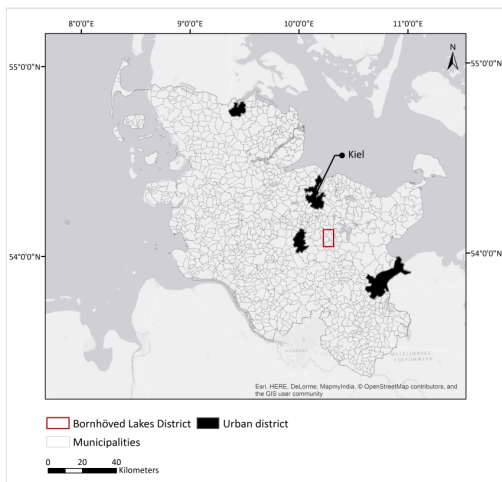


Figure 3.

Assessment units for Schleswig-Holstein: Municipalities (data on administrative boundaries from GeoBasis-DE / BKG 2017b).

Bornhöved Lakes District

The Bornhöved Lakes District is located approximately 30 km south of the city of Kiel, on the border between the landscape regions *Hügelland* and *Geest* (Fig. 2). The appearance and characteristics of the landscape have been influenced greatly by the Weichselian glaciation (Fränzle et al. 2008). In the study area, six glacially formed lakes can be found which are surrounded by forest and agricultural areas (Fränzle et al. 2008). The extent of the Bornhöved Lakes District, which has been defined as a case study area for ecosystem services research, is approximately 60 km² (Kandziora et al. 2013). The Bornhöved Lakes District has already been identified as a case study area in several completed and current research and monitoring projects (Kandziora et al. 2013, Müller et al. 2006, Fränzle et al. 2008). According to Fränzle et al. (2008) and Fohrer and Schmalz 2012, the Bornhöved Lakes District can be regarded as a representative landscape for northern Germany.

Materials and methods

All spatial analyses were executed with the GIS Software ArcMap 10.3. We primarily used the toolboxes *Analysis Tools*, *Geostatistical Analyst Tools* and *Spatial Analyst Tools*. For statistical computation, we used the software R with the development environment RStudio. The package *dplyr* was used in order to simplify the handling of large datasets. For statistical computations, the package *corrplot* was crucial. Due to data availability, we preferred data from the year 2010 as input data. However, if no data were available for that time period, proximate time periods were selected.

Supply of nutrient regulation

The assessment of the potential supply of the ecosystem service nutrient regulation is based on the ecosystem service matrix by Burkhard et al. (2014). The matrix can be used to distinguish nutrient regulation for different land cover types. CORINE land cover data^{*7} from the European Union was selected as the underlying dataset. The CORINE dataset is hierarchically organised into three levels differentiating in total between 44 land cover classes (EEA 1995). In this study, the 2012 CORINE dataset in ArcGIS polygon shape format was applied. Fig. 4 presents the spatial distribution of the CORINE land cover classes in the two study areas. For both study areas, Schleswig-Holstein and the Bornhöved Lakes District, non-irrigated arable land and pastures are the dominant land use/land cover (LULC) classes (Fig. 4). Hotspots of continuous urban fabric, discontinuous urban fabric and industry or commercial units are agglomerated around the four urban districts of Lübeck, Kiel, Flensburg and Neumünster and in the area adjacent to Hamburg in the southwest of the study area. More natural LULC classes are distributed rather randomly in both areas.

CORINE land cover classes were chosen as geospatial units to be placed in the rows (y-axis) of the ecosystem services matrix (Burkhard et al. 2014). For each land cover type occurring in the study area, the corresponding potential for nutrient regulation, derived from

an expert-based assessment, was specified on a relative scale from zero to five by Burkhard et al. (2012a), where five stands for the highest potential. The expert-based assessment was not executed specifically for this study but the potentials have been adopted from the study by Burkhard et al. (2012a). By means of ArcMap 10.3, the values assigned to the CORINE land cover classes were presented in ecosystem service maps for the study areas.

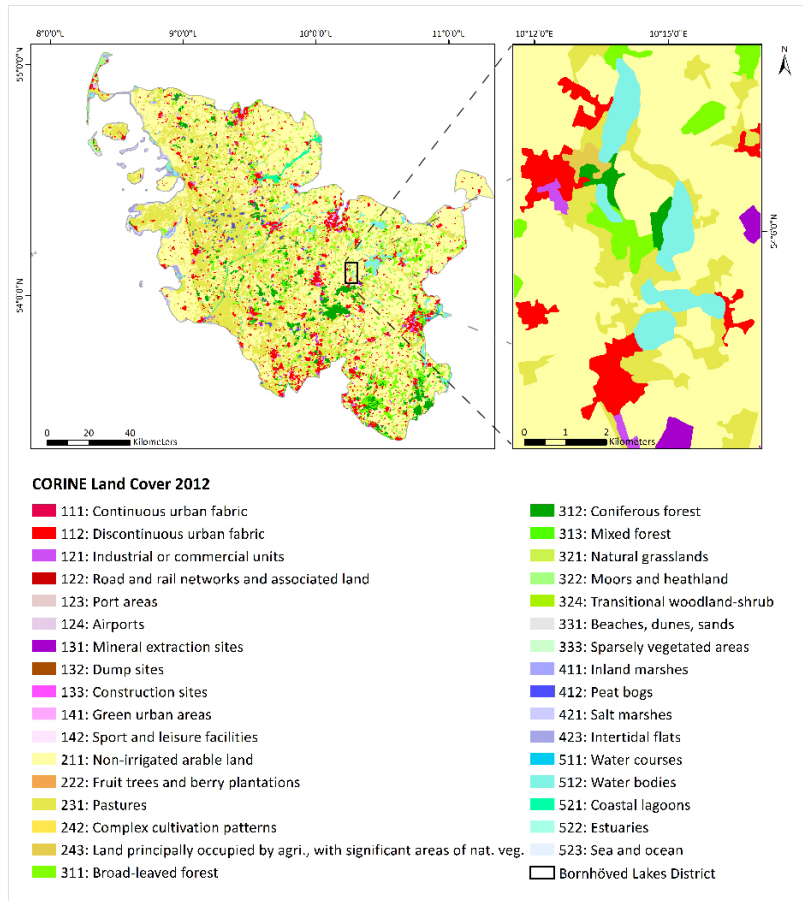


Figure 4.

Distribution of CORINE land cover classes in 2012 in Schleswig-Holstein (left) and the Bornhöved Lakes District (right; data from GeoBasis-DE / BKG 2017a).

Demand for nutrient regulation

In Schleswig-Holstein, the anthropogenic transformation of the nutrient cycle primarily leads to nutrient oversupply, as excess nutrients are introduced into the environment by means of agricultural practices (Trepel 2016, Kreins and Henseler 2015, Taube et al. 2015, Larsson and Granstedt 2010). At these locations, there is a significant demand for the

ecosystem service nutrient regulation. In order to obtain data on the nutrient surplus, we calculated nutrient budgets. Data from the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010) ⁸ served as the basis for the budget calculations. We included the following parameters in the budgets: Organic fertiliser (from livestock) and mineral fertiliser with corresponding losses, compost, biological fixation, nitrogen deposition (UBA 2015), yield, digestate from biogas plants and sewage sludge. An overview on inputs and outputs and on the corresponding methods used for calculating the different parameters is presented in Table 2.

Parameter	Indicator with quantification unit	Quantification method and data source	References
Nutrient input	Mineral fertiliser (kg N/ha*year)	Calculation of mineral fertiliser through estimation of: Mineral Fertiliser=1.06*Yield-0.6*(Organic Fertiliser+Digestate)-0.8*Biological Fixation	Taube et al. (2015), Bach et al. (2014)
	Organic fertiliser from livestock (kg N/ha*year)	Data on livestock from <i>Landwirtschaftszählung</i> 2010 (Statistikamt Nord 2010) ⁹ ; Data on annual N-production through manure from the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern (2008) ¹⁰	Taube et al. (2013)
	Digestate from biogas plants (kg N/ha*year)	Data on biogas plants from LLUR (2016) ¹¹ Calculation data for N-formation from digestate related to the average substrate composition (Taube et al. 2013); Reference values (e.g. average performance biogas plants) related to biogas plants in Schleswig-Holstein	Taube et al. (2013)
	Compost (kg N/ha*year)	Constant value from Heidecke et al. (2012)	Heidecke et al. (2012)
	Sewage sludge (kg N/ha*year)	Data on amount of sewage sludge (in 2011) and share applied on agricultural fields from <i>Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein</i> ¹² (Kleinhans 2013); N-content sewage sludge from Taube et al. (2013)	Taube et al. (2013)
	Biological nitrogen fixation (kg N/ha*year)	Data on land use (grassland and legumes) from <i>Landwirtschaftszählung</i> 2010 (Statistikamt Nord 2010); Data on efficiency of nitrogen fixation from Landwirtschaftskammer Niedersachsen (2017a) ¹³	DüV (2007) ¹⁴

	N-Deposition (wet, dry and occult) (kg N/ha*year)	Data on nitrogen deposition in Germany in 2009 for different land use types from <i>Umweltbundesamt</i> (UBA 2015)	-
Nutrient output	Yield (crop and grassland) (kg N/ha*year)	Data on yield for 2010 from <i>Landwirtschaftszählung</i> 2010 (Statistikamt Nord 2010); Data on N-content of grass/crop type from <i>DüV</i> (2007)	-
	NH ₃ loss from organic fertiliser (%)	Rates on nitrogen application and nitrogen input from <i>Landwirtschaftskammer</i> Niedersachsen (2017b)	<i>DüV</i> (2007)
	Loss through application of mineral fertiliser (%)	Rate for loss through application of mineral fertiliser calculated based on the nitrogen budget by Heidecke et al. (2012)	Heidecke et al. (2012)

Due to the data privacy law, data for some municipalities was not available on the scale of municipalities within the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010). In order to avoid such data gaps, the available data on the scale of municipalities was compared to the data on the scale of counties. The calculated differences between the two datasets were allocated to the affected municipalities. The relative extent of the agricultural area of the corresponding municipalities was used as a factor for the allocations.

With regard to the issue of scale, we used different spatial references for the nutrient budgets in the two case study areas. For the federal state of Schleswig-Holstein, we allocated the nutrient budgets solely to the corresponding municipalities. Thus, the resolution of the result corresponds to the resolution of the input data, the *Landwirtschaftszählung* (Statistikamt Nord 2010). In order to allow for comparability, we used the same approach in the Bornhöved Lakes District. However, in addition to that, aiming to assess the smaller case study area in more detail, we allocated the nutrient budgets to the respective areas within each municipality.

Organic fertiliser from livestock

The calculation of the nitrogen content of organic fertiliser from livestock was based on data from the Statistikamt Nord (2010), collected within the framework of the *Landwirtschaftszählung* 2010. The level of detail of the data varied - from *Großvieheinheit* (GVE)^{*15} over main livestock species to a precise register of all livestock, taking age and purpose of livestock into account. In order to ensure an optimal accuracy but also to prevent data complexities, data on the main livestock species were selected. In order to obtain the total amount of nitrogen used in the form of organic fertiliser, specifications of the nitrogen content of manure specified for the different evaluated livestock species were needed. For that, appendix five of the German fertiliser ordinance (*DüV* 2007) was accessed. However, the classification of livestock strongly differs in several points from the livestock classification given by the statistical data. Therefore, it was more convenient to

refer to the following publication with regard to the reference values of nitrogen concentrations in manure: *Richtwerte für die Untersuchung und Beratung zur Umsetzung der Düngeverordnung in Mecklenburg-Vorpommern* (Table 53) by the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern (2008)^{*16}. Still, some values needed to be calculated through averaging and/or summing up reference values of different categories because the classification did not correspond to the classification of the statistics precisely enough (Suppl. material 1).

Digestate from biogas plants

The substances used as substrate for biogas production in Schleswig-Holstein (manure, corn silage, cereal, grass silage, bio waste and remnants) were adopted from Taube et al. (2013). In conformity with Taube et al. (2013), the share of nitrogen from manure in the digestate was neglected in order to prevent double-counting. Taube et al. (2013) expect 5% nitrogen losses through storage. Taking this nitrogen loss into account, Taube et al. (2013) calculated that approximately 74 tonnes of nitrogen per megawatt installed electric power are generated in Schleswig-Holstein. By combining the data from Taube et al. (2013) with information on average biogas plant outputs in Schleswig-Holstein (Agentur für Erneuerbare Energien e.V 2017^{*17}) and general information on the performance of biogas plants (Bayerische Landesanstalt für Landwirtschaft 2008^{*18}), the overall nitrogen content of the digestate in Schleswig-Holstein in 2010 and the average nitrogen content per year and biogas plant were calculated.

Biological nitrogen fixation

Data from the *Landwirtschaftszählung 2010* (Statistikamt Nord 2010)^{*19} served as the basis for the calculation of the biological nitrogen fixation. The extent of grassland in each municipality was multiplied by the nitrogen fixation efficiency (Landwirtschaftskammer Niedersachsen 2017a^{*20}). The Landwirtschaftskammer Niedersachsen (2017a) differentiates between varying shares of legumes in the grassland (between 5 and 40 %). The values of nitrogen fixation concerning the shares of legumes were averaged. The result was multiplied by the area of grassland in each municipality. Data on the cultivation of legumes was only available for counties and the computed amount of nitrogen fixation through legumes added up to less than 0.2 kilograms of nitrogen per hectare. Therefore, nitrogen fixation through pure legume cultivation was neglected.

Sewage sludge

Data on the amount of sewage sludge applied to agricultural soils in Schleswig-Holstein was available for the year 2011 by Kleinhans (2013) from the MELUR. In order to obtain data on nitrogen input through sewage sludge in agricultural fields, a reference value for the nitrogen content in sewage sludge was taken from Taube et al. (2013) and multiplied with the amount of sewage sludge. We divided the total nitrogen content by the agricultural area of Schleswig-Holstein. The result shows the average amount of nitrogen input per hectare on agricultural soils in Schleswig-Holstein.

Compost

As no statistical data was found on the quantity of compost applied to agricultural soils in Schleswig-Holstein, the values computed by Heidecke et al. (2012) were used in this study. The authors determined the average amount of nitrogen input per hectare on agricultural soils in Schleswig-Holstein through the application of compost.

Nitrogen deposition

The data on nitrogen deposition in 2009 was provided by the UBA (2015). The data was available for all of Germany. The total nitrogen deposition values combine wet, dry and occult nitrogen deposition. Differentiating ten different land use types (grassland, semi-natural, arable, permanent crops, coniferous forest, deciduous forest, mixed forest, water, urban and others), spatially differentiated deposition values were available for the whole study area.

Yield

Information on the area used for the different crop types was available from the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010), on the spatial scale of municipalities. However, no precise information was given on the actual yield. Yield quantity was only available for higher administrative units. In order to enable the calculation on the level of municipalities, the average yield (t/ha*year) was calculated for each crop type. We then multiplied the outcome by the data available at the municipality level. Specifications of the nitrogen content of the evaluated crop plants were also needed and were taken from the DüV (2007)²¹. In the DüV (2007), the authors distinguish between different crude protein contents for each crop type. As this information was not available for the crops in Schleswig-Holstein, average values were selected. Suppl. material 2 lists the values utilised for the calculation of the nitrogen content per crop type. The specified nitrogen content per crop type was defined as the nitrogen content which is removed as primary or secondary product from the field. Thus, the nitrogen content of standard remnants was not included in the analysis (KTBL 2009).

Loss of nitrogen in organic fertiliser from stable, storage and application

According to the Landwirtschaftskammer Niedersachsen (2017b)²², which refers to the DüV (2007), the application and the input of nitrogen from organic fertiliser (manure) can be differentiated. The application of organic fertiliser from livestock considers nitrogen losses which are attributed to losses in the stable and losses resulting from the storage of fertiliser. In contrast to that, the input of nitrogen from organic fertiliser also considers nitrogen losses which occur during the application of the fertiliser. The Landwirtschaftskammer Niedersachsen (2017b) differentiates the nitrogen loss factor between different manure types (e.g. liquid manure and solid manure). For this study, average loss values for all manure types were taken into account (Suppl. material 3).

Loss through application of mineral fertiliser

We used the data computed by Heidecke et al. (2012) and calculated a loss rate based on the nitrogen budget for 2010 on the level of municipalities in Schleswig-Holstein.

No specifications on import and export of fertilisers were available on the relevant spatial scales. Therefore, the nitrogen budget was computed assuming that no import and export occurred. The same applies for digestate from biogas plants. The final budget calculation is similar to the formula used by Bach (Taube et al. 2015, Bach et al. 2014). However, because our parameters differ from the parameters selected by Bach et al. (2014), the formula was slightly modified, resulting in the following:

$$\text{Budget} = \text{Mineral Fertiliser} + \text{Organic Fertiliser} + \text{Digestate (excl. Manure)} + \text{Biological Fixation} + \text{Nitrogen Deposition} + \text{Compost} + \text{Sewage Sludge} - \text{Yield} - \text{Loss of Organic Fertiliser (Stable, Storage and Application)} - \text{Loss of Mineral Fertiliser (Application)}$$

The nitrogen status

In order to assess the potential ecosystem service supply and demand, two more important datasets were collected: groundwater nitrate concentration and the nitrate leaching potential. After nitrogen is introduced into the environment, the potential for the ecosystem to regulate nitrogen inputs influences the quantity of nitrogen available for nitrate leaching. However, the actual nitrate leaching is also dependent on other factors. The *Landesamt für Landwirtschaft, Umwelt und ländliche Räume* (LLUR 2011a) assessed the nitrate leaching potential in Schleswig-Holstein. According to the LLUR (2011a), the following factors are relevant for computation: soil type and texture, soil horizon classification, humus content, state of decomposition, state of consolidation, substance volume, leak water rate, mean capillary rise, precipitation and the climatic water balance. The data were classified into categories from one to five, whereby five represents the highest nitrate leaching potential. Data on the measured nitrate concentration in the groundwater bodies in Schleswig-Holstein were downloaded from the online portal "*Wasserkörper- und Nährstoffinformationssystem Schleswig-Holstein*" (MELUR 2016) for the year 2013. In order to obtain continuous spatial data, the measured values were interpolated using the IDW interpolation method (software: ArcMap 10.3).

The measured groundwater nitrate concentration was defined as the focal indicator for the nitrogen status in the study area. The influence of the ecosystem service nutrient regulation, the nitrate leaching potential and the actual nitrogen budget on the nitrogen status in the study area was tested. In order to analyse this relationship statistically, the correlations between the parameters were calculated for Schleswig-Holstein and the Bornhöved Lakes District. In order to assess the issue of scale and spatial resolution, in total five different datasets (Table 3) were statistically analysed.

A rank-order correlation analysis was executed, whereby the parameters groundwater nitrate concentration, nitrogen budget, nitrate leaching potential and nutrient regulation

potential were incorporated. According to literature, the following correlations were expected: nitrogen surpluses correlate positively to the groundwater nitrate concentration (Wick et al. 2012, Power 2010, Rumohr et al. 1996, European Council 1991, Tivy 1987). In addition to that and in consistency with the assumptions and definitions given in this study, a negative correlation was expected between the nutrient regulation potential and the groundwater nitrate concentration (Gaines and Gaines 1994). As explained earlier, the LLUR assessed the nitrate leaching potential incorporating several site-specific characteristics. Thus, we expect that a positive correlation exists between the nitrate leaching potential and the groundwater nitrate concentration. As a consequence, a negative correlation presumably will arise between the nitrate leaching potential and the nutrient regulation potential. The correlation between the nitrogen budget and the nutrient regulation potential allowed us to draw conclusions on the coincidence of ecosystem service potential supply and demand.

Table 3.

Datasets used for the statistical analysis.

Dataset	Study area	Grid/ Scale*23	Budget reference
SH_M	Schleswig-Holstein	Municipalities	Municipalities
SH_LG	Schleswig-Holstein	Large grid	Municipalities
B_LG_B2	Bornhöved Lakes District	Large grid	Municipalities
B_LG_B4	Bornhöved Lakes District	Large grid	CORINE Land Classes
B_FG_B4	Bornhöved Lakes District	Fine grid	CORINE Land Classes

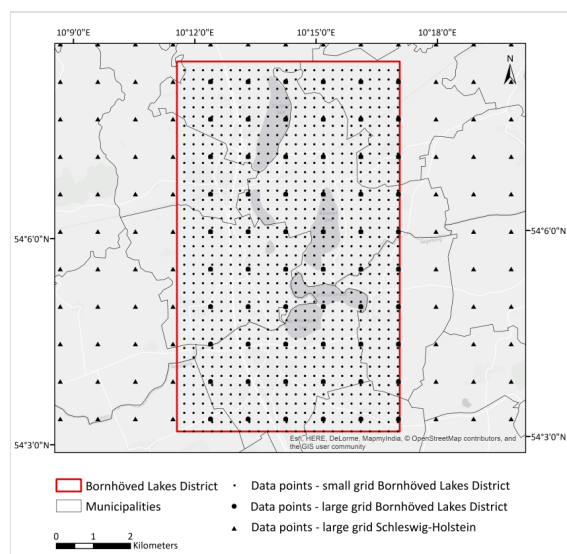


Figure 5.

Assessment units for Schleswig-Holstein and the Bornhöved Lakes District: Large and fine point grid (data on administrative boundaries from GeoBasis-DE / BKG 2017b).

First, the statistical analysis was executed for average values from each municipality. Second, the same analysis was executed using an original values excerpt via a point grid (approximately 1 kilometer spacing). A spatially more explicit analysis was executed for the Bornhöved Lakes District case study area. Here, the nitrogen budget was allocated to the corresponding CORINE land cover classes, thereby generating a spatially more explicit demand for nutrient regulation. In addition to the point grid, an additional finer point grid was created with approximately 250 m spacing (Fig. 5). The rank-order correlation analysis was repeated for these datasets.

Fig. 6 gives a schematic overview on the workflow to compute potential supply and demand for the ecosystem service nutrient regulation and on the statistical analyses.

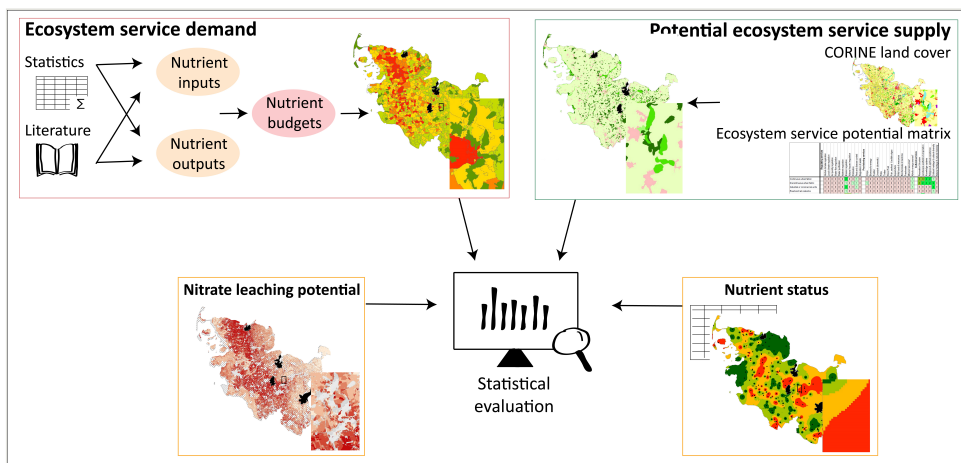


Figure 6.

Overview of the methodological procedure for the assessments of the ecosystem service nutrient regulation and the nutrient status on the two scales Schleswig-Holstein and Bornhöved Lakes District (CORINE = Coordination of Information on the Environment²⁴).

Results

Supply of nutrient regulation

The potential supply of the nutrient-regulating ecosystem service was evaluated and mapped for Schleswig-Holstein and the Bornhöved Lakes District using the ecosystem service matrix (Burkhard et al. 2014) based on CORINE land cover types (Fig. 4). The qualitative values on nutrient regulation for the matrix assessment have been adopted from Burkhard et al. (2014) (p. 15). In Table 4, the relevant values are shown. Fig. 7 shows the spatial distribution of the ecosystem service nutrient regulation potential supply.

Table 4.

Adopted ecosystem service potential supply values for nutrient regulation. Scale 0 = no relevant potential; 1 = low relevant potential; 2 = relevant potential; 3 = medium relevant potential; 4 = high relevant potential; 5 = very high (maximum) relevant potential (based upon Burkhard et al. (2014)).

LULC classes	Nutrient regulation potential
Continuous urban fabric	0
Discontinuous urban fabric	0
Industrial or commercial units	0
Road and rail networks	0
Port areas	0
Airports	0
Mineral extraction sites	0
Dump sites	0
Construction sites	0
Green urban areas	2
Sport and leisure facilities	1
Non-irrigated arable land	1
Permanently irrigated land	1
Ricefields	1
Vineyards	1
Fruit trees and berries	2
Olive groves	1
Pastures	1
Annual and permanent crops	1
Complex cultivation patterns	1
Agriculture & natural vegetation	2
Agro-forestry areas	2
Broad-leaved forest	5
Coniferous forest	5
Mixed forest	5
Natural grassland	4

Moors and heathland	3
Sclerophyllous vegetation	2
Transitional woodland shrub	2
Beaches, dunes and sand plains	1
Bare rock	0
Sparsely vegetated areas	1
Burnt areas	0
Glaciers and perpetual snow	0
Inland marshes	4
Peatbogs	4
Salt marshes	2
Salines	0
Intertidal flats	1
Water courses	3
Water bodies	3
Coastal lagoons	3
Estuaries	3
Sea and ocean	3

The largest part of the study area is characterised by low nutrient-regulating potentials (Fig. 7). High regulatory potentials are distributed rather patchily over Schleswig-Holstein. However, areas with high potentials are agglomerated in the south and southeast of the study area (Fig. 7). Consistent with the distribution of the nutrient regulation potential in Schleswig-Holstein, the largest part is also featured with rather low nutrient regulation potentials, with similar potentials also being evident in the Bornhöved Lakes District. Medium and high potentials can be found mainly in the central part of the area. There are also areas with no relevant nutrient regulation potential. These are distributed randomly throughout both study areas.

Demand for nutrient regulation

The largest oversupply of nitrogen can be found in municipalities located in the northwest of the study area (Fig. 8). An agglomeration of municipalities with relatively low nitrogen budgets (lower than 40 kilograms of nitrogen per hectare per year) is located in the southeast of the study area. With regard to the regional landscapes, municipalities in the *Geest* show a tendency for larger nitrogen surpluses. There, the nitrogen budget increases from south to north. In the Bornhöved Lakes District, the majority of municipalities have a

nitrogen budget lower than 40 kilograms per hectare per year. Municipalities with higher nitrogen budgets can be found in the west of the study area. The municipality with the highest nitrogen surplus is Ruhwinkel. Compared to the adjacent municipalities, Ruhwinkel is featured by relatively high nitrogen inputs through the application of digestate and organic fertilisers from livestock.

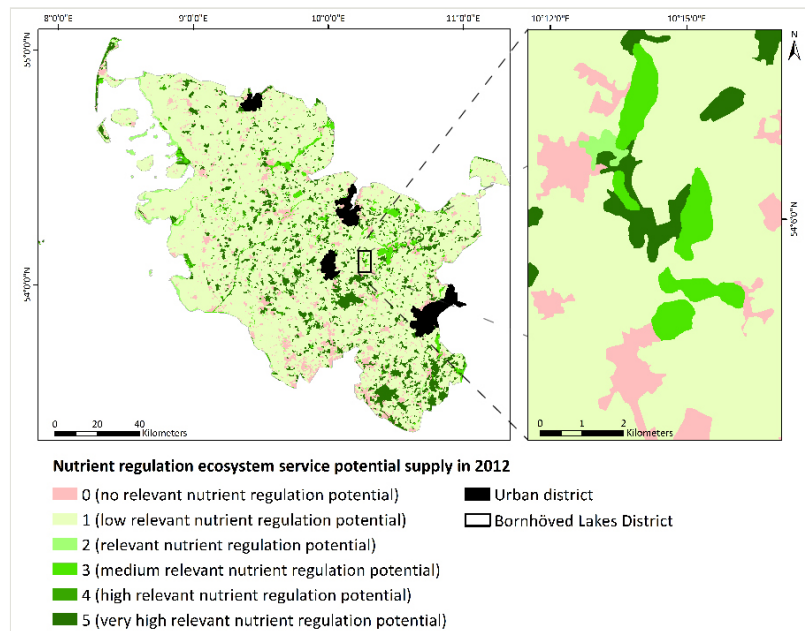


Figure 7.

Nutrient regulation ecosystem service potential supply in 2012 in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) (application of ecosystem service potential matrix by Burkhard et al. 2014; CORINE Land Cover data from GeoBasis-DE / BKG 2017a).

For the Bornhöved Lakes District, the nitrogen budget was mapped in a spatially more explicit manner (Fig. 9). In the first step, the nitrogen budget was mapped excluding nitrogen deposition. Furthermore, the remaining nitrogen budget was not assigned to the corresponding municipalities, but assigned to the CORINE LULC classes “land principally occupied by agriculture” (243), “non-irrigated arable land” (211) and “pastures” (231) in the corresponding municipalities. Thus, areas with CORINE classes, other than these, have a nitrogen budget equal to zero. High nitrogen budgets (61 - 80 kg N/ha*year) can be found in the west of the Bornhöved Lakes District. Medium nitrogen budgets are located in the south; the remaining area shows low nitrogen budgets. In the next step, atmospheric nitrogen deposition was mapped separately. The greatest share of the area is characterised by nitrogen deposition rates between 16 and 18 kilogram nitrogen per hectare per year. Higher and lower nitrogen deposition values are distributed rather randomly throughout the study area. In the third and last step, both values were combined in order to obtain the total nitrogen budget. The largest share of the area shows medium

nitrogen budgets (41 – 60 kg N/ha*year). Very low and low budgets are distributed randomly throughout the Bornhöved Lakes District and can be found along the eastern border of the study area, respectively. High nitrogen budgets are located in the southwest and southeast. The relatively high nitrogen inputs on the agricultural grounds that belong to the municipality of Ruhwinkel can still be identified.

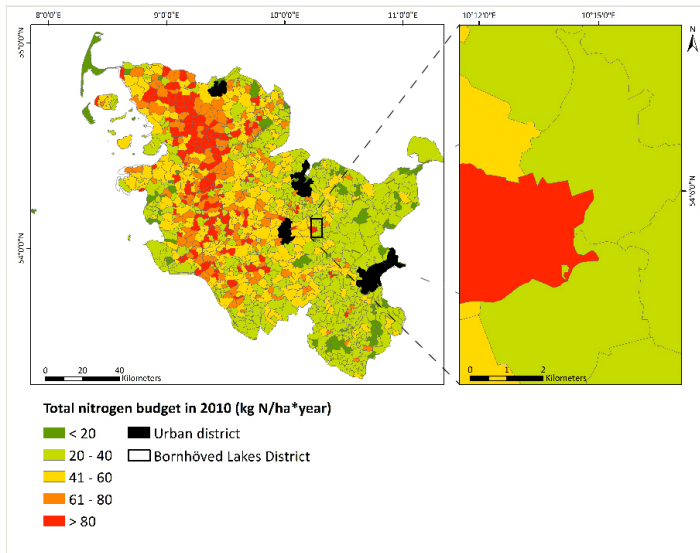


Figure 8.

Total nitrogen budget in 2010 in Schleswig-Holstein Holstein (left) and the Bornhöved Lakes District (right) on the municipality scale (data on agricultural census 2010 from Statistikamt Nord 2010²⁵; data on nitrogen deposition 2009 from UBA 2015; data on administrative boundaries from GeoBasis-DE / BKG 2017b).

The nitrogen status

Consistent with Taube et al. (2015) and the Nitrate Directive (European Council 1991), the groundwater nitrate concentration was selected as the focal indicator for the nitrogen status of the environment. It can be assumed that responses to changing parameters (i.e. nitrogen budget) can be detected in the measured nitrate concentration after a specific time lag (Rumohr et al. 1996). In order to take that time lag into account and remain in accordance with recent publications on the nutrient status of Schleswig-Holstein (e.g. Taube et al. 2015), data from 2013 was selected.

In 2013, the groundwater nitrate concentration was distributed rather heterogeneously (Fig. 10). Lowest concentrations (<10 mg/l) were found in the northeast (from Flensburg to Eckernförde) of Schleswig-Holstein and along the central part of Schleswig-Holstein's North Sea coastline. Hotspots of nitrate concentrations were distributed rather patchily throughout the federal state, mostly in the hinterland. The largest area with relatively high nitrate concentrations (>50 mg/l) was located in the east of Schleswig-Holstein. In the

remaining part, medium concentrations (10-50 mg/l) were mostly dominant. The Bornhöved Lakes District is located at the western boundary of the largest hotspot. Thus, high nitrate concentrations (>50 mg/l) were found in approximately half of the case study area. From southeast to northwest, the nitrate concentrations decreased. However, only a very small part of the Bornhöved Lakes District showed low nitrate concentrations (<10 mg/l).

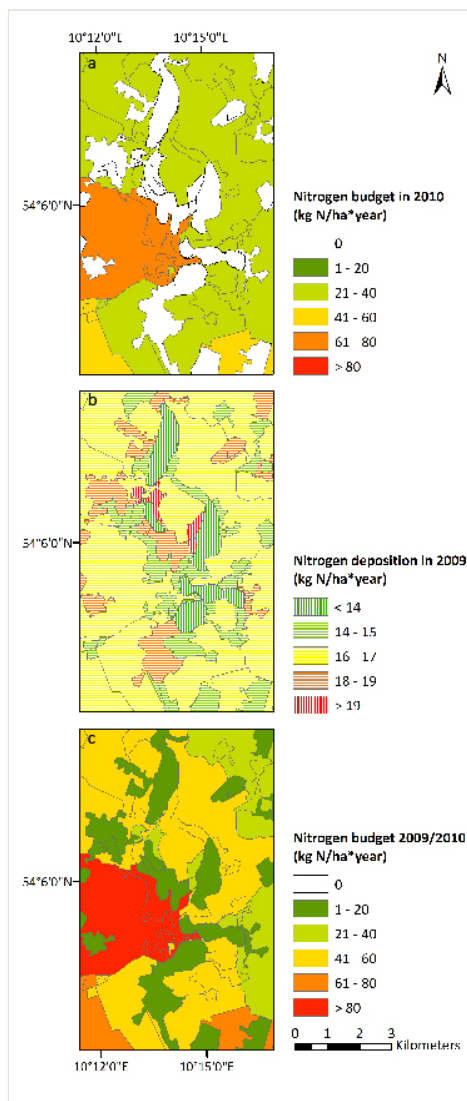


Figure 9.

Nitrogen budgets in the Bornhöved Lakes District: (a) nitrogen budget 2010 (excl. nitrogen deposition) for each municipality allocated to arable land, (b) atmospheric nitrogen deposition in 2009, (c) total nitrogen budget 2009/2010 (data on agricultural census 2010 from Statistikamt Nord 2010²⁶; data on nitrogen deposition 2009 from UBA 2015).

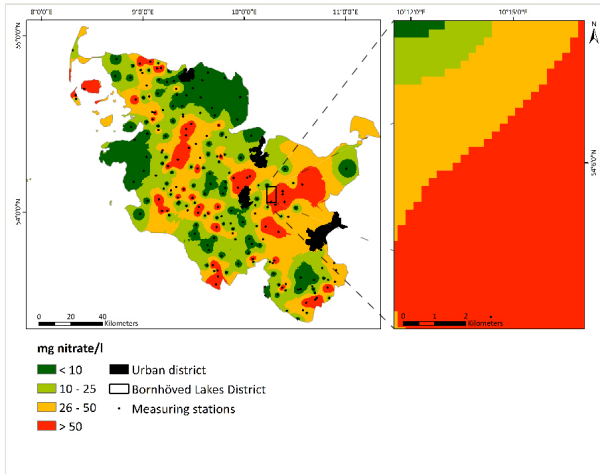


Figure 10.

Interpolated groundwater nitrate concentration in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) in 2013 (data from *Wasserkörper- und Nährstoffinformationssystem Schleswig-Holstein* from the MELUR 2016).

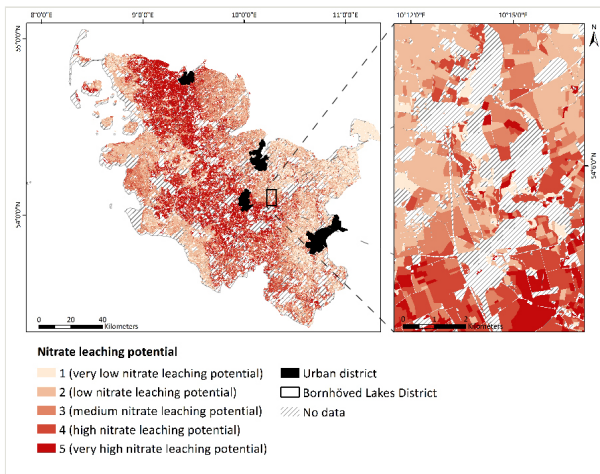


Figure 11.

Nitrate leaching potentials in Schleswig-Holstein (left) and the Bornhöved Lakes District (right) (data from LLUR 2011b).

Low nitrate leaching potentials can be found along both coastlines of Schleswig-Holstein (Fig. 11). Lowest potentials agglomerate at the central part of the Baltic Sea coastline. High potentials are located in the hinterland, increasing from south to north. Thus, the area with high potentials coincides with the spatial extent of the *Geest*. In accordance with this pattern, in the Bornhöved Lakes District, the potential decreases from south to north (Fig. 11).

Statistical evaluation

In contrast to the datasets for the area of Schleswig-Holstein, all datasets on the scale of the Bornhöved Lakes District revealed a negative correlation between the nutrient regulation potentials and the groundwater nitrate concentrations (Fig. 12). For all of these datasets, the correlations are calculated to be significant at the 0.05 level. In addition, for all datasets on the scale of the Bornhöved Lakes District, stronger positive correlations were found between the nitrate leaching potential and the groundwater nitrate concentration compared to the Schleswig-Holstein datasets. As expected for these datasets, negative correlations exist between the nitrate leaching potential and the nutrient regulation potential, even though none of these correlations is statistically significant. Except for the dataset on the municipality scale (SH_M), the correlation analysis revealed negative correlations between the nitrogen budgets and the groundwater nitrate concentrations. Both datasets for the area of Schleswig-Holstein reveal a very weak negative correlation between the nitrogen budget and the nutrient regulation potential. Focusing on to the Bornhöved Lakes District, the dataset with the lowest resolution (BLD_LG_B2) indicates a positive correlation between these two variables. However, for both Bornhöved Lakes District datasets, including the spatially more explicit nitrogen budget (BLD_LG_B4 and BLD_FG_B4), stronger negative correlations can be found between the nitrogen budget and the nutrient regulation potential. Only for the dataset with the highest spatial resolution can this correlation be found significant.

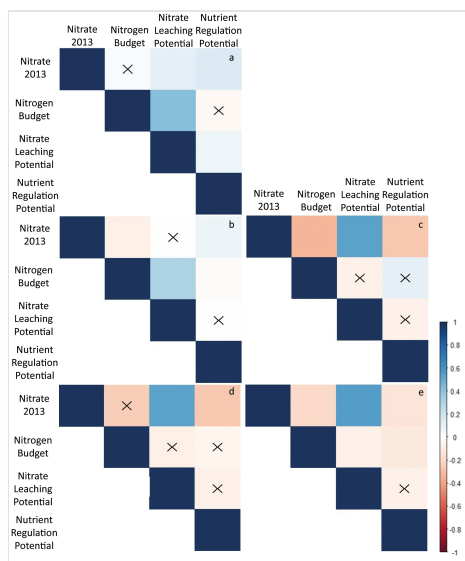


Figure 12.

Correlograms for each dataset (a: SH_M; b: SH_LG; c: B_LG_B2; d: B_LG_B4; e: B_FG_B4; for explanation see Table 3) including nutrient regulation potentials, nitrate leaching potentials, nitrogen budgets and groundwater nitrate concentrations (cross indicates insignificant correlation at the 0.05 level).

Discussion

Spatial distribution of supply and demand potentials

The potential supply of nutrient regulation seems to be distributed randomly throughout the study areas Schleswig-Holstein and Bornhöved Lakes District. Small- and medium-sized patches of high nutrient regulation potentials are scattered throughout a landscape dominated by low nutrient regulation potentials. The biogeochemical properties of different nutrients vary and, as a result, the corresponding processes in the environment also change. For reasons of simplification, we analysed the ecosystem service nutrient regulation by using the nutrient nitrogen as an example. Here, one must note that the potential supply values for nutrient regulation which have been adopted from the expert-based assessment by Burkhard et al. (2014), do not differentiate between different nutrients. The potential supply is thus not specifically harmonised for nitrogen but depicts a more general trend. Furthermore, the spatial distribution modelling was solely dependent on the primary vegetation and land use pattern, because the potential supply of nutrient regulation was mapped qualitatively based on the matrix values provided by Burkhard et al. (2014) and CORINE land cover classes. As nutrient regulation is dependent on further parameters such as soil type, texture and moisture, it is questionable whether the allocation of nutrient regulation potentials, based solely on land cover classes, is sufficient in order to characterise local conditions and nutrient regulation is dependent. However, this approach is an efficient way to gain an overview of the investigated study areas. The quantification of the demand for nutrient regulation on the municipality scale supports the assumption by Taube et al. (2015) on the regional differentiation of the nitrogen budget in Schleswig-Holstein. A tendency for higher nitrogen budgets in the west of the study area was identified, which partly confirms the nitrogen budgets published by Taube et al. (2015) (p. 19). In addition, the relative distribution of the nitrogen budget, to a large extent, conforms to the nitrogen budget calculated on the scale of landscape forms, published by Taube et al. (2015) (p. 20). In the Bornhöved Lakes District on the municipality scale, high nitrogen budgets were found in the west. The greatest share of the area had relatively low nitrogen budgets (<40 kg N/ha*year). However, the spatially more explicit nitrogen budgets revealed a more heterogeneous picture. Low nitrogen budgets (<40 kg N/ha*year) could only be found along the eastern border of the study area and in small fragments throughout the Bornhöved Lakes District. High nitrogen budgets (>60 kg N/ha*year) could still be found in the west but also in the southeast of the study area. The remaining area showed medium nitrogen budgets (41-60 kg N/ha*year).

With respect to nitrogen budgets, the following aspects need to be kept in mind: The computation of the nitrogen budget is highly dependent on input data. Most parameters were based on the data of the *Landwirtschaftszählung* 2010 (Statistikamt Nord 2010²⁷). Due to data privacy, the agricultural census data on the scale of municipalities was not complete, as some data had been censored. The data had been corrected on the municipality scale in order to obtain more realistic results. Still, the correction factor for the municipalities is solely based on the extent of the agricultural area in the corresponding

municipality. This extrapolation may downgrade the obtained results. The parameters relevant for the nitrogen budget could be calculated by employing different calculation techniques and methodologies. Thus, the nitrogen budgets are influenced by the selected approach. For instance in this study, nitrogen inputs from organic fertilisers (livestock) were corrected by stable, storage and application losses, as the DÜV (2007) allows the input values to be corrected by these parameters, even though these emissions will also end up in a waterbody, eventually. The same is true for the deduction of nitrogen losses through the application of mineral fertilisers.

The methodology employed for the calculation of mineral fertiliser inputs was adopted from Taube et al. (2015) (p. 14) which is based upon Bach et al. (2014) (p. 18) and consists of a calculation which estimates mineral fertiliser quantities in relation to the quantities of organic fertiliser, digestate, biological fixation and yield for the area of Schleswig-Holstein in 2010. The approach by Taube et al. (2015) is based on data from 416 model farms (adapted from 14,700 real farms – InVeKoS²⁸ data, <https://www.zi-daten.de/>). Taube et al. (2015) claim to provide a more realistic nitrogen budget. However, their input data and model were not available for this research. Thus, this methodology could not be adopted for comparison.

One must also keep in mind that, for the calculation of the nitrogen input through biological nitrogen fixation, the nitrogen fixed by legume cultivation was neglected because the relevant data was not available on the municipality scale but only on the county scale and only added up to 0.2 kilograms of nitrogen per hectare in 2010. Another point of potential criticism may arise from the fact that the analysis of this study did not consider seasonal variability. Rumohr et al. (1996) report, amongst others, on the seasonal variability of groundwater nitrate concentrations in the Bornhöved Lakes District. The variability can primarily be attributed to the diverging nitrogen assimilation through plants throughout the year (Rumohr et al. 1996). None of this information could be checked by this study.

Nutrient status and statistical evaluation

The groundwater nitrate concentrations, which served as indicators for the nutrient status, were found to be distributed heterogeneously. The distribution partly followed a trend expected from the distribution of the nitrate leaching potential and the computed nutrient budget. In the north and west of the federal state, the occurrence of high groundwater nitrate concentration was roughly located in areas with high nutrient budgets and high nitrate leaching potentials. These conditions were particularly found in the area of the *Geest*. Conforming to the poor sandy soils of the *Geest* area, the nitrate leaching potentials were relatively high. The same co-occurrence was found for low concentrations and potentials.

In the eastern part of Schleswig-Holstein, the groundwater nitrate concentration cannot be easily explained by the distribution of the nitrogen budget and nitrate leaching potential. Even though, the area is characterised by low to medium nitrate-leaching potentials as well as relatively low nutrient budgets, a large area is featured by relatively high groundwater nitrate concentrations. As the Bornhöved Lakes District is located at the western boundary

of the hotspot, high groundwater nitrate concentrations (>50 mg/l) were found in approximately half of the case study area, declining from southeast to northwest. This trend follows the distribution of the nitrate leaching potentials. In order to find out more about the interrelations of the datasets, including the potential supply of the ecosystem service nutrient regulation, a statistical evaluation was performed in the form of a rank-order correlation analysis. The parameters, nitrogen budget, nutrient regulation potential, nitrate leaching potential and groundwater nitrate concentration, were correlated with each other for all different datasets (Fig. 12).

The correlation analysis revealed a positive correlation between the nitrate leaching potential and the groundwater nitrate concentration. This correlation was expected. For the Bornhöved Lakes District, this correlation was stronger than for the datasets covering the whole federal state. The correlation between nutrient regulation potential and the groundwater nitrate concentration only fulfilled the (expected) negative correlation for the Bornhöved Lakes District. As a consequence, the same was true for the correlation between the nitrate leaching potential and the nutrient regulation potential. It is noticeable that the spatially more explicit datasets indicated a negative correlation between the nitrogen budget and the nutrient regulation potential. This correlation implies that there is a spatial mismatch between the ecosystem service potential supply and demand in the study area. The more aggregated nitrogen budget datasets suppress this condition. However, the statistical analysis could not prove the expected positive influence of the nitrogen budget on the groundwater nitrate concentration. This circumstance provokes the question whether the groundwater nitrate concentration dataset is suitable as a nitrogen status indicator as the opposite effect could be expected from existing knowledge (Wick et al. 2012).

Previous publications (Taube et al. 2015, Rumohr et al. 1996) and Directives have specified groundwater nitrate concentration as an indicator for the nitrogen status of an area. On this account, the same indicator was selected for this research. Official data on groundwater nitrate concentrations at the measuring stations was provided by the MELUR (2016) in the online portal [Wasserkörper- und Nährstoffinformationssystem Schleswig-Holstein](#). Thus, the same data on nitrate concentrations in Schleswig-Holstein's groundwater bodies as in previous studies were used in this study. The data available from the measuring stations was interpolated (employed interpolation method: IDW) for the whole study area. The fact that this indicator is not based on a spatially continuous original dataset but only on approximately 230 values (measuring stations) for the whole area of Schleswig-Holstein has to be considered a limitation. This limitation became even more evident for the Bornhöved Lakes District, because only one original data point is located within the study area (Fig. 10). The surrounding area of the Bornhöved Lakes District with high groundwater nitrate concentrations is also featured by only a few measuring stations. This circumstance decreased the certainty and the accuracy of the extent of the groundwater nitrate concentration hotspots and may lead to incorrect correlations with regard to the nutrient status. Rumohr et al. (1996) measured groundwater nitrate concentrations in the Bornhöved Lakes District in the first half of the 1990s at eight measuring stations. They discovered that the groundwater nitrate concentrations on agricultural grounds were higher compared to other ecosystems. It can be assumed that the results of the statistical analysis

with such accurate data on the current groundwater nitrate concentrations would correspond better with the expected values. Besides, the diverse measurement and quantification units of the different parameters also decrease the explanatory power of the statistical analysis. In particular, the comparison between physical entities (i.e. kilogram nitrogen per hectare per year) and the specification of nutrient regulation potential and nitrate leaching potential on a relative scale from zero and one to five, can lead to decreasing quality of the outcomes.

Still, by evaluating the results of the statistical analysis, it was possible to rank the relative validity of the results according to the spatial resolution and scale/study area (Fig. 13). For that matter, the validity of the outcomes was defined as the degree of conformity of the results with the expectations gained from the literature review. The results on the smallest scale with the finest grid and the highest spatial differentiation were found to deliver the most valid results. Whereas the computation of average values on the municipality scale led to imprecise or even incorrect data. The fact that municipalities are administrative with no geological or natural units most likely emphasises the inexpediency of the averaged values.

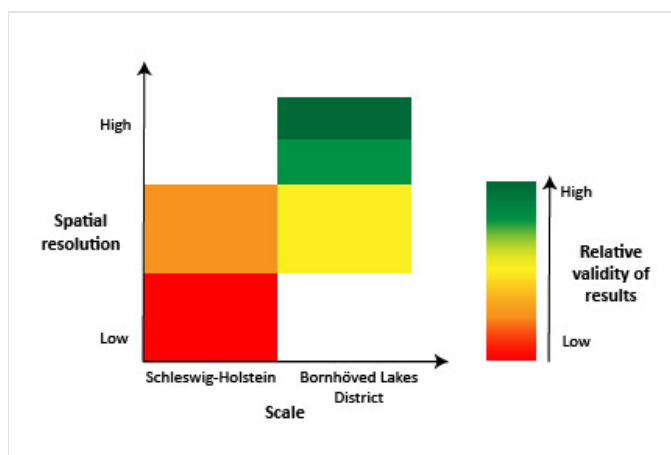


Figure 13.

Relative dependency between validity of results, scale and spatial resolution.

Relevance for land management and ecosystem service research

The results obtained by this research contribute to the recently ongoing debate on the topic of nutrient management. On the one hand, the research supports the suggested regional differentiation (Taube et al. 2015). On the other hand, the methodological uncertainties detected confirm the necessity for strict regulations with regard to the application as well as declaration of all kinds of fertilisers on farmland. In order to determine the value of this study for ecosystem service research, one needs to highlight the general picture rather than the explicit results obtained from this research. Contrary to the theoretical evaluation

of the ecosystem service concept, the integration of ecosystem services in applied sectors such as environmental management features challenges (de Groot et al. 2010). Egoh et al. (2007) state, amongst others, that the integration of ecosystem services into different research areas lags behind. Another gap exists between the theory and practice with regard to the quantification of ecosystem services (Crossman et al. 2013). Hou et al. (2013) go even further by pointing out uncertainties evolving from ecosystem services research on the landscape scale. Amongst others, uncertainties originate from respondents' preferences (in expert-based approaches), initial data uncertainty, technical problems, methodological uncertainties and complexities of natural systems (Hou et al. 2013).

Burkhard et al. (2012a) executed research with regard to mapping of ecosystem service supply, demand and budgets. They state that the “[...] supply of multiple goods and services by nature should match the demands of society, if self-sustaining human-environmental systems and a sustainable utilization of natural capital are to be achieved” (Burkhard et al. 2012a, p. 1). According to them, suitable indicators are required and diverse datasets need be integrated for assessments of both supply of and demand for ecosystem services on different temporal and spatial scales. Methods for ecosystem service quantifications are diverse, from mapping, modelling and field measurements to expert opinion (see *ESMERALDA*²⁹ project). According to Seppelt et al. (2011), the methodologies should be weighted differently according to the reliability of the data and results.

As specified in Chapter 2, ecosystem services are defined as the benefit human beings experience from the environment. The definition implies the existence of a demand by human society (Burkhard et al. 2012a). This study deals, to a great extent, with the identification of the demand for the ecosystem service nutrient regulation. Through the calculation of nutrient budgets in the study areas, nutrient surpluses were identified. As eutrophication has been recognised as a threat to society in research as well as in decision-making, the localisation of hotspots emphasises the demand for the ecosystem service nutrient regulation in the study areas. The practical implementation through this study confirms the constraints identified in current research (Schulp et al. 2014, Hou et al. 2013). Constraints arise from the usage of different methodologies and datasets for the computation of supply and demand of/for the ecosystem service as well as from the comparison of a rather abstract concept to specific data on nitrogen surplus. The results from the statistical analysis support this notion. In order to combat this issue, more research is necessary assessing the practical implementation of ecosystem services and, as specified by Hou et al. (2013), on ecosystem service assessments on the landscape scale in general.

Further research

In the meantime, it would be interesting to undertake the calculation of mineral fertiliser according to Taube et al. (2015) on the municipality scale. Most likely, higher and more realistic mineral fertiliser quantities will emerge. More accurate information on fertiliser

usage will increase the validity of the results and thereby enhance the usability of results for decision-making and sustainable land management. For future works, it is also of interest to assess the nutrient situation detached from administrative units, e.g. subdividing the study areas into catchment areas rather than municipalities. The outcome of the correlation analysis supports the usefulness of the transformation from administrative boundaries to natural boundaries. Besides, it would be interesting to assess the potential supply of nutrient regulation in more depth. A quantification of the potential nutrient regulation, incorporating side-specific characteristics such as data on soil types and textures, is an interesting approach, worthy of pursuing.

Conclusions

With regard to nutrient regulation in Schleswig-Holstein and the Bornhöved Lakes District, the potential supply and demand of/for nutrient regulation have been analysed using the example of nutrient nitrogen. Revising the objectives of the study, the following outcomes can be stated:

1. Assessing the potential supply and demand of/for nutrient regulation in the study areas. The greatest share of Schleswig-Holstein and the Bornhöved Lakes District are featured by a low potential supply of nutrient regulation. Areas with no or higher potential supply are spread out in patches of varying size throughout the study areas. In Schleswig-Holstein, a slight tendency for a greater share of relatively high potential supply can be detected in the southeast. In the Bornhöved Lakes District, there is a slight agglomeration of patches with higher potential supply in the centre and in the northeast. The distribution of the demand for nutrient regulation in Schleswig-Holstein indicates a clearer trend. Municipalities with low demand are located in the southeast. Municipalities with high values are agglomerated in the northwest of the study area. In the Bornhöved Lakes District, the demand for nutrient regulation is highest in the west. **Do potential supplies and demands of/for nutrient regulation coincide in Schleswig-Holstein and the Bornhöved Lakes District?** No, in both study areas, relatively high demands for nutrient regulation coincide with low potential supplies of this ecosystem service.
2. Testing the statistical relationship amongst the nitrogen budget, nutrient regulation potential, nitrate leaching potential and the actual nutrient status of the study area. The statistical analysis implies that there is a positive relationship between the nitrate leaching potential and the groundwater nitrate concentration. Contrary to the data on Schleswig-Holstein, focusing on the Bornhöved Lakes District, the analysis revealed the expected negative relation between the ecosystem service potential nutrient regulation and the nutrient status. Contradicting the assumptions, the analysis cannot prove the positive effect of the nitrogen budget on the nutrient status. **Is it possible to prove the influence of the ecosystem service nutrient regulation on the nutrient status statistically?** Yes, but only for the smaller case study area, the Bornhöved Lakes District, where the statistical evaluation revealed

the regulative influence of the ecosystem service on the nutrient status defined as the groundwater nitrate concentration.

3. Giving useful advice on the usability of the different methodologies and scales assessed. When comparing the nitrogen budgets in the Bornhöved Lakes District on the municipality scale with the spatially more explicit nitrogen budgets, it can be stated that relevant information is lost through the aggregation according to administrative boundaries. Hotspots of high nitrogen budgets vanish and a relatively homogenous picture arises. It is relevant that the calculation and aggregation of environmental data on administrative units were accompanied by a loss in accuracy and even validity of the data. In this study, such an aggregation led to incorrect assumptions on the correlations between relevant parameters. In order to prevent data falsification, original data resolution should be retained. In addition, the study has shown that, by increasing the spatial differentiation of the input data, the validity of the results is improved to a large extent. In addition, a decrease in grid size influenced the results positively. However, this occurred to a less extreme extent than the spatial differentiation of the input data. **Does higher resolution data result in more valid outcomes?** Yes, the evaluation of the results shows that by increasing the resolution of data, the results become more appropriate and applicable.

In this study, the theoretical concept of regulating ecosystem services was applied to a land management issue which is highly relevant for decision-making on the scale of the study area and beyond. The study gives insight into the nitrogen situation in landscapes of Schleswig-Holstein. The results confirm the recently ongoing debate on the issue of fertiliser usage with regard to the environmental burden as well as the regional differentiation. The application of the ecosystem service concept allowed the comparison of the potential nutrient regulation supply and demand and revealed general and specific spatial mismatches between both. Moreover, the study also ascertained a regional differentiation for this mismatch. The *Geest*, which is most vulnerable to nitrogen surpluses because of the poor sandy soils which add to the high nitrate leaching potential of the area, was identified as the hotspot for a diverging potential supply and demand of nutrient regulation. It is of great relevance to strictly regulate agricultural nutrient inputs through organic (livestock and digestate) as well as mineral fertilisers in order to attain sustainable land management which is mandatory for securing the functionality and quality of our environment, most notably our soils and water bodies, our food and health.

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Supplementary materials

Suppl. material 1: Nitrogen excretion of livestock [doi](#)

Authors: Bicking et al.

Data type: table

Brief description: Nitrogen excretion (in kg N/year) of livestock (data from the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern 2008)

Filename: Appendix 1.pdf - [Download file](#) (366.34 kb)

Suppl. material 2: Average yield of agricultural crops in Schleswig-Holstein in 2010

[doi](#)

Authors: Bicking et al.

Data type: table

Brief description: Average yield (in t/ha) of agricultural crops in Schleswig-Holstein in 2010 (data from Statistikamt Nord 2010), nitrogen content (in kg N/dt fresh weight) of crop plants (data from DüV 2007) and corresponding estimated nitrogen content per hectare.

Filename: Appendix 2.pdf - [Download file](#) (456.61 kb)

Suppl. material 3: Relevant nitrogen application and input rates [doi](#)

Authors: Bicking et al.

Data type: table

Brief description: Relevant nitrogen application and input rates considering nitrogen losses (data from Landwirtschaftskammer Niedersachsen 2017b).

Filename: Appendix 3.pdf - [Download file](#) (322.77 kb)

Endnotes

- *1 eng.: State Agency for Agriculture, the Environment and Rural Areas
- *2 http://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm
- *3 <http://www.esmeralda-project.eu/>
- *4 eng.: Statistical Agency North
- *5 eng.: uplands
- *6 eng.: State Agency for Agriculture, the Environment and Rural Areas
- *7 <http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-types-2006>
- *8 eng.: agricultural census 2010 (Statistical Agency North)
- *9 eng.: agricultural census 2010 (Statistical Agency North)
- *10 eng.: Ministry of Agriculture, Environment and Consumer Protection in Mecklenburg-Vorpommern
- *11 eng.: State Agency for Agriculture, the Environment and Rural Areas
- *12 eng.: Ministry of Energy, Agriculture, the Environment and Rural Areas
- *13 eng.: Chamber of Agriculture Lower Saxony
- *14 eng.: German fertilizer ordinance
- *15 eng.: livestock unit
- *16 eng.: Ministry of Agriculture, Environment and Consumer Protection in Mecklenburg-Vorpommern
- *17 eng.: Renewable Energies Agency
- *18 eng.: Bavarian State Research Center for Agriculture
- *19 eng.: agricultural census 2010 (Statistical Agency North)
- *20 eng.: Chamber of Agriculture Lower Saxony
- *21 eng.: German fertilizer ordinance
- *22 eng.: Chamber of Agriculture Lower Saxony
- *23 see Figs 3, 5
- *24 <http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-types-2006>
- *25 eng.: Statistical Agency North
- *26 eng.: Statistical Agency North
- *27 eng.: agricultural census 2010 (Statistical Agency North)
- *28 eng.: Integrated Administration and Control System (IACS)
- *29 <http://www.esmeralda-project.eu/>

4

Refining the quantification of the nutrient regulation ES demand

Publication title:

Quantification and mapping of the nutrient regulation ecosystem service
demand on a regional and local scale

Bicking, S., B. Steinhoff-Knopp, B. Burkhard and F. Müller

Submitted to: Ecosystems and People

in review

In this paper, the methodology to assess the demand for the ES nutrient regulation was refined and applied in another study area on different spatial scales: on the scale of municipalities and on the scale of individual field parcels in the county of Höxter. According to the spatial scale and the corresponding available input data, the methodology was adjusted. Agricultural management options, such as crop rotation, were considered in the assessment on the scale of the individual field parcels. The calculated ES demand was compared to the spatial distribution of the nitrate leaching and denitrification potential.

Quantification and mapping of the nutrient regulation ecosystem service demand on a regional and local scale

Sabine Bicking ^{a*}, Benjamin Burkhard ^{b,c}, Bastian Steinhoff-Knopp ^b, Felix Müller ^a

a) Institute for Natural Resource Conservation, Department of Ecosystem Management, Christian Albrechts University Kiel, Olshausenstr. 40, 24098 Kiel, Germany

b) Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany

c) Leibniz Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany

*Corresponding author: sbicking@ecology.uni-kiel.de

Abstract

Within this study, the nutrient regulation ecosystem service (ES) demand was quantified and mapped on two different spatial scales in an agriculturally-dominated landscape in the federal German state of North Rhine-Westphalia. The demand was assessed in the county of Höxter on the municipality scale (regional scale) and in a case study area on the individual field scale (local scale). As an indicator for the nutrient regulation ecosystem service demand, nitrogen budgets were calculated. The assessment includes a comparison of an *agriculturally* calculated nitrogen budget and an *ecologically* calculated nitrogen budget. The agricultural calculation is oriented toward legal regulations and considers volatile nitrogen losses from fertilizers, whereas the ecological calculation incorporates the total amount of nitrogen and includes also the atmospheric nitrogen deposition. Furthermore, on the local scale, the positive effects of further agricultural practices (a.o. crop rotation) on the nutrient regulation ES demand were identified. The spatial distribution of the nutrient regulation ES demand was compared to the distribution of the nitrate leaching and denitrification potential in order to analyze the relative vulnerability of the individual fields to nutrient oversupply. The findings of this study can be used to support sustainable agricultural practices and land management strategies on the local scale.

Keywords: Nutrients, nitrogen budget, farming practices, crop rotation, nitrate leaching potential, denitrification potential, vulnerability assessment

1 Introduction

The excess of nutrients in agricultural systems leads to high nutrient losses, which pose a serious threat to the environment. Lost nitrogen and phosphate degrade ground- and surface water quality and threaten biodiversity as well as the climate (Sutton et al. 2013; Kuhn 2017; Taube 2018). The enrichment of nutrients in water bodies leads to eutrophication (Welte and Timmermann 1985; Fu et al. 2012; Chislock et al. 2013; Dominati 2013; Jónsson et al. 2016; Jónsson and Davídsdóttir 2016). Through eutrophication processes, the ecological status of water bodies is endangered, for instance through the excessive growth of phytoplankton and macroalgae, harmful algal blooms and especially the formation of hypoxic zones (Selman and Greenhalgh 2009). In order to reduce these effects, the German Fertilizer Ordinance (dt.: Düngeverordnung, DüV, 2017) implements the EU Nitrates Directive 91/676/EEC into national regulations, aiming to reduce nitrate (NO_3^-) emissions from the agricultural sector into water bodies (The European Council 1991; DüV 2017; Kuhn 2017). Initiated by infringement proceedings of the European Commission against Germany concerning the national nutrient situation, the DüV (2017) as well as the German Fertilizer Law (2017) have recently been revised. The modified DüV includes measures limiting the amount of applied fertilizers, measures concerning management and technical practices as well as sanctions for violating these regulations (DüV 2017; Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018).

The concept of ecosystem services (ES) has been developed in order to increase the understanding of the interrelations between human activities and the environment. Ecosystem services are defined by Burkhard et al. (2012a) as “[...] the contributions of ecosystem structure and function – in combination with other inputs – to human well-being”. ES analyses aim, amongst others, to assess the capacity of ecosystems to provide desired benefits. Thus, they are convenient to support sustainable land management (Smith et al. 2012). This is highlighted by the adoption of the ES concept in policies addressing ecological threats. Within the Biodiversity Strategy to 2020, the European Union has asked its member states to map and assess the states of their ecosystems and the services they provide (Maes et al. 2012). Thus, this study is executed in a highly relevant framework integrating contemporary research and assessment approaches as well as political requirements.

The ES concept defines ecosystem properties and conditions as the functional base for an ecosystem to deliver a certain ES (Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017; Maes et al. 2018). Ecosystem properties and conditions correspond to biophysical structures and processes (Maes et al. 2014; Burkhard and Maes 2017; Syrbe et al. 2017). The ecosystem condition is associated with the ecological integrity (EI) of an ecosystem (Syrbe et al. 2017) and represents its general functionality (Müller and Burkhard 2012; Schneiders and Müller 2017). It is determined by the physical, chemical and biological characteristics, structures and quality features of an ecosystem (Maes et al. 2014; Erhard

et al. 2017; Maes et al. 2018). The evaluation of the ecosystem conditions is highly relevant for a comprehensive ES assessment (Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017).

Generally, ES can be divided into three main categories; provisioning, regulating and cultural ES (Kandziora et al. 2013; Burkhard et al. 2014; Soheli et al. 2015; Stoll et al. 2015; Haines-Young and Potschin 2017; Schneiders and Müller 2017). In the context of this study, the regulating ES nutrient regulation was assessed (for definition see section 2.2). Within the ES concept, the *ES potential* has been defined to refer to the hypothetical maximum yield of selected ES (Burkhard et al. 2014), whereas the *ES flow* describes ES that are actually used in a specific area and time, driven by a *demand* for ES (Syrbe et al. 2017). The potential and demand for the ES nutrient regulation have been assessed in previous studies (Barrios 2007; de Bello et al. 2010; Bicking et al. 2018; Bicking et al. 2019). Thereby, the ES concept has been proven to be a suitable approach for assessing the nutrient situation within the agricultural context (Power 2010; Willemsen et al. 2017). The suitability of the ES concept is supported in particular by the strong dependence of agricultural systems on ES on the one hand and the provision of ES in the form of e.g. crop production on the other hand (Power et al 2010).

Bicking et al. (2018) quantified the nutrient regulation ES demand by calculating a nitrogen budget in the federal German state of Schleswig-Holstein on the spatial scale of municipalities. Besides scientific publications on the assessment of the nutrient regulation ES and the calculation of a nitrogen budget (Leip et al. 2011; Eurostat 2013; Özbek and Leip 2015), also the DüV (2017) was considered in this study. Thereby, aspects concerning fertilizer management and the calculation of nutrient budgets were reviewed. Based upon the literature research, two different methodologies were developed for calculating the nitrogen budget; a nitrogen budget from the agricultural and a nitrogen budget from the ecological perspective (for more information see section 3.1).

Another objective of this study was the comparison of the nutrient regulation ES demand on different spatial scales. Therefore, the nutrient regulation ES demand was quantified and mapped on the municipality scale (regional scale) in the county of Höxter and on the scale of individual fields (local scale) in the case study area Eversen. The primary focus of this study lied on the quantification of the nutrient regulation ES demand on the field scale. Nitrogen and phosphorus are the two nutrients which mostly limit production in both natural and agricultural systems (Vitousek et al. 2002). Therefore, they are commonly applied to agricultural grounds in vast amounts (Vitousek et al. 1997; Aulakh and Malhi 2005; Power 2010). Based upon its relevance for crop production (Bruns 2012) and the contemporary discussions and the infringement proceedings of the European Commission against Germany concerning the national nutrient situation, the calculation was executed exemplarily for the nutrient nitrogen.

The study includes an evaluation of the effects of different agricultural practices on the nutrient regulation ES demand. Different crop rotation systems, as well as further management options, were considered in the local assessment and their influence on the nutrient regulation ES was evaluated. Subsequently, the spatial distribution of the nutrient regulation ES demand was compared and linked to the nitrate leaching and denitrification potential in order to perform a vulnerability analysis. A vulnerability analysis evaluates the weakness of a system in consideration of a potential threat (Wisner et al. 2004; Weißhuhn et al. 2018). In this study, the vulnerability of the system in regard to nutrient surplus was assessed. The assessment aimed to analyze the spatial distribution of the damage potential of excess nutrient loads based upon the environmental and management constellations and could operate as an early warning system identifying hotspot areas (Weißhuhn et al. 2018).

The overall objective of this study was to generate knowledge on the agricultural nutrient situation on the regional and local scale in the study area. In this regard, the authors compared the results on the two spatial scales. Above all, the study aimed to deliver findings which can support the development of sustainable strategies for local land management and agricultural practices.

The study was guided by the following three research questions:

1. Does the calculated nutrient regulation ES demand in the case study area Eversen resemble the nutrient regulation ES demand on the scale of the municipalities in the county of Höxter?
2. Do the calculated nitrogen budgets depend on agricultural practices such as crop rotation, the establishment of flower strips and fellow land?
3. How can nitrate leaching and denitrification potentials be used in the assessment of the nutrient regulation ES?

In the following section, background information on the study area, the ES nutrient regulation and the investigated crop rotation is given. Thereafter, the materials and methods used in the study are introduced, followed by a description of the results. The findings of the study are discussed and finally, conclusions are drawn with regard to the study objectives and the corresponding research questions outlined above.

2 Background information

In the following section the study area, the ES nutrient regulation, as well as the potential influences of crop rotation, are introduced.

2.1 Study area

The study area is located in the county Hoexter in the federal state of North Rhine-Westphalia (NRW), Germany (Figure 1). The study area is part of the natural regions Lippe Uplands (dt.: Lipper Bergland),

Oberwälderland, Warburger Börde and Egge region (dt.: Egge). The annual mean temperature and precipitation in the area are 9.9°C and 918 mm (Deutscher Wetterdienst 2019), respectively. The municipality Nieheim within the county Höxter is of primary importance for the study, as the agricultural grounds of the cooperating farmer are located within this municipality, close to the village Eversen. Eversen, with a population of 472 people, belongs to the city of Nieheim (Kreis Höxter 2018). This focal study area, which is called Eversen due to its proximity of the respective village, is situated between 135 and 231 m above sea level. The soil types Luvisol and Cambisol are dominating the landscape, which is primarily used as agricultural land (Geologischer Dienst NRW 2016b; Geologischer Dienst NRW 2016a). Structural elements, such as hedgerows and trees, divide the agricultural fields and increase the diversity and heterogeneity of the landscape (UIH Ingenieur- und Planungsbüro 2016). Geologically, the area is featured by the lower and middle Keuper materials from the Triassic period (Geologischer Dienst NRW 2016b). The focal study area around Eversen is located at the southern border of the Lippe Uplands (von Zezschwitz 2001). The Lippe Uplands belong to the main landscape type of the German Central Uplands and have a spatial extent of approximately 1087 km² (Andres 1989; Bundesamt für Naturschutz 2012). The landscapes of the Lippe Uplands are featured by strong variations in relief such as rounded peaks, steep ridges, hills and flat depressions. Within the Lippe Uplands, the case study area is situated in the Steinheimer Börde, a fertile loess region (Andres 1989; UIH Ingenieur- und Planungsbüro 2016).

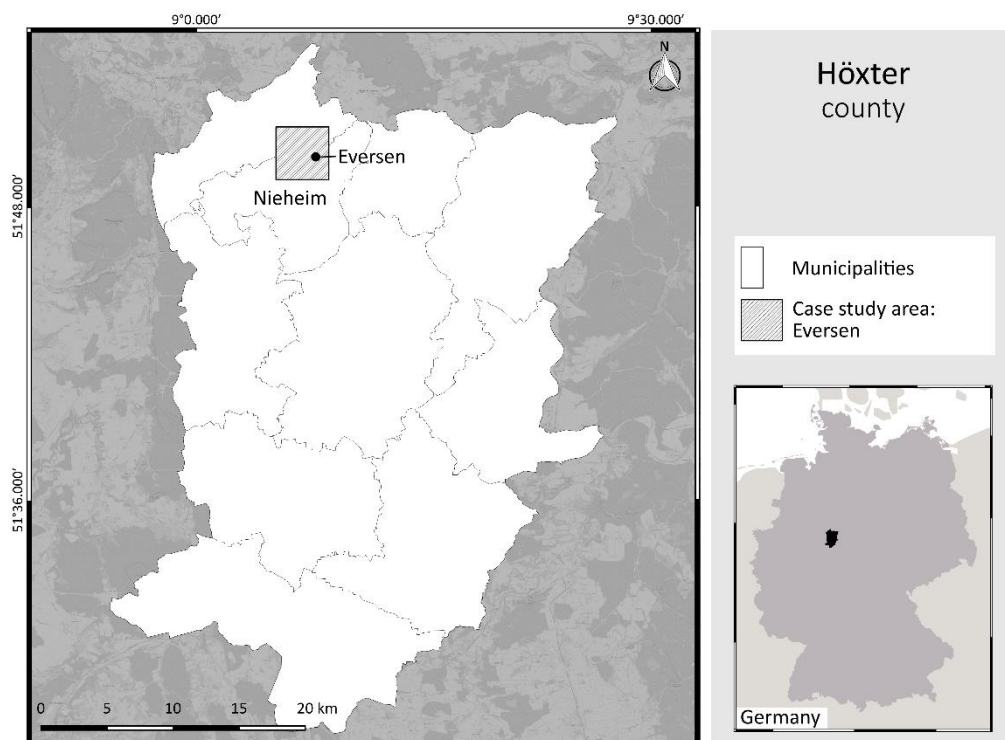


Figure 1: Location of the study areas Höxter and Eversen (base maps: OpenStreetMap, 2019 and GeoBasis-DE / BKG, 2019).

2.2 Nutrient regulation

Nutrient regulation, the ability of an ecosystem to recycle nutrients (Burkhard et al. 2014), is a major concern when it comes to agricultural practices and land management. Due to intensive agricultural practices, natural nutrient cycles have been altered (Vitousek et al. 1997). For instance, through the application of vast amounts of fertilizers onto the grounds, the naturally closed nutrient cycles are opened up (Tivy 1987; Chapin et al. 2002). This means, that in- and outputs of nutrients are getting out of balance. As a result, areas might suffer from either nutrient deficiency or nutrient oversupply (Sutton et al. 2011b; Sutton et al. 2011a; Sutton et al. 2013; Özbek and Leip 2015).

The application of vast amounts of nutrients can increase short term biomass production (Vitousek et al. 2002). However, this increased production comes with side costs (Galloway et al. 2004; Drinkwater and Snapp 2007; Vitousek et al. 2009; Power 2010). The oversupply of nutrients in agricultural systems leads to high nutrient losses which pose a serious threat to the environment. Nitrogen and phosphate degrade the ground- and surface water quality and threaten biodiversity and the climate (Sutton et al. 2013; Kuhn 2017; Taube 2018). Enrichment of nutrients in water bodies leads to eutrophication (Welte and Timmermann 1985; Fu et al. 2012; Chislock et al. 2013; Dominati 2013; Jónsson et al. 2016; Jónsson and Davídsdóttir 2016). Besides, high groundwater nitrate concentration can pose a significant risk to human health (Follett and Follett 2001; Townsend et al. 2003; Galloway et al. 2004; Umweltbundesamt 2018a).

Another aspect worth of mentioning is the fact that livestock farmers need to get rid of the manure and slurry produced on their farms. Therefore, the application of organic fertilizer onto agricultural fields often has two targets, disposing manure and slurry on the one hand and supplying nutrients to the agricultural grounds on the other hand. Of course, the application of nutrients should be driven by the nutrient demand of the crops rather than a.o. the storage capacities of manure holding tanks. Usually, further intensive agricultural practices come along with the vast application of nutrients; monoculture or short-term crop rotations, intensive tillage and application of plant protectants, just to name a few (Power 2010). All of these measures aim to increase one single ES, crop production. However, these practices degraded the environment and decrease the condition of the ecosystem and thereby the potential supply of other ES (Baulcombe et al. 2009; Power 2010; Bruns 2012). Accessorily, these circumstances also decrease the future potential of the ecosystem to provide the ES crop production. Thus, even though the application of vast amounts of nutrients can increase a single ES in the short-run, the long-run provision of multiple ES is diminished (Power 2010). In order to guarantee for long-term food security and thus human health, it is of great importance to ensure sustainable nutrient situations, where in- and outputs of nutrients are in balance (Baulcombe 2009; Vitousek et al. 2009). The ES nutrient regulation supports these targets, securing sustainable nutrient cycles (Tivy

1987). As outlined in the introduction, the federal republic of Germany is subject to nutrient surplus situations rather than nutrient deficiencies. The spatial distribution of the nutrient surplus in Germany exhibits regional differences with the highest nitrogen surpluses in the Northwest and Southeast of the country (Klement and Bach 2017).

As a consequence of the vast applications of both organic and mineral fertilizer onto the agricultural grounds in Germany, the nutrient concentration of a large share of the ground and surface waters is dramatically high. For instance, in many cases, the critical limit for the nitrate groundwater concentration of 50 mg/l was exceeded (Court of Justice 2018; Umweltbundesamt 2018b). According to the Umweltbundesamt (2018a), 27,1 % of the 1200 groundwater bodies in Germany were in a bad chemical condition with reference to nitrate (> 50 mg N/l) in 2017. Also, the groundwater body located in the center of Höxter was defined to be in a bad chemical state with reference to nitrate concentrations in 2017 (Umweltbundesamt 2018a). In addition to the environmental motivations, the limit of the nitrate concentration of 50 mg/l arises from the human health perspectives outlined above (Umweltbundesamt 2018a). In particular, young infants are highly sensitive to acute exposure of high nitrate concentrations. This aspect emphasizes the imperative to comply with the critical limit for the nitrate groundwater concentration. Therefore, there is a high demand for the ES nutrient regulation. In that sense, both, policy and the society as such, striving for a clean environment and compliance with the regulations, can be defined as beneficiaries of the ecosystem service (Villamagna et al. 2013; Bicking et al. 2018). Power (2010) mentions a different perspective and states that the agroecosystem provides and consumes ES, simultaneously. In order to ensure for instance a stable supply of the provisioning ES crop production, agroecosystems are strongly dependent on other (mainly regulating) ES, such as nutrient regulation (Power 2010; Burkhard et al. 2012b).

In the context of the ES nutrient regulation, studies also refer to the capacity of ecosystems to provide filtering, absorption and retention of nutrients (Dominati 2013; Jónsson et al. 2016; Jónsson and Davídsdóttir 2016). Thus, the ES nutrient regulation ensures a functioning and sustainable nutrient cycle (Tivy 1987). The capacity of ecosystems to provide nutrient regulation differs. More natural ecosystems have in general, based for instance on higher biodiversity, more stable structures and functions as well as more mature matter and water cycles, higher capacities to provide multiple regulating ES, including nutrient regulation (Fu et al. 2012; Burkhard et al. 2014). Concurrently with the biogeochemical properties of different nutrients, the corresponding processes in the environment differ. In that respect, it needs to be considered that this study only deals with the nutrient nitrogen. As outlined above, the sustainable management of nitrogen supports long-term crop production and at the same time prevents excess quantities of nitrogen to enter and consequently pollute the environment.

2.3 Crop rotation

Crop rotation refers to the sequence of specific crops planted on one field, whereby the succeeding crop belongs to a different family than the previous crop (PAN Germany 2010). Crop rotation is crucial in supporting the long-term productivity of crop cultivation. Proper crop rotation reduces weed and disease pressure, preserves soil fertility and at the same time secures economic viability (Bruns 2012; Bayerische Landesanstalt für Landwirtschaft 2016). The following advantages can be gained using crop rotation (European Commission – DG ENV 2010; PAN Germany 2010; VALERIE 2017):

- Preventing soil depletion
- Improving or maintaining soil fertility
- Reducing soil erosion
- Controlling insect/mite pests
- Reducing the build-up of pests
- Preventing diseases
- Controlling weeds
- Spreading the workload on time
- Mitigating risk of weather changes
- Limiting dependence on agricultural chemicals

In general, crop rotation affects different highly relevant environmental issues, such as species diversity, biodiversity at the landscape level, soil fertility and soil health, water and climate change (European Commission – DG ENV 2010; Bruns 2012). As crop rotation is such an integral part of sustainable land management, it is addressed in different policies at the EU level. The 2003 Common Agricultural Policy (CAP, European Commission 2019) demands farmers to maintain their fields in a Good Agricultural and Environmental Condition (GAEC). One of the defined standards of the GAEC deals with crop rotation. The Agri-Environmental Measures (AEM) aim to encourage farmers by using financial means to apply agricultural production methods, which sustain and/or enhance the environmental condition (European Commission; The European Council 2005). The financed AEMs may include measures on crop rotation. In addition to that, the European policy on organic farming (The European Council 2007) holds crop rotation as keystone aiming for holistic sustainable farming management. In the form of enhanced crop management (e.g. intercropping, soil covers) and crop-specific guidelines, crop rotation was included within the Nitrate Directive (The European Council 1991). The significance of crop rotation within EU policies underlines the high relevance of this agricultural practice. Therefore, management options with regard to crop rotation have been considered within this study. In order to identify the effects of different crop rotation systems on the nitrogen budget, the nitrogen budget were calculated for different crop rotation systems. Table 1 gives an overview of the crop rotation systems, which have been considered within this study. The 4-year cycle crop rotation systems listed in the table have formerly been employed in the case study

area. Nowadays, the farmer changed to the 5-year crop rotation systems, including grass/clover cultivation.

Table 1: Crop rotation systems considered in the calculation of the nitrogen budgets.

Crop rotation cycle	Crop types			Note
4 years	Rapeseed	Silage maize	Field bean	Former systems
	Wheat			
	Triticale			
	Barley			
5 years	Rapeseed	Silage maize	Field bean	Current systems
	Grass/clover			
	Wheat			
	Triticale			
	Barley			

3 Material and Methods

Subsequent to the information on the research objective of the study and the knowledge outlined in the previous sections, the following section provides insights into the applied methods and underlying datasets. The differences between the *agricultural* and *ecological nitrogen budgets* are outlined in detail with regard to the considered parameters and their calculations.

3.1 Nitrogen budget

The methodological elaboration for the calculation of the nitrogen budget has been influenced by the DüV (2017). As stated in the introduction, the DüV (2017) is the German legislation limiting nutrient emissions from the agricultural sector, implementing regulations specified in the EU Nitrates Directive (The European Council 1991). In the following section, relevant aspects of the DüV (2017) are summarized. Only aspects, which are relevant for the study, are considered. The summary focusses on information on fertilizer application planning and the calculation of the nutrient balance emphasizing all matters related to nitrogen.

Concerning the obligatory fertilizer application planning, the DüV (2017) defines default nutrient requirements for agricultural plants. In this context, also certain correction values related to the yield are specified (DüV 2017; Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018). Considering the N requirements, thresholds for mineral fertilizer applications are dependent on N delivery from the soil and from organic fertilizers. For the N delivery from organic fertilizer, only a specified share of the original N application has to be considered. Certain circumstances, such as

specific weather conditions, may allow for a correction of the calculated limit (DüV 2017; Kuhn 2017; Taube 2018). Nutrient contents of manure may be measured or default values from the DüV (2017) may be used for fertilizer planning. The Nitrates Directive limits the application of manure N to 170 kg per hectare and year. The DüV (2017) maintains the threshold but considers additional (plant-based) nutrient sources, such as digestate from biogas plants and compost, and lowers default loss factors considering potential losses in the stable and during application. However, the threshold is calculated on farm level and does not need to be met on each individual plot (The European Council 1991; DüV 2017; Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018; Taube 2018).

The DüV (2017) specifies regulations concerning the calculation of nutrient balances, covering the methodological approach, surplus thresholds and sanctions. The nutrient balance is calculated as a surface balance for N and P, whereby the nutrient removal through harvest is subtracted from the nutrient inputs via organic and/or mineral fertilizers (DüV 2017; Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018; Taube 2018). For nutrient inputs via manure, default loss rates referring to NH₃ losses in the stable and during storage and application are subtracted. This applies for instance when slurry or solid manure from cattle are applied onto a field. For the nutrient balances, only 85% and 70%, respectively, of the nitrogen content of the applied organic fertilizer need to be accounted for. Again, default values for nutrient contents for manure and harvested products are specified in the DüV (2017). The calculated multi-year average surplus needs to comply with a certain threshold. Farmers may calculate the nutrient surplus at the farm-level or aggregate the calculation from an individual plot-level to farm level. Thus, the nutrient surplus refers to the average of the farm and not to single plots. Besides, only farms with specific size and intensity characteristics need to calculate nutrient balances (DüV 2017; Kuhn 2017).

The DüV (2017) specifies sanctions for violating the regulations concerning the nutrient surpluses. Besides, the DüV (2017) contains regulations concerning fertilizer blocking periods, respective manure storage capacities and manure application techniques (DüV 2017; Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018). The DüV (2017) empowers the federal states to prescribe farmers to submit their nutrient balance to the responsible institutions and the DüV (2017) specifies additional measures to be considered in so-called pollution hotspot areas. The respective federal states select three additional measures in minimum, which have to be taken in these areas (Kuhn 2017; Bundesanstalt für Landwirtschaft und Ernährung 2018). Summarizing, the DüV (2017) does not demand a plot-related recording of the actual fertilization, only the overall farm budget is relevant.

Consistent with the objective of this study, a methodology to calculate spatially explicit nitrogen budgets was developed. Next to the DüV (2017), further literature (Leip et al. 2011; Bach et al. 2014; Özbek and Leip 2015; Taube et al. 2015; Bicking et al. 2018) was used for the development of the

calculation methods. The nitrogen budgets were calculated on two different spatial scales: On the municipality scale in the county of Hötter (regional scale) and on the scale of individual fields of one farm in the investigation area Eversen (local scale).

According to Taube (2018), the share of organic fertilizer which is accounted for in the nutrient balances according to the DüV (2017) is too low, considering the technological development of the last 20 years aiming to increase the nutrient utilization rate. The DüV (2017) specifies the remaining share can be considered to be lost, whereas Taube (2018) claims, the values are well below the technical recommendations of the federal state authorities and also lower compared to the regulations in other countries (e.g. Denmark). He argues, that a necessary and technically meaningful differentiation of the values according to crop types or time of application was omitted and that altogether, the DüV (2017) has no effect with regard to better utilization of organic fertilizers and thus a reduction of nutrient losses into the environment.

Beside this criticism, from the ecological perspective the priority of the nitrogen budgets should be the generation of knowledge on the genuine nutrient situation, and aiming at maximizing crop production should only be the secondary target. Only then, the nutrient budgets can support sustainable agricultural practices. Therefore, two different calculations have been performed; an *agricultural nitrogen budget*, which considers the loss factors for the application of fertilizers, in line with the specifications in the DüV (2017), and an *ecological nitrogen budget*, which considers the total amount of fertilizer applied. In addition to that, the *ecological nitrogen budget* also considers atmospheric N-deposition as a nitrogen input parameter. Table 2 gives an overview of the parameters considered in the two different approaches.

Table 2: Parameters considered for the agricultural and ecological nitrogen budget calculation.

Parameter	Agricultural nitrogen budget	Ecological nitrogen budget
Mineral fertilizer	x	x
Organic fertilizer from livestock	x	x
Digestate from biogas plants	x	x
Compost	x	x
Sewage sludge	x	x
Biological nitrogen fixation	x	x
Atmospheric N-deposition		x
Yield	x	x
Fertilizer loss rates	x	

Even though the general approaches on the two spatial scales resemble each other, differences with regard to both methodology and data source arose. Therefore, the following section presents the approach on the two different spatial scales separately.

3.1.1 Municipality scale

On the municipality scale, the calculation has mainly been based on official regional statistics.

Table 3 summarizes the different parameters, which have been considered for the calculation of the nitrogen budgets, the respective methods and specific data sources that have been used.

Table 3: Overview of methodologies and data sources used for the parameters considered for the calculation of the nitrogen budget on the scale of the county and the municipalities (after Bicking et al. 2018).

Parameter	Indicator with quantification unit	Quantification methods and data sources
Nutrient input	Mineral fertilizer (kg N/(ha*year))	Calculation of mineral fertilizer through estimation of: $\text{Mineral fertilizer} = 1.06 \times \text{Yield} - 0.6 \times (\text{Organic fertilizer} + \text{Digestate}) - 0.8 \times \text{Biological fixation}$ (1) based upon Taube et al. (2015); Bach et al. (2014); Landwirtschaftskammer NRW (2018)
	Organic fertilizer from livestock (kg N/(ha*year))	Data on livestock from agricultural census 2016 by Landesbetrieb Information und Technik NRW (IT.NRW, 2016); data on annual N-production through manure from the Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern (2008)
	Digestate from biogas plants (kg N/(ha*year))	Data on average digestate application from the Nutrient Report NRW 2017 (dt.: Nährstoffbereich NRW, Landwirtschaftskammer Nordrhein-Westfalen 2018)
	Compost (kg N/(ha*year))	Data on average compost application from Nährstoffbericht NRW (Landwirtschaftskammer Nordrhein-Westfalen 2018)
	Sewage sludge (kg N/(ha*year))	Data on average sewage sludge application from Nährstoffbericht NRW (Landwirtschaftskammer Nordrhein-Westfalen 2018)

	Biological nitrogen fixation (kg N/(ha*year))	Data on cultivation (grassland and legumes) from agricultural census 2016 from IT.NRW (2016); average values on the efficiency of nitrogen fixation from Landwirtschaftskammer Niedersachsen (2016)
	N-deposition (wet, dry and occult) (kg N/(ha*year))	Data on nitrogen deposition in Germany in 2009 for different land use types from the Umweltbundesamt (UBA, 2009)
Nutrient output	Yield (crop and grassland) (kg N/(ha*year))	Data on crop cultivation and harvest from agricultural census 2016 (IT.NRW, 2016); data on N-content of grass/crop type from DüV (2017)
	Stable, storage and application loss rates (%)	Average deduction rates calculated based upon DüV (2017)

The calculation of the mineral fertilizer which is based on Taube et al. (2015) and Bach et al. (2014) is optimized for the nitrogen situation in the federal state of Schleswig-Holstein and has been applied in that spatial context (Taube et al. 2015; Bicking et al. 2018). In order to guarantee maximum accuracy of the estimation, the three constants of the equation (1.06, 0.6 and 0.8) would need to be adapted for the nitrogen situation in the municipalities of the county of Hötter according to Bach et al. (2014). However, due to data limitations, the constants of the equation were maintained. Nevertheless, in order to validate the findings, the results were compared to the data published in the Nutrient Report NRW 2017 by the Landwirtschaftskammer NRW (2018).

3.1.2 Field scale

The general structure of the nitrogen budget calculation on the individual field scale resembles the calculation described above. Most information was provided by the farmer, either from his field record system or through personal communication (Table 4). In the investigated period, no compost and sewage sludge have been applied onto the inspected fields. The crop type related agricultural practices considered in the nutrient budgets on the field scale are summarized in crop type specific profiles (Appendix 1).

Table 4: Overview of methodologies and data sources used for the parameters considered for the calculation of the nitrogen budget on the field scale.

Parameter	Indicator with quantification unit	Quantification methods and data sources
Nutrient input	Mineral fertilizer (kg N/(ha*year))	Data on application from field record system (von Ruschkowski 2018)
	Organic fertilizer from livestock (kg N/(ha*year))	Data on application from field record system (von Ruschkowski 2018); data on N-content of organic fertilizer from field record system (von Ruschkowski 2018) and from laboratory report by Landwirtschaftliche Untersuchungs- und Forschungsanstalt NRW (Landwirtschaftliche Untersuchungs- und Forschungsanstalt 2018)
	Digestate from biogas plants (kg N/(ha*year))	Data on application from field record system (von Ruschkowski 2018)
	Compost (kg N/(ha*year))	n/a
	Sewage sludge (kg N/(ha*year))	n/a
	Biological nitrogen fixation (kg N/(ha*year))	Data on cultivation (grassland and legumes) from field record system (von Ruschkowski 2018); data on specific efficiency of nitrogen fixation derived from Landwirtschaftskammer Niedersachsen (2016) and further sources (a.o. Loges et al. 1998; Sächsische Landesanstalt für Landwirtschaft 2007; Loges 2013)
	N-deposition (wet, dry and occult) (kg N/(ha*year))	Method and data source is adapted from the calculation on the scale of the municipalities
Nutrient output	Yield (crop and grassland) (kg N/(ha*year))	Yield estimated by the farmer; data on average N-content of grass/crop type from DüV (2017)
	Stable, storage and application loss rates (%)	Specific deduction rates based upon specification in field record system (von Ruschkowski 2018) according to DüV (2017)

3.2 Nitrate leaching and denitrification potential

The denitrification potential, represented by the denitrification rate in kg NO₃-N / ha / a, was evaluated and made available by the Geologischer Dienst (Geological Service) NRW (2017a). The Geologischer Dienst NRW (2017a) based the evaluation on information on a broad set of soil parameters including soil texture, soil-water condition and soil organic carbon. The dataset is provided as part of the soil map of North Rhine Westphalia on the scale 1:50'000 (Geologischer Dienst NRW 2017b). The nitrate leaching potential is represented by the *soil water exchange rate* in % / a. For the quantification of the soil water exchange rate, a method by Müller and Waldeck (2011) was applied, considering soil depth, texture, plant available water, yearly evapotranspiration and precipitation as well as the groundwater level. Soil data was obtained from the soil map of North Rhine Westphalia, climate data was provided by the Climate Data Center of the German Meteorological Service (DWD Climate Data Center 2018a; DWD Climate Data Center 2018b).

Data of the individual spatial components were mapped using the GIS software ArcGIS and QGIS. Besides, a statistical comparison of the maps was performed using R. For that matter, the map comparison statistic was adopted (Hagen-Zanker 2006; Schulp et al. 2014). The map comparison statistic summarises the relative differences of the compared maps (Schulp et al. 2014) and is calculated for each pair of maps based upon the following formula:

$$MCS = \frac{\sum_{n=1}^N \left(\frac{|a - b|}{\max(a, b)} \right)}{N} \quad (1)$$

Where *MCS* is the map comparison statistic, and *a* and *b* correspond to the normalized values of the assessed indicators (nitrogen budget, nitrate leaching potential and denitrification potential). The statistical analysis aims to identify the average difference between each pair of compared datasets (Hagen-Zanker 2006; Schulp et al. 2014; Ma et al. 2019).

Vulnerability analysis

Subsequently, the datasets were used for performing an ecosystem vulnerability analysis. As outlined in the introduction, vulnerability analyses aim to assess the weaknesses of a certain system in regard to a potentially harmful threat (Wisner et al. 2004; Weißhuhn et al. 2018). In our case, the potentially harmful threat is the surplus of nutrients, causing eutrophication. Vulnerability is commonly outlined as a function of exposure, sensitivity and adaptive capacity (Turner II et al. 2003; Füssel 2007; Frazier et al. 2014; Weißhuhn et al. 2018). Thereby, the exposure stands for the probability of the specific hazard, the sensitivity describes the susceptibility to the hazard and the adaptive capacity measures the ability of the system to deal with the hazard (Weißhuhn et al. 2018). Translated to the datasets of

this study, the nitrogen budget (nutrient regulation ES demand) was used as exposure to the hazard of nutrient oversupply. The nitrate leaching potential measures the sensitivity of the ecosystem and the denitrification potential assesses the adaptive capacity of the ecosystem to cope with the potential nutrient surplus. The spatial representation of the ecosystem's vulnerability allows for the identification of hotspot areas. Specific land management plans with regard to for instance protection can be developed for and implemented in these hotspots areas (Zurlini et al. 1999; Aretano et al. 2015). The relative vulnerability of the individual fields was estimated based on a GIS analysis. Therefore, the datasets of the nutrient regulation ES demand, nitrate leaching and denitrification potential were normalized and combined, weighted evenly (Appendix 2). Both the nutrient regulation ES demand and the nitrate leaching potential increase the relative vulnerability whereas the denitrification potential reduces the relative vulnerability (Formula 2).

Relative vulnerability

$$= \text{nutrient regulation ES demand} + \text{nitrate leaching potential} \quad (2)$$

$$- \text{denitrification potential}$$

4 Results

In the following section, the findings on the nutrient regulation ES demand, the nitrate leaching and denitrification potential are shown. Firstly, the spatial distribution of the calculated nitrogen budgets is presented on the scale of the municipalities. Subsequently, the results on the farm scale are depicted.

4.1 Municipality scale

The assessment of the nutrient regulation ES demand on the municipality scale in the county Höxter revealed that each municipality exhibits nitrogen surpluses (Figure 2). According to the agricultural calculation, the highest nitrogen surpluses occurred in the Northwest of the study area. These municipalities were also characterized by very high ecological nitrogen budgets. However, according to the ecological nitrogen budget, also the municipality located in the Southeast was characterized by very high values. The average annual agricultural and ecological nitrogen budget in the study area was 58 and 98 kg N per hectare, respectively. Thus, the ecologically calculated annual nitrogen budget was on average 40 kg N per hectare higher than the respective agricultural amount.

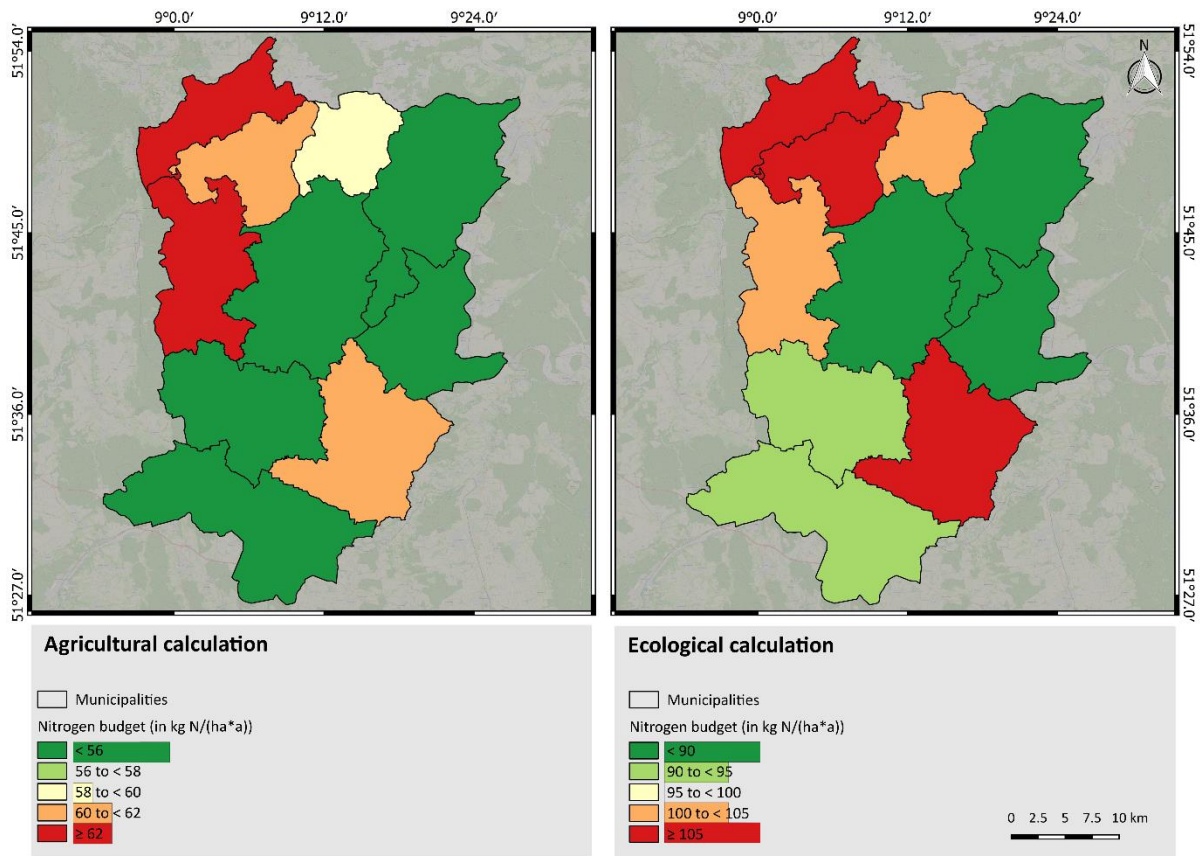


Figure 2: Nutrient regulation ES demand based upon the agricultural (left, reference year 2016) and ecological (right, average 2008-2018) calculation of the nitrogen budget in the municipalities in Höxter (please consider the respective legends of the nitrogen budgets). The frequency distribution refers to the number of municipalities in the respective categories (base maps: OpenStreetMap, 2019 and GeoBasis-DE / BKG, 2019).

4.2 Field scale

In the case study area Eversen, the nitrogen budget was assessed on the scale of individual fields. Both the agricultural nitrogen budget and the ecological nitrogen budget were calculated. On average, the ecologically calculated annual nitrogen budget was 49 kg N per hectare higher than the agriculturally calculated annual nitrogen budget. The assessment includes an evaluation of different crop rotation systems (see Table 1). The nitrogen budgets were calculated for the different crop rotation systems. The average agricultural practices of the season 2017/2018 in terms of fertilizer application were taken as a base for the calculation.

Table 5: Annual average nitrogen budget for the 4-year and 5-year crop rotation system. The green shading highlights the lowest budget within the respective crop rotation system.

Crop rotation (ø 2017/2018)						
4-year cycle				5-year cycle		
				Rapeseed	Silage maize	Field bean
Rapeseed	Silage maize	Field bean	Grass/ clover	Grass/ clover	Grass/ clover	Grass/ clover
Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
Triticale	Triticale	Triticale	Triticale	Triticale	Triticale	Triticale
Barley	Barley	Barley	Barley	Barley	Barley	Barley
ø budget (agri) in kg N/(ha*a)	-5	-27	-11	-4	-21	-8
ø budget (eco) in kg N/(ha*a)	53	34	26	45	30	24

Table 5 presents the calculated average annual nitrogen budgets for the assessed crop rotation systems. Generally, the agricultural budgets deliver lower values. The findings demonstrate the differences in the two calculation methods. According to the agricultural nitrogen budgets, for both the 4- and 5-year cycle, the crop rotation systems including maize deliver the lowest budgets. According to the ecological budget calculation, the respective crop rotation systems including field beans result in the lowest annual nitrogen budgets. Crop rotation including rapeseed delivers the highest nitrogen budgets for all considered rotation systems and calculation methods. Generally, the 5-year crop rotation system results in lower annual nitrogen budgets compared to the 4-year crop rotation system. On average, the nitrogen budgets are 10% lower compared to the 4-year crop rotation system.

In addition to the fertilizer application and the crop rotation system, further management options have been implemented aiming to prevent soil erosion and surface runoff and to support nutrient regulation. Since 2017, some field margins have been left fallow and flower strips have been cultivated. The implementation of these measures decreased the annual average nitrogen budget by 3%.

As outlined in section 3.1, the share of nutrients which should be considered in the budget according to the DüV (2017) is under criticism. According to Taube (2018), these specifications and regulations have no effect in terms of improving the use of organic fertilizers and thus reducing nutrient losses to the environment. Therefore, the ecological nitrogen budget under consideration of the additional management options has been defined as the most appropriate indicator for the nutrient regulation

ES demand. The nutrient regulation ES demand has been quantified and mapped for the individual fields in the case study area Eversen (Figure 3).

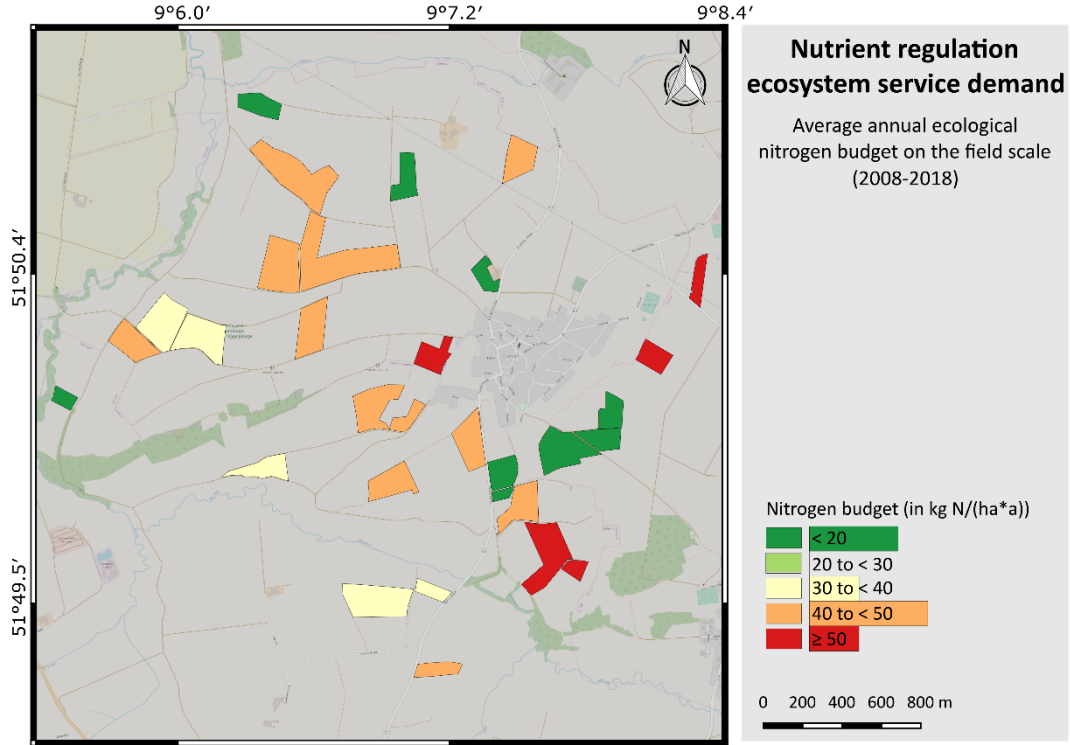


Figure 3: Nutrient regulation ES demand on the individual fields in the case study area Eversen based on the average annual ecological nitrogen budget from 2008 to 2018. The frequency distribution refers to the number of fields in the respective categories (base map: OpenStreetMap, 2019).

The findings indicate a spatial variation of the nutrient regulation ES demand. Generally, the annual average nitrogen budget of the individual fields ranged between 14 and 52 kg N per hectare, with an overall average of around 32 kg N per hectare. As explained in the introduction, in order to guarantee a holistic ES assessment, underlying relevant ecosystem conditions need to be assessed. Therefore, we examined two soil functions, which are highly relevant for the ES nutrient regulation, namely the nitrate leaching and denitrification potential (Figure 4).

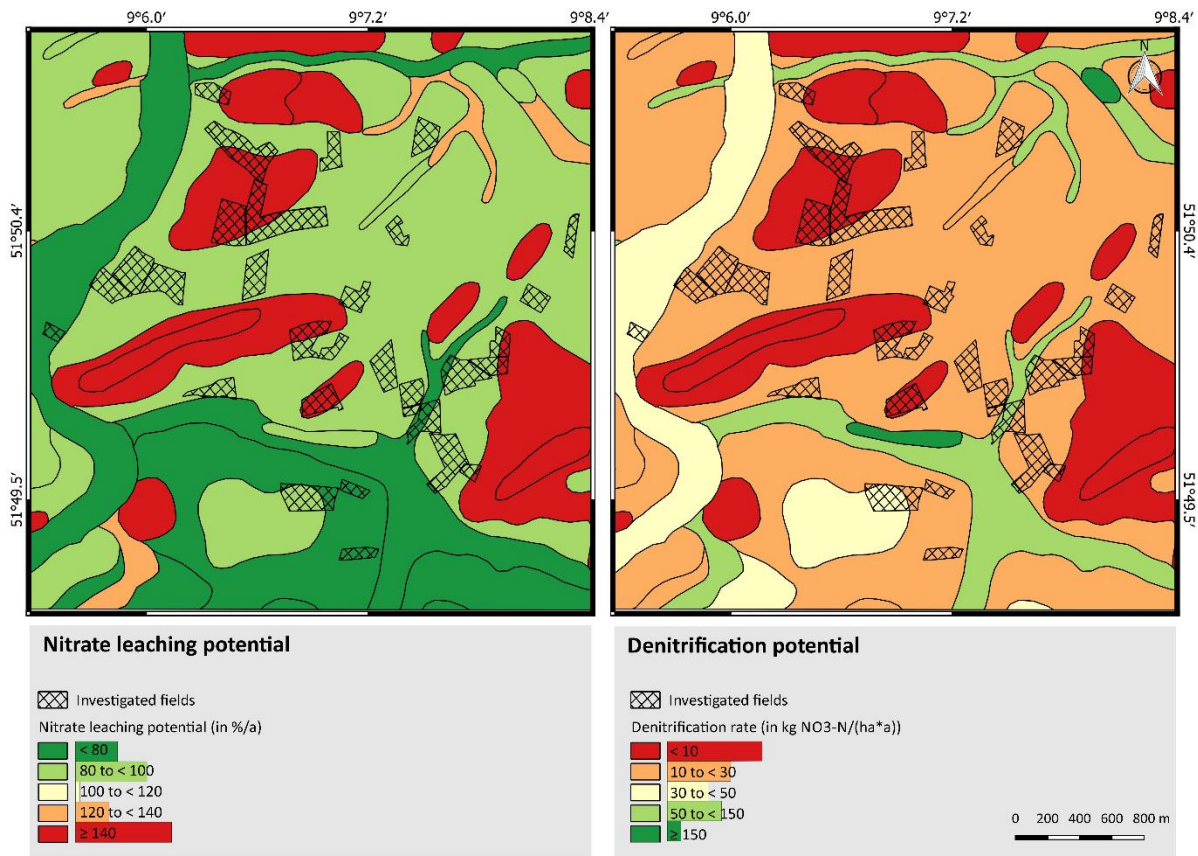


Figure 4: Nitrate leaching potential and denitrification potential (Geologischer Dienst NRW 2017a) in the case study area Eversen (please consider the respective color schemes of the two potentials). The frequency distribution refers to the number of polygons in the respective categories.

As outlined in section 3.2 the nitrate leaching and denitrification potential are based on different soil properties and the climatic conditions. Thus, the differentiation within the study area originates from the spatial distribution of these environmental characteristics. Therefore, the underlying spatial patterns of the two potentials resemble each other. Nevertheless, both potentials have a distinct spatial distribution (Figure 4). Overall, the study area is characterized by rather low nitrate leaching potentials. However, scattered patches with higher nitrate leaching potentials are spread throughout the whole study area. Additionally, these patches feature low denitrification potentials (denitrification rates: < 10 kg NO₃-N/(ha*a)). These areas correspond to the soils with the lowest field capacities in the study area. The largest part of the study area is characterized by medium denitrification potentials (denitrification rates: 10-30 kg NO₃-N/(ha*a)). Areas with higher than average denitrification rates rarely coincide with the location of the fields which have been investigated. Visually comparing the spatial distribution of the nitrate leaching and denitrification potential to the nutrient regulation ES demand (Figure 3 and Figure 4) no distinct correlation was detected. These findings are supported by the map comparison statistics, which deliver the following results (Table 6).

Table 6: Map comparison statistics (MCS) of nutrient regulation ES demand, nitrate leaching and denitrification potential. Identical maps result in an MCS of zero, an MCS of 0.5 indicates that the pair of maps are random and an opposing pair of maps produce an MCS of 1.

Relevant datasets	Nutrient regulation ES demand	Nitrate leaching potential	Denitrification potential
Nutrient regulation ES demand	(0)	0.47	0.47
Nitrate leaching potential		(0)	0.56
Denitrification potential			(0)

The map comparison statistics indicate fairly randomness between each pair of maps. This supports the assumption that each dataset contributes auxiliary information to the assessment. Taking this into consideration, a vulnerability analysis was performed which combines the spatial distribution of the nutrient regulation ES demand with the respective datasets of the nitrate leaching and denitrification potential. Thereby, the ecosystem’s vulnerability to the oversupply of nutrients was assessed. The nutrient regulation ES demand, in the form of the nitrogen budget, has been defined as the exposure to the hazard of nutrient oversupply. The nitrate leaching and denitrification potential served as sensitivity and adaptive capacity of the ecosystems, respectively.

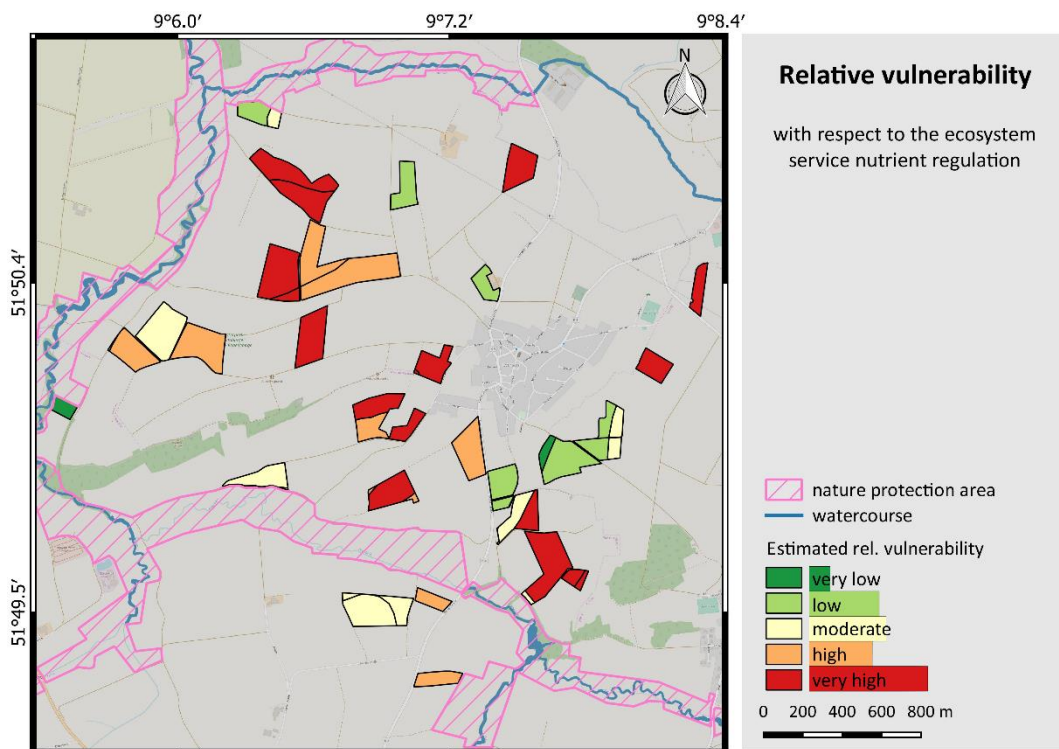


Figure 5: Location of water courses, nature protection areas and estimated relative vulnerabilities with respect to the ES nutrient regulation on the individual fields in the case study area Eversen. The relative vulnerability accounts for the nutrient regulation ES demand (ecological), the nitrate leaching and the denitrification potential. The frequency distribution refers to the number of polygons in the respective categories (base map: OpenStreetMap, 2019).

The qualitative vulnerability assessment identified hot- and cold spots of relative vulnerability (Figure 5) in the case study area Eversen. A large share of the fields located in the cross section from Northwest to Southeast was characterized by very high vulnerability. In addition to that, the three fields in the Northwest fall into the same category. In these areas, the soil functions and agricultural practices coincided in the most unfortunate combination. Another aspect, which should be considered with respect to the vulnerability of the area, is the proximity of the fields to water bodies and nature protection areas (Figure 5). The case study area is surrounded by both. This proximity should be perceived as an additional incentive to implement a sustainable nutrient management concept.

5 Discussion

5.1 General Findings

The compared nutrient budgets on the municipality and the individual field scales were calculated based on datasets with different temporal resolutions. The primary input dataset for the municipality scale was the agricultural census for the year 2016 (IT.NRW, 2016). The calculation on the field scale was based on the field record system, which includes data for the years 2008-2018 (von Ruschkowski 2018). For each spatial scale, the annual average nitrogen budgets (in kg N/(ha*a)) were calculated. Besides, on both spatial scales, the nitrogen budgets were calculated using two different approaches. Firstly, an agricultural nitrogen budget was calculated which has been developed based on the DÜV (2017) and further agricultural literature (a.o. Leip et al. 2011; Bach et al. 2014; Özbek and Leip 2015; Taube et al. 2015). It considers nitrogen deduction rates for fertilizer application. Secondly, an ecological nitrogen budget was calculated which attempts to consider the whole nitrogen cycle. Therefore, no deductions were applied and additionally the atmospheric N-deposition was considered as an input parameter. Expectedly, on both spatial scales, the agricultural nitrogen budget was lower than the ecological nitrogen budget.

On the municipality scale (regional), the difference between the two budgets was on average 40 kg N per hectare and year. In the case study area Eversen, on the field scale (local), the average difference was 49 kg N per hectare and year. Thus, on the local scale, the difference was approximately 23% higher compared to the regional scale. Generally, the assessment on the field scale delivered lower nitrogen budgets compared to the assessment on the municipality scale. The case study area Eversen is located within the municipality of Nieheim. According to the regional assessment, the average annual ecological nitrogen budget in Nieheim was 109 kg N per hectare. The investigated fields delivered ecological annual nitrogen budgets up to 52 kg N per hectare. Thus, the farm generally generated lower nitrogen budgets compared to its corresponding municipality.

The fertilization practices on the individual fields were compared to the defined N requirements according to the fertilization planning of the DüV (2017). For each agricultural crop type, crop profiles were compiled which refer to agricultural practices related to fertilization and residual management and the estimated yield (Appendix 1). The comparison refers to the general N requirements of the agricultural crop (DüV, 2017 Appendix 4). Exceptions of the N requirements, due to for example specific N soil contents, were not considered. However, the comparison indicates that the fertilization practices were well below the defined N requirements according to the DüV (2017). The fertilization practices for rapeseed reached closest to the N requirements defined by the DüV (2017). The comparison of the different crop rotation systems for both the annual agricultural budget and the annual ecological budget corresponds to our understanding. The annual average nitrogen budget is generally lower in the 5-year crop rotation system, compared to the 4-year crop rotation system. These findings are in line with the literature (European Commission – DG ENV 2010; PAN Germany 2010; Bruns 2012; VALERIE 2017). Furthermore, the comparison also supports the findings outlined above on the differences between the agricultural and ecological budget. The agricultural calculation identifies the lowest nitrogen budgets for the crop rotation system including maize. However, according to the ecological calculation, the crop rotation system including field beans performs best. As the agricultural budget allows for nitrogen deduction and only the ecological budget delivers integral insights into the total amount of nitrogen introduced into the environment, the crop rotation system including field beans can be considered as a best practice of the compared systems. These findings support the conception of the different calculation methods (agricultural and ecological) outlined above. The crop rotation including rapeseed delivers highest nitrogen budgets for all considered crop rotation systems. Next to the relatively high fertilizer application rates for rapeseed, the high product-to-residue ratio, which implies relatively high amounts of nitrogen remaining on the field after harvest, explains these findings.

According to the agricultural calculation on the field scale, even negative nitrogen budgets occurred in the case study area, which might cause nitrogen deficiency in the long run. Nevertheless, as discussed in section 3.1, the loss values considered in the calculation of the agricultural nitrogen budget are subject to criticism (Taube 2018). According to Taube (Taube 2018), the nutrient share which is considered in the budgets is too low from the ecological and also technical perspective. Therefore, it is most likely, that the calculated agricultural nitrogen budgets reflect an incorrect impression of the nutrient situation. Therefore, the ecological nitrogen budget has been selected as the indicator for the nutrient regulation ES demand in the case study Eversen.

The assessment of the nutrient regulation ES demand on the field scale allows further spatially explicit investigations. The findings of the nutrient regulation ES demand were compared to the spatial

distribution of the nitrate leaching and denitrification potential. All information was combined in order to assess the relative vulnerability of the area to nutrient oversupply. The consideration of the adjacency of nature protection areas and watercourses to the agricultural fields increased the significance of the evaluation. Of course, land management and agricultural practices of the entire corresponding catchment area are of relevance for the quality of water bodies. Nevertheless, the impact factor in particular with reference to the lack time increases with increasing proximity. In addition to the surface water, also groundwater bodies should be considered in an integrated assessment. As the spatial representation of the ecosystem's vulnerability allows for the identification of hotspot areas (Weißhuhn et al. 2018), the evaluation can serve as a foundation to detect areas where special attention needs to be paid with respect to land management strategies or agricultural practices (Zurlini et al. 1999; Aretano et al. 2015). The spatially explicit vulnerability evaluation can serve in particular as a base for designating additional environmental conservation measures. Measures, such as the establishment of flower strips, fallow land or the cultivation of green infrastructure such as hedgerows, can be implemented on areas which are identified to exhibit high or very high vulnerability to nutrient oversupply. In the case study area Eversen, the fields located in the West and in the cross-section from Northwest to Southeast were characterized by (very) high vulnerability. In particular, these fields should be paid special attention concerning balanced nitrogen in- and outputs.

5.2 Strengths, uncertainties and limitations of the approach

The calculations of the nitrogen budgets on the farm scale were primarily based on data and information that were obtained directly from the farmer. Information such as the application of fertilizers on the fields was recorded in the field record system of the farmer (2018). The information was available and specified with regard to the quantity as well as to the date of application. Concerning the average yield per hectare, the information was of different quality. The yield of the different crop types was not weighted and recorded accordingly. The farmer estimated the average yield for the different crop types. Next to the general uncertainty of this approach, the information on the average yield is static and no annual variation is included. Besides, the formula for the estimation of the mineral fertilizer requires temporal and spatial adaptation according to Bach et al. (2014). These adaptations have not been performed due to data limitations.

However, in order to validate the findings of the study, the values on the municipality scale were compared to the information provided for the federal state of NRW on the scale of counties (Landwirtschaftskammer Nordrhein-Westfalen 2018). The official elaboration specified an average annual nitrogen surplus of 60 kg N per hectare in the county of Höxter, whereas this study identified an average annual nitrogen surplus of 58 kg N per hectare according to the agricultural calculation.

The official numbers on the amount of nitrogen from organic fertilizer (from livestock) after deduction of nitrogen losses in the county of Höxter in 2016 are in line with the findings of this study. The dissimilarity between these results is only 0.6%. Most likely, the discrepancy of the nitrogen budgets originates from differences in methodological approaches and available datasets. Due to data privacy law, some information has not been available on the municipality scale. In these cases, information from higher administrative units has been considered and the information has been attributed to the corresponding municipalities. This process involves uncertainties and is most likely responsible for some of the results' variations. Another limitation of the assessment on the municipality scale is the neglect of organic fertilizer exports and imports. Due to data unavailability, the assessment was based on the assumption that organic fertilizer from livestock was applied in the municipality where it was produced.

Crop rotation has been considered within this study in terms of the calculation of the nitrogen budgets. The calculation was based on a summation of the in- and outputs of the different crop types within the considered period of time (4 and 5 years). This summation included aspects related to biological nitrogen fixation through legumes. However, it did not include further crop type-specific aspects such as vegetation period (including winter soil coverage), root mass and tillage practices, which influence the nutrient cycle (Jacobs et al. 2009; Bruns 2012; Jie et al. 2013; Busari et al. 2015). More complex modeling, which allows for the consideration of these aspects, would most likely result in even more significant differences between the three considered crop rotation systems (Power 2010). Another limitation of the assessment is the fact that all calculations were based on the total nitrogen quantities and no differentiations were made between organic and inorganic nitrogen. The mobility and plant availability of organic and inorganic nitrogen (Smith and Hadley 1989) were not considered. Thus, no differences arose between biologically fixed nitrogen (e.g. through the cultivation of field beans), organic and mineral fertilizer application.

In addition to the specific uncertainties and limitations, which originate from the methodological approach, also general uncertainties of ES research need to be considered (Hou et al. 2013). General uncertainties arise from the complexities of ecosystems and human-environmental interactions. Therefore, the ES concept is of multi-, inter- and transdisciplinary nature (Burkhard 2017; Maes 2017), incorporating, in particular, the ecological and socio-economic research domains. Besides, challenges arise from the terminology within the ES concept. For instance, the differentiation between ES potential, flow and demand need to be taken into account (Burkhard et al. 2012b; Burkhard et al. 2014; Schröter et al. 2014; Dunford et al. 2017; Bicking et al. 2018). Additionally, for the interpretation of the results, input data, applied methodologies and in particular, the employment of proxies need to be considered. With reference to this study, the nitrogen budgets were used as a proxy for the nutrient

regulation ES demand. The careful consideration of all these challenges is essential for the interpretation of the findings from ES assessments in order to safeguard the comprehension of the results (Dunford et al. 2017).

The embedment of the analysis in the ES framework allowed for a comprehensive assessment of the nutrient situation. The major focus of this study was the calculation of nitrogen budgets as an indicator of the ES demand. As proposed by recent literature, the ecosystem conditions and related functions are the fundamentals for an ecosystem's ES supply capacity (Power 2010; Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017; Maes et al. 2018). Therefore, the study included an assessment of some fundamental ecosystem functions with regard to the ES nutrient regulation: Nitrogen leaching and denitrification potential. Both of these soil functions account for the ES potential of nutrient regulation. However, more information would be necessary to ensure an integral assessment of the nutrient regulation ES supply.

5.3 Future research

A promising approach for further assessments is the development of an elaborated model for the calculation of the nitrogen budgets on the field scale. This model should be developed for the case study area in order to enable the inclusion of further temporal and spatial explicit variations. The highly elaborated model package RAUMIS-GROWA-DENUZ-WEKU (Heidecke et al. 2014; Ackermann et al. 2015; Wendland et al. 2015) could serve as an example for developing a methodological approach which allows for integral assessments on local scales. Just as the package RAUMIS-GROWA-DENUZ-WEKU, the model should integrate an assessment of further relevant nutrients, in particular phosphorous, and comprise a comprehensive hydrological model. In particular, general aspects concerning seasonality and further agricultural practices such as tillage should be included. The model should allow for temporal-explicit specifications with regard to fertilizer application and further agricultural practices. The model should be applied aiming to generate profound knowledge on the processes and functions which play crucial roles in agro-ecosystems. Eventually, the insights can be used in order to increase the integral understanding of ecosystems as parts of complex social-ecological systems.

6 Conclusions

This study contributes to the contemporary debate with reference to nutrient management, surplus and nitrate groundwater concentrations. The nutrient regulation ES demand on the municipality scale in the county of Höxter and on the field scale in the case study area Eversen was assessed. The nitrogen budget was defined as indicator, which has been quantified and mapped on both spatial scales. The assessment in the case study area Eversen additionally included an evaluation of further agricultural

practices and a vulnerability assessment incorporating information on soil functions. Summing up the knowledge obtained from the study, the research questions are taken up and the following can be stated:

1. Does the nutrient regulation ES demand in the case study area Eversen resemble the nutrient regulation ES demand on the municipality scale in the county of Höxter?

Both assessments indicated high nitrogen budgets in the respective study areas. The calculation based on the municipalities scored higher surplus values for both the ecological and agricultural calculation. This indicates, that the assessed fields in the case study area Eversen were characterized by a lower than average nutrient regulation ES demand, compared to the regional average. The assessment on both spatial scales revealed the discrepancies between the agricultural and ecological nitrogen budget calculation. Thereby, the discrepancy between the agricultural and ecological calculation was even larger on the individual field scale. This highlights the relevance for obligatory spatially explicit nitrogen budget assessments, which need to consider all ecologically relevant nitrogen quantities.

2. Do the calculated nitrogen budgets depend on agricultural practices such as crop rotation, the establishment of flower strips and fellow land?

The assessment identified the effects of different agricultural practices on the nutrient regulation ES demand. The comparison of different crop rotation systems revealed that the assessed 5-year crop rotation systems result in lower average annual nitrogen budgets than the 4-year crop rotation system. Generally, the crop rotation including field beans leads to lowest nitrogen budgets within their respective system. Besides, the effect of additional agricultural measurements aiming to reduce surface runoff, prevent erosion and increase nutrient regulation on the nutrient regulation ES demand was identified through the calculation of the nitrogen budgets.

3. How can nitrate leaching and denitrification potential be used in the assessment of the nutrient regulation ES?

The ES concept indicates that the capacity of an ecosystem to provide ES is based on the ecosystem's conditions. Ecosystem conditions correspond to structures, processes and functions of an ecosystem, which are associated with ecological integrity (EI). One measure of EI, which is highly relevant for the capacity of an ecosystem to provide the ES nutrient

regulation, is the reduction of nutrient loss. Within this study, the nitrate leaching and denitrification potentials served as indicators for reduction of nutrient loss. Even though there were no direct measures on the actual nutrient regulation ES potential and ES flow available for this study, the incorporation of the nitrate leaching and denitrification potential already increased the scope of the ES assessment. The combination of the nutrient regulation ES demand with the nitrate leaching and denitrification potential was used in order to estimate the relative vulnerability of the case study area in the context of the ES nutrient regulation. Commonly, a vulnerability assessment incorporates information on the exposure, sensitivity and adaptive capacity with reference to a specific hazard. In this study, the nitrogen budget, nitrate leaching and denitrification potential were used as indicators for these parameters. The assessment identified hot- and cold spots of vulnerability in the study area and can, therefore, it can be used in order to support sustainable land management policies and agricultural practices concerning fertilization strategies. For instance, the information on the spatial distribution of the relative variability on the field scale can support the farmer with crop rotation and fertilization planning decisions. Besides, the farmer can commission soil nutrient analysis on fields, which are identified to have a high nutrient regulation demand and/or install conservation measures aiming to prevent unsustainable nutrient conditions, safeguarding the environment and concurrently securing their own future prospects

Generally, the study embraced the contemporary nutrient issue, which originates from conventional agricultural practices and intensive land management. The assessment of the nutrient regulation ES demand depicts that high nitrogen budgets are common practices. In this context, the agricultural and ecological budget were compared. A strong variation was discovered between the different budgets. The agricultural budget even depicted nutrient deficiency situations in the case study area Eversen. However, the share of the nutrients which are considered in the agricultural budget is too low and not in line with current scientific and technological development (Taube 2018). The ecological budget, on the other hand, considered all nutrient inputs, even atmospheric deposition. From the ecological perspective, this budget has the greatest significance.

Besides, the study also identified the reducing effects that agricultural practices such as specific crop rotation systems and the establishment of flower strips have on the nitrogen budget. Next to these findings, also the spatial assessment of the nutrient regulation ES demand and the spatial vulnerability assessment delivered valuable results. The study area Höxter is an agriculturally dominated landscape. Therefore, sustainable agricultural practices and land management strategies are essential in order to safeguard on the one hand the production of amongst others food and fodder and on the other hand, to prevent environmental pollution and consequential degradation of soils and water bodies. The

findings of this study can serve as a foundation for the development of land management policies and agricultural practice plans aiming to decrease nitrogen budgets and thereby reducing the nutrient regulation ES demand.

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Appendix

	Wheat		Barley		Triticale		Silage maize	
	former system	current system	former system	current system	former system	current system	former system	current system
Average harvest (dt/ha)	90		80		80		500	
Residuals remaining on the field (%)	30		30		30		[-]	
Average N-content in plant biomass (kg N/dt FM)								
in grain	1.81		1.65		1.65		0.38*1	
in straw	0.5		0.5		0.5		[-]	
Ratio primary to secondary product (1:X)	0.8		0.7		0.9		[-]	
Nitrogen input (kg N/ha)								
agricultural calculation	164	173.4	154	141	162	157	84	107
ecological calculation	210.2	211.6	194.2	214.2	208.2	195.2	168.2	202
Nitrogen output (kg N/ha)								
in harvest of grain	162.9		132		132		[-]	
in harvest of straw	25.2		19.6		25.2		[-]	
in total harvest	188.1		151.6		157.2		190	
Nitrogen budget (kg N/ha)								
agricultural calculation	-24.1	14.7	2.4	-10.6	4.8	-0.2	-106	-83
ecological calculation	22.1	23.5	42.6	62.6	51	38	-21.8	12
	Rapeseed		Field bean		Grass/ clover			
	former system	current system	former system	current system	former system	current system		
Average harvest (dt/ha)	40		45		80 (DM)			
Residuals remaining on the field (%)	30		30		[-]			
Average N-content in plant biomass (kg N/dt FM)								
in grain	3.35		4.1		0.5*1			
in straw	0.7		1.5					
Ratio primary to secondary product (1:X)	1.7		1		0.2*2			
Nitrogen input (kg N/ha)								
agricultural calculation	200.56	172.8	197.5	197.5	[-]	234		
ecological calculation	270.9	254.1	212.7	212.7	[-]	248.3		
Nitrogen output (kg N/ha)								
in harvest of grain	134		184.5		[-]			
in harvest of straw	33.3		31.5		[-]			
in total harvest	167.3		216		232			
Nitrogen budget (kg N/ha)								
agricultural calculation	33.24	5.48	-18.5	-18.5	[-]	2		
ecological calculation	103.58	86.78	-3.3	-3.3	[-]	16.3		

*1) whole plant

*2) dry mass per fresh mass

Appendix 1: Crop type specific nutrient profiles on the field scale. Diverse data sources are specified in Table 4.

Nutrient regulation ES demand		Nitrate leaching potential		Denitrification potential		Relative vulnerability	
in kg N/(ha*a)	reclassified	in %/a	reclassified	in kg NO ₃ - N/(ha*a)	reclassified	calculated index	reclassified
< 20	1	< 80	1	< 10	1	< 3.4	very low
20 to < 30	2	80 to < 100	2	10 to < 30	2	3.4 to < 4.8	low
30 to < 40	3	100 to < 120	3	30 to < 50	3	4.8 to < 6.2	moderate
40 to < 50	4	120 to < 140	4	50 to < 150	4	6.2 to < 7.6	high
>= 50	5	>= 140	5	>= 150	5	>= 7.6	very high

Appendix 2: Classification scheme of nutrient regulation ES demand, nitrate leaching and denitrification potential as input data for the assessment of the relative vulnerability and calculated vulnerability values/ index and respective relative vulnerability classes.

5

Refining the assessment of the nutrient regulation ES potential

Publication title:

Bayesian Belief Network-based assessment of nutrient regulating ecosystem services in Northern Germany

Bicking, S., B. Burkhard, M. Kruse and F. Müller

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Triggered by the results of the preceding papers on the spatial distribution of the nutrient regulation ES demand, this paper deals with a more profound assessment of the nutrient regulation ES potential in the federal state of Schleswig-Holstein. The assessment incorporated, next to the ES matrix approach, further spatial information on ecosystem conditions and properties. The nutrient regulation ES potential was derived on the basis of the three main landscape regions in the study area.

Bayesian Belief Network-based assessment of nutrient regulating ecosystem services in Northern Germany

Sabine Bicking^{a,b}, Benjamin Burkhard^{b,c}, Marion Kruse^a, Felix Müller^a

a Institute for Natural Resource Conservation, Department of Ecosystem Management, Kiel University, Olshausenstr. 40, 24098 Kiel, Germany; corresponding author: sbicking@ecology.uni-kiel.de

b Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany

c Leibniz Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany

Abstract

This study aims to assess the potential supply of the ecosystem service (ES) *nutrient regulation* on two spatial scales, the federal German state of Schleswig-Holstein (regional) and the Bornhöved Lakes District (local), exemplarily for the nutrient nitrogen. The methodology was developed using the ES matrix approach, which can be applied to evaluate and map ES at different geospatial units such as land use/land cover classes. A Bayesian Belief Network (BBN) was constructed in order to include additional spatial information on environmental characteristics in the assessment. The integration of additional data, which describes site-specific characteristics such as soil type and slope, resulted in shifted probability distributions for the *nutrient regulation* ES potential. The focal objective of the study was of methodological nature: to test the application of a BBN as an integrative modelling approach combining the information from the ES matrix with additional data sets. In the process, both study areas were assessed with a regional differentiation with regard to the predominant landscape types. For both study areas, regional differences could be detected. Furthermore, the results indicate a spatial mismatch between ES demand and supply of the *nutrient regulation* potential. Land management and agricultural practices seem not to be in harmony with the spatial patterns of the environmental

characteristics in the study areas. The assessment on the local scale, which comprised higher resolution input data, emphasized these circumstances even more clearly.

Key words: BBN, nitrogen, ecosystem service potential, budget, Schleswig-Holstein, Bornhöved Lakes District

Introduction

Research on the interrelations between human activities and the environment is of key importance for our society. Increased understanding of the environment and of the effects of our behaviour on the environment will support sustainable policy and decision making. In particular, decision making with regard to spatial planning, land and resources management and agricultural practices has to be founded on precise information in order to support sustainable land use. In this regard, the concept of ecosystem services (ES) is a valid assessment approach. The concept commonly differentiates between three ES categories: regulating, provisioning and cultural ES, all of which contribute to human well-being (i.e. (1–6)) ES analyses can be used to support spatial planning and attaining sustainable land management (7,8). The relevance of this approach is consolidated also in European policy. Through the Biodiversity Strategy 2020, the European Union called upon its member states to map and assess the states of their ecosystems and the services they provide (Target 2 Action 5 of the Biodiversity Strategy; see (9)). This demand emphasizes the need for simple and applicable methods for ES assessment and mapping. In several previous studies, the assessment and mapping of the ES supply and demand has been based on the ES matrix approach by Burkhard et al. ((2,10) also in (11,12)). The matrix has been used to distinguish, amongst others, ES supply for different land cover types. CORINE land cover data (13) from the European Union has often been selected as underlying data set (10,14). When using land use land cover (LULC) data such as CORINE, the spatial ES modelling is dependent on the prevailing land cover types, which usually are strongly related to vegetation and land use patterns. Based on that, ES can be qualitatively mapped based on expert knowledge and on the matrix values

provided by Burkhard et al. (10) related to the CORINE land cover classes. This so called 'tier 1' ES mapping approach (15) has been proven to be efficient to raise awareness and for gaining an overview of ES in study areas (2,14,16,17). However, it is questionable whether ES allocation solely based on one spatially explicit data set (such as land cover) is sufficient in order to represent local ecosystem conditions (10,14). As most study areas are not homogenous, but differ, e.g., in geomorphology, soil type and texture, it is reasonable to suppose that ES supply differs spatially throughout the study area, for instance also within one land use class (18).

This study therefore aims at assessing the influence of several site-specific characteristics and properties on the potential supply of a selected ES. The research was executed for the ES *nutrient regulation*, which is defined as the ability of an ecosystem to recycle nutrients (10). We refer here to *ES potential*, which has been defined by Burkhard et al. (10) as the hypothetical maximum yield of selected ES. ES potential is different from *ES flow*, which describes ES that are actually used in a specific area and time, driven by demand for ES (19).

The assessment was tested on two spatial scales: regional and local. The federal state of Schleswig-Holstein (regional scale) and the Bornhöved Lakes District (local scale) were selected as study areas. A Bayesian Belief Network (BBN) was developed for the analysis. BBNs are multivariate statistical models which feature a probabilistic modelling approach (20,21). The BBN was constructed based on the ES matrix approach by Burkhard et al. (10). The goal of the research was to come up with a more differentiated ES classification for the *nutrient regulation* ES potential. The approach integrated additional data on site-specific social-ecological system properties with the original *nutrient regulation* ES potential based upon the matrix approach which uses CORINE LULC as proxy for the ES potential. The study can be understood as an attempt to test the convenience of integrating various data sets and information by means of a BBN in the two study areas. The aim was not to compile a model that describes reality in a complete and all-embracing manner. Instead we wanted to test the influence of integrating additional data in the evaluation of the *nutrient regulation* ES potential. Special attention was paid to the assessment of regional differences within the two study areas which were examined

based on the prevailing landscape types. The BBN was used in both study areas to examine the assumption that the site-specific characteristics of the prevailing landscape types strongly influence the *nutrient regulation* ES potential. Besides, the issue of spatial scale was explored with regard to data mining, implementation and running of the BBN and interpretation of the results.

Resulting from the issues described above, the following hypotheses were tested in this study:

- I. The inclusion of data on site-specific properties for the assessment of the *nutrient regulation* ES potential results in a more scattered distribution of the ES potentials compared to the ES matrix values provided by Burkhard et al. (10).
- II. The assessment of the *nutrient regulation* ES potential results in a regional differentiation in Schleswig-Holstein.
- III. The probability distribution of the *nutrient regulation* ES potential in the Bornhöved Lakes District resembles the distribution for Schleswig-Holstein.

2 Background information

This section comprises information on the study areas followed by some general knowledge about nutrients focusing on nitrogen and the ES *nutrient regulation*.

2.1 Physical features of the study areas

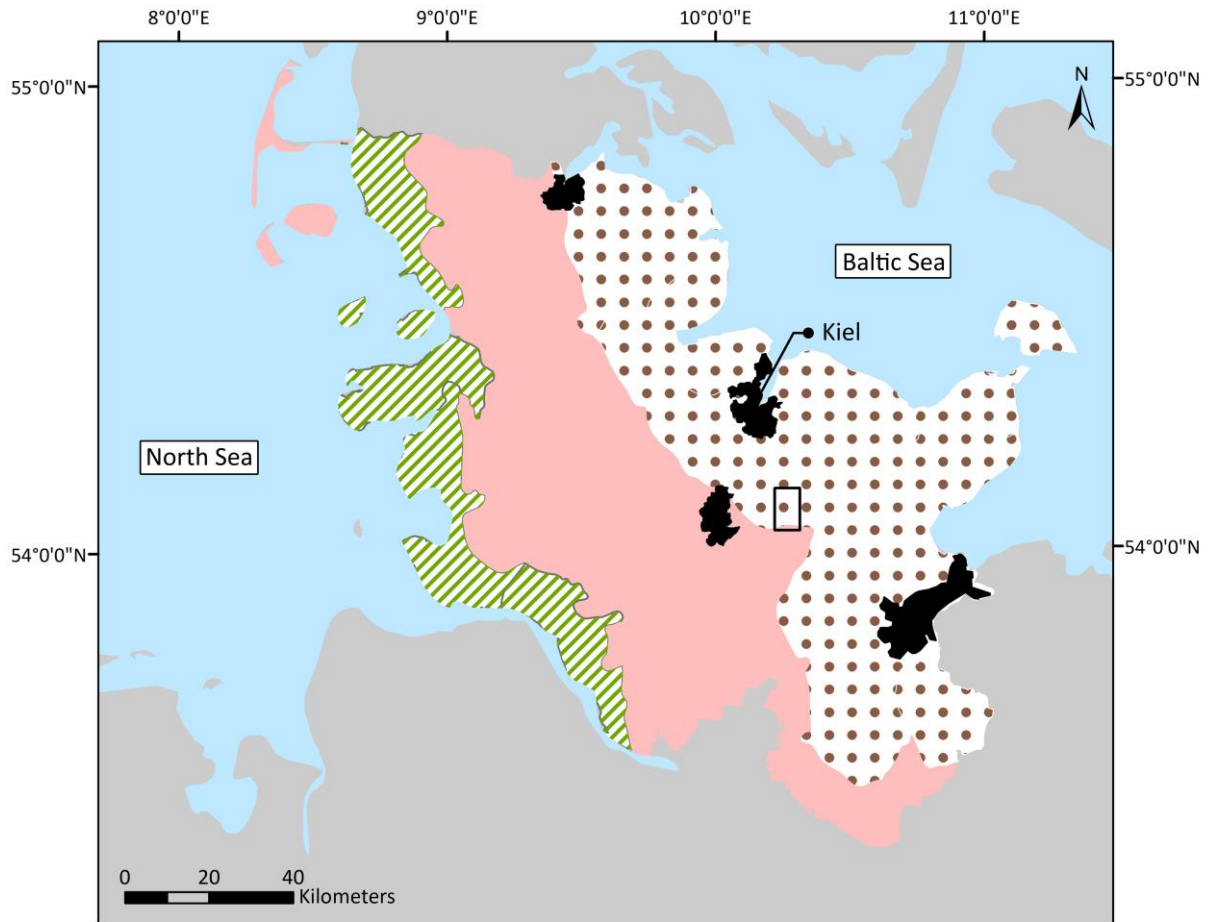
In the following two paragraphs, the two study areas are described and their characteristics are depicted.

2.1.1 Schleswig-Holstein

The federal state of Schleswig-Holstein is located in Northern Germany and has a spatial extent of 15'802 km² (22). The adjacency of the North Sea to the West and the Baltic Sea to the East of the study area (Fig 1) leads to maritime and humid climatic conditions, with an annual mean temperature of around 8°C and a precipitation average of approximately 840 mm (23). The Pleistocene, the last glacial

period, played an important role in the creation and formation of today's landscapes. Especially the last two glaciations of the Pleistocene, the Saalian and the Weichselian glaciation, highly influenced the geological and geomorphological conditions of Schleswig-Holstein (24). Particularly, the varying expansions of the glaciers during the Saalian and the Weichselian glaciation led to the regional natural conditions within the study area (24,25). As a consequence, the landscapes of Schleswig-Holstein reveal three main landscape types (25,26): *Hügelland*, *Geest* and *Marsch* (Fig 1).

Contrary to the Saalian glacier, the Weichselian glacier only covered the Eastern part of Schleswig-Holstein. During that time, the area of the *Geest* embodied the outwash plains of the glacier (24,26). Therefore, the area of the *Geest* is characterized by poorer, sandy soils (24,26). Due to erosion, the landscape of the *Geest* features only little relief. The landscape of the *Hügelland* demonstrates the impact of the Weichselian glaciation on the area, as rolling hills formed by the moraines and small lakes as well as deep embayments prevail (24–26). Resulting from the geological history, the soils of the *Hügelland* are rather fertile. The area of the *Marsch*, in the Western part of Schleswig-Holstein, is also characterized by fertile soils. Unlike the *Geest* and *Hügelland*, the *Marsch* originates from Holocene marine sediments and is thus the youngest of the three landscape types (25,27).



Main landscape types

- Geest
- Bornhöved Lakes District
- Hügelland
- Urban district
- Marsch

Fig 1. Schleswig-Holstein study area, showing the differentiation between main landscape types and the location of the local case study Bornhöved Lakes District (based on data from Landesamt für Landwirtschaft, Umwelt und ländliche Räume).

The diversity of the varying landscape types within the study area is of great relevance for this research, because the influence of site-specific properties, originating from these differences, on the *nutrient regulation* ES potential was assessed. The distribution of several site-specific characteristics, e.g. soil types, correlates with these main landscape types (28).

2.1.2 Bornhöved Lakes District

The study area representing the local scale is called Bornhöved Lakes District. It is located within the federal state of Schleswig-Holstein, more precisely around 30 kilometres south of the state capital city Kiel. The area has been selected as case study area for several previous research and monitoring projects (4,29,30). The case study area that was selected for ES research has an extent of 60 km² (4,31). The Northern and the central parts of the study area belong to the *Hügelland*, the Southern part to the *Geest* (Fig 1). Thus, great influences of the Weichselian glaciation can be seen in the landscape (30). There are six glacially-formed lakes surrounded by forests and agricultural areas in the Bornhöved Lakes District, which has been characterized by Fränzle et al. (30) and Fohrer and Schmalz (32) as a representative landscape for Northern Germany.

2.2 Ecochemical features of the investigated nutrients

Nutrients are chemical elements that plants and animals require for growth, reproduction and survival (33,34). On Earth, there are constant and natural cycles of nutrients (35,36). The cycles depicts how nutrients enter the ecosystem, how they are transferred within the ecosystem and how they eventually leave the ecosystem. Nutrients can be divided into two categories: mineral and non-mineral elements (37). Non-mineral elements, which are used in large quantities by all organisms, are carbon, hydrogen and oxygen. However, also mineral elements are indispensable for life to exist. For agroecosystems and plant growth in general, the following nutrients are of great relevance: nitrogen, phosphorus, potassium, calcium, magnesium and sulphur (38). Nutrients move within an ecosystem through the biosphere, hydrosphere, lithosphere and atmosphere (39). Plants take up nutrients from the soil. Subsequently, the plants are consumed by animals or human beings. After physical ingestion processes, the nutrients are excreted. Otherwise they return to the environment as soon as the organism dies. The organic matter is broken down in the soil by microorganisms which transform the nutrients back to their original mineral form (39). However, this cycle varies for the different nutrients because of their biogeochemical properties.

2.2.1 Nutrient regulation

Nutrient regulation has been defined by Burkhard et al. (10) as the ability of an ecosystem to recycle nutrients. Other studies, which focused on the ES provided by soils, referred to filtering, absorption and retention of nutrients in this context (40–42). The ES *nutrient regulation* is highly relevant for agricultural practices and land management. Under natural conditions, a steady-state is reached with regard to the nutrient pool (36). This means, that in- and outputs are in balance (36,43,44) and the cycle is almost closed (37).

Agricultural practices generate vast changes in the natural nutrient cycles (45,46). The usage of fertilizers and the demand for high yields result in an artificial opening of the nutrient cycle (36,37). As a consequence of the opened nutrient cycle, affected areas may suffer from nutrient deficiency or nutrient oversupply. Both of these circumstances degrade the environment and jeopardize biodiversity and human health. The *nutrient regulation* ES combats both of these issues, ensuring a functioning and sustainable nutrient cycle (36). *Nutrient regulation* varies for different ecosystems. Especially natural ecosystems such as forests and grasslands have a high potential for *nutrient regulation* (10,18). Besides LULC, other factors are of relevance for determining the *nutrient regulation* ES potential, such as slope (18), soil conditions and climatic conditions. As summarized by Bicking et al. (14), the beneficiaries of the ES *nutrient regulation* are diverse. On the one hand, the society as such strives for a clean environment (41,47). In consideration of the quantity of the associated directives and regulations arising from national as well as European legislation, also politics as such can be defined as a beneficiary. On the other hand, according to Power (48), agriculture provides and consumes ES at the same time. Amongst others, agriculture provides crops for fodder and food production. In order to ensure this provision of ES, the agricultural system is dependent on other ES, such as *nutrient regulation* (2,48).

The biogeochemical properties of different nutrients vary and thus associated processes in the environment differ. For reasons of simplification, we analysed the *nutrient regulation* ES potential exemplarily for the element nitrogen alone.

2.2.2 Nitrogen

Nitrogen occurs naturally in inert as well as in reactive forms on our planet (49). The elementary nitrogen which makes up approximately 78% of our atmosphere is the inert nitrogen gas (dinitrogen, N_2) (37,50). Due to natural processes as well as anthropogenic activities, reactive forms of nitrogen are created from the inert nitrogen gas (37,51). The natural processes are biological nitrogen fixation and lightning (37). The anthropogenic activities which create reactive nitrogen comprise fossil fuel combustion and the creation of synthetic fertilizer through the Haber-Bosch process (37,50). Reactive forms of nitrogen are (52): nitrate (NO_3^-), ammonia (NH_3), ammonium (NH_4^+), nitric oxide (NO), nitrous oxide (N_2O) and organic bound nitrogen (N_{org}). All organisms are dependent on reactive nitrogen as a building component for proteins and their hereditary materials (51). Plants are dependent on that essential nutrient for growth, reproduction and survival. The nitrogen cycle is influenced by biological processes and varies according to climatic conditions and depends on soil properties (both physical and chemical) (39,46). There are several sources for nitrogen inputs into an ecosystem, including biological fixation, atmospheric fixation (lightning) and nitrogen deposition, industrial fixation (mineral fertilizer), from soil organic matter, crop residues and animal manures (53,54). Generally speaking, nitrogen is available to plants as ammonium or nitrate (46,53,55). Other nitrogen sources must be converted before being taken up by plants. Nitrogen in soils undergoes several transformations (46,53,56,57) (Fig 2):

- Nitrogen fixation: The conversion of atmospheric nitrogen to a plant available form.
- Mineralization: Organic nitrogen in the soil is converted into inorganic nitrogen (ammonium) by microbial activity.
- Nitrification: The biological transformation from ammonium to nitrate.
- Denitrification: Bacterial transformation from nitrate to gaseous nitrogen which is transferred to the atmosphere.
- Immobilization: The conversion of inorganic nitrogen to organic nitrogen by i.e. micro-organisms.

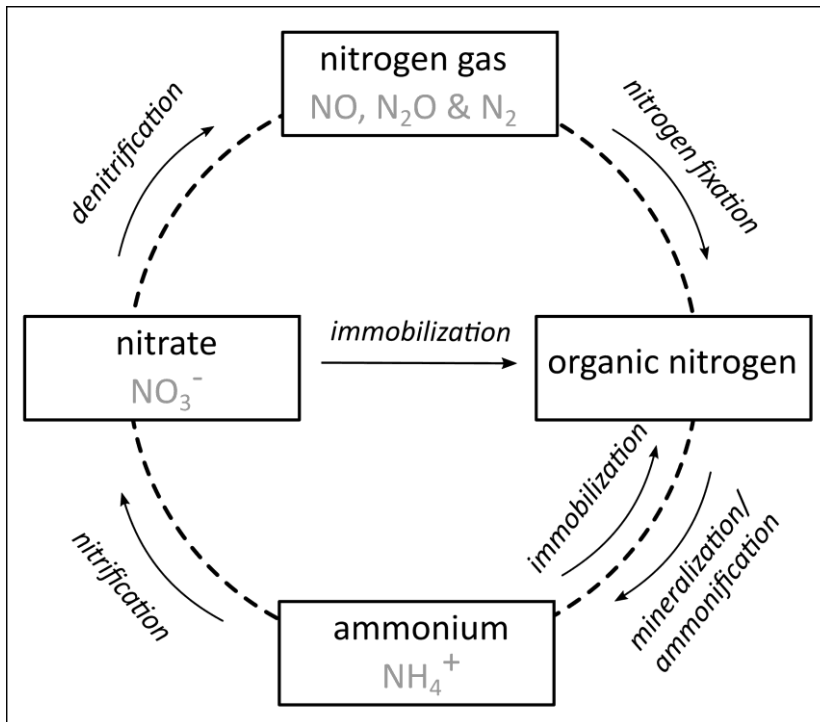


Fig 2. Simplified nitrogen cycle (after (57)).

Alongside biological transformations, physical processes, such as leaching, are also relevant for the nitrogen cycle. Leaching describes the downward movement of soluble nitrate in the soil with soil water as transport medium (40,53). Leached nitrate enters either the ground or surface water and degrades the quality of water bodies through eutrophication (18,40–42,58). Thus, eutrophication results from the excess input of nitrate or other nutrients into a water body (59). All in all, leaching, denitrification, volatilization, crop removal and soil erosion and runoff can possibly lead to nitrogen losses in a soil system. Sustainable management of nitrogen is of great importance, as insufficient nitrogen availability in our soils decrease crop production and excess quantities pollute our environment. When excess nutrients are introduced to the ground or surface water, eutrophication processes occur and endanger the ecological status of our water bodies.

3 Materials and methods

3.1 Bayesian Belief Networks

Bayesian Belief Networks (BBNs) are multivariate statistical models. They feature a probabilistic modelling approach (20,21,60) and are characterized by a high model transparency (20). The model as such consists of two parts: a direct acyclic graph (DAG) and conditional probability tables (CPTs) (20,21,61,62). The DAG depicts the dependencies between the different variables which are included in the BBN. The CPTs on the other side store the strength of the links in the graph (63). Within the DAG, dependencies are depicted as arrows representing cause-effect relations between the variables or more precisely so-called nodes (20,21). Within the acyclic graph, arrows lead from parent nodes to child nodes (20,61,64,65). The development of the DAG can be based on different techniques, e.g. system understanding by experts or learning from empirical observations (20,65). All variables which are included in the BBN contain a limited number of states. Their realized value must belong to one of these states (20). The BBN features the ability to consider uncertainties as the realized value of a particular variable can be allocated to multiple states using probabilistic methods. The CPTs store the conditional probabilities indicating the strengths of the causal relations between the different nodes (20). The BBN can be used as an integrated modelling framework bridging the gap between quantitative and qualitative data (20,62,64,66). To obtain quantitative model outputs, Bayesian inference is used to propagate these probabilities through the network (63,65). Bayesian inference is based upon the Bayesian theorem (67,68):

$$\Pr(A|B) = \frac{\Pr(B|A) \Pr(A)}{\Pr(B)} \quad (1)$$

The formula indicates that the conditional probability, or posterior probability, of an event A after event B ($\Pr(A|B)$) is observed in terms of the prior probability of A ($\Pr(A)$), prior probability of B ($\Pr(B)$), and the conditional probability of B given A ($\Pr(B|A)$). In other words, the BBN is composed

of a set of interconnected nodes. Each node represents one variable within the model. For each variable/node, there are different possible states. The causal relationship between the variables is depicted in the form of arcs. The certainty of the individual states of the nodes is determined from the certainty of each possible state of all connected nodes and their causal relationship.

For this study, we used the Software GeNIe Modeler developed by BayesFusion LLC. GeNIe is a graphical user interface to SMILE (Structural Modeling, Inference, and Learning Engine). The software allows for interactive model building and learning (21).

3.1.1 Structuring the BBN and finding cause-effect relations

We built the DAG by aligning our knowledge of the analysed social-ecological system to the data available for this research. The model development was based on the protocol by Cain (69). In the first step, we developed a general network structure including three nodes:

- the predominant landscape types,
- the preliminary *nutrient regulation* ES potential (based upon the ES matrix approach), and
- the new *nutrient regulation* ES potential.

Further variables (nodes), representing environmental characteristics, and connections were added to the network which seemed relevant according to various literature sources, expert knowledge and general system understanding. In addition to the nodes aiming to describe the *nutrient regulation* ES potential, further nodes/variables were added.

Another aim of this study was to assess ES budgets based on ES supply and demand balances. Therefore the following variables were added to the network: *nutrient regulation* ES demand, reclassified *nutrient regulation* ES potential and *nutrient regulation* ES budget. The ES demand has been defined by Jones et al. (70) as the quantity of beneficiaries and their ES needs. As described in Chapter 2.2.1 the beneficiaries of the *nutrient regulation* ES are diverse. For this modelling exercise, the nutrient surplus (exemplarily for nitrogen) which has been calculated as indicator for the *nutrient regulation* ES demand by Bicking et al. (14), was added to the BBN. The ES budget assessment, aiming

to provide information on sustainable or unsustainable conditions, was included as a very rough estimation in order to give an idea of areas of *nutrient regulation* ES over, respective undersupply. In the next step, we incorporated the available data sets (see Chapter 3.2 below) and assessed the correlation directions (positive or negative) and degrees (strengths) where possible. However, several cause-effect relations of our BBN remained open and could not be determined statistically based on the input data sets. In that case, literature evaluation in combination with expert knowledge was harnessed. The expert evaluation was executed in several rounds of valuation and all results were reviewed repeatedly. Experts from different research domains, among which soil sciences, agricultural sciences, hydrology/limnology, (physical) geography and biology, were consulted. Fig 3 indicates which nodes are based on quantitative and qualitative approaches.

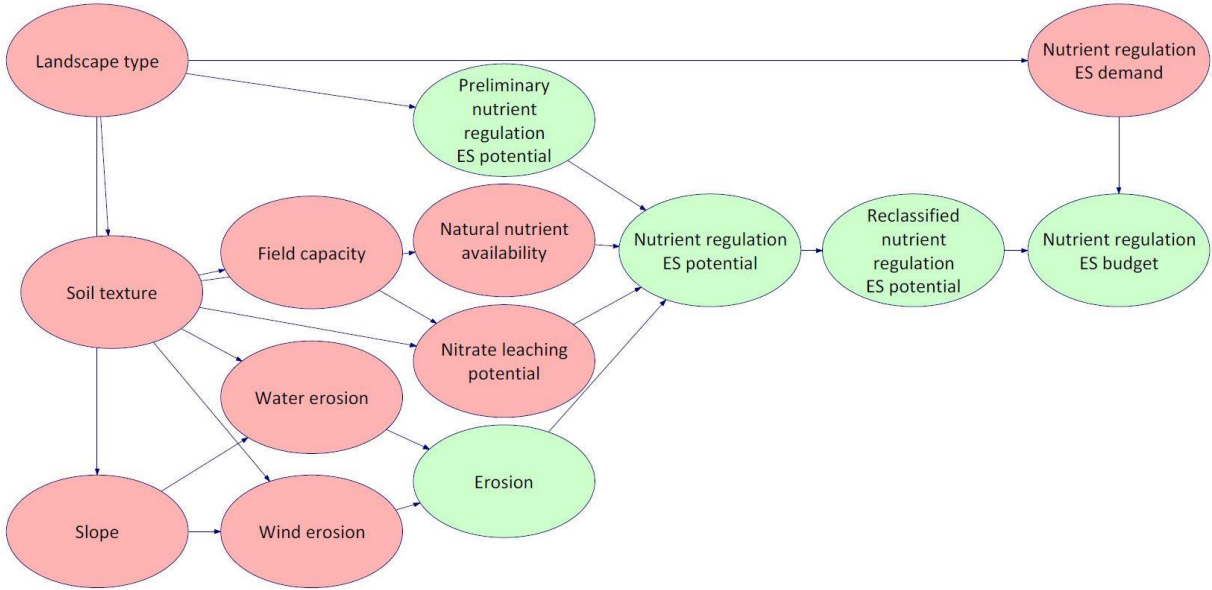


Fig 3. Structure of the BBN; colours are indicating quantitative (red) /qualitative approach (green).

The model consists in total of 14 nodes (Fig 3). The variables can fall into different states for each node. Table 1 gives an overview on the possible states for each of the nodes. The number of states for each node is dependent on the available data and the general assertion of the respective node. If possible and reasonable, we tried to define three states for each node. Furthermore, we tried to conform to classifications and evaluations of the original input data sets (see Chapter 3.2). An exception is the definition of the states of the node slope, where we used a quantile classification.

Table 1. Nodes and corresponding states.

Node	States	Description
Landscape type	Hügelland	Landscape region: Hügelland
	Geest	Landscape region: Geest
	Marsch	Landscape region: Marsch
Soil texture	sand	Predominant soil texture: sand
	peat	Predominant soil texture: peat
	silt_clay	Predominant soil texture: silt/clay
	other	Predominant soil texture: other
Slope	low	Slope: 0 – 0.2039°
	medium	Slope: 0.2039 – 0.6581°
	high	Slope: 0.6581 – 13.4431°
Field capacity	low	Field capacity: < 200 mm
	medium	Field capacity: 200-300 mm
	high	Field capacity: > 300 mm
Wind erosion	no	No wind erosion
	low	Low wind erosion
	medium	Medium wind erosion
	high	High wind erosion
Water erosion	no	No water erosion
	low	Low water erosion
	medium	Medium water erosion
	high	High water erosion
Natural nutrient availability	low	< 300 kmol _c /ha
	medium	300 – 600 kmol _c /ha
	high	> 600 kmol _c /ha
Nitrate leaching potential	low	Low nitrate leaching potential
	medium	Medium nitrate leaching potential

	high	High nitrate leaching potential
Erosion	low	Low erosion potential
	medium	Medium erosion potential
	high	High erosion potential
Preliminary <i>nutrient regulation</i> ES potential	P_no	No relevant potential
	P_1	Low relevant potential
	P_2	Relevant potential
	P_3	Medium relevant potential
	P_4	High relevant potential
	P_5	Very high relevant potential
<i>Nutrient regulation</i> ES potential	P_no	No relevant potential
	P_1	Low relevant potential
	P_2	Relevant potential
	P_3	Medium relevant potential
	P_4	High relevant potential
	P_5	Very high relevant potential
Reclassified <i>nutrient regulation</i> ES potential	low	Low potential supply of <i>nutrient regulation</i>
	medium	Medium potential supply of <i>nutrient regulation</i>
	high	High potential supply of <i>nutrient regulation</i>
<i>Nutrient regulation</i> ES demand	low	Nitrogen surplus: ≤ 40 kg N/ha
	medium	Nitrogen surplus: 41-60 kg N/ha
	high	Nitrogen surplus: > 60 kg N/ha
<i>Nutrient regulation</i> ES budget	sustainable	Potential higher than demand for <i>nutrient regulation</i> ES

	unsustainable	Potential lower than demand for <i>nutrient regulation ES</i>
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3.1.2 Validation of the BBN

For model validation, we chose different types of validation processes: expert-based, sensitivity analysis and k-fold cross validation. In a first step, in order to validate the structure and validity of the model, experts were consulted. Concerns were related to oversimplification of the model structure and subjectivity which comes along with the generation of the CPT table. In a next step, a sensitivity analysis was executed for the target variable *nutrient regulation ES* potential (Fig 4). Such a sensitivity analysis determines the influence of the other variables on the target variable (21,65), indicating the effect of minor changes on the probability of a state on the probability distribution of the target variable (63). Thus, these variables affect the results more significantly. Within the BBN software GeNIe, an algorithm by Kjaerulff and van der Gaag (71) is implemented which performs the sensitivity analysis. The algorithm calculates for one or more target nodes, derivatives of the posterior probability distributions over the target nodes over each of the numerical parameters. The higher the derivative for a variable, the larger is the influence on the respective posteriors (21). The sensitivity analysis (Fig 4) reveals that the target variable, which is the *nutrient regulation ES* potential, is most sensitive to the variables landscape type, soil texture, field capacity, nitrate leaching potential and preliminary *nutrient regulation ES* potential.

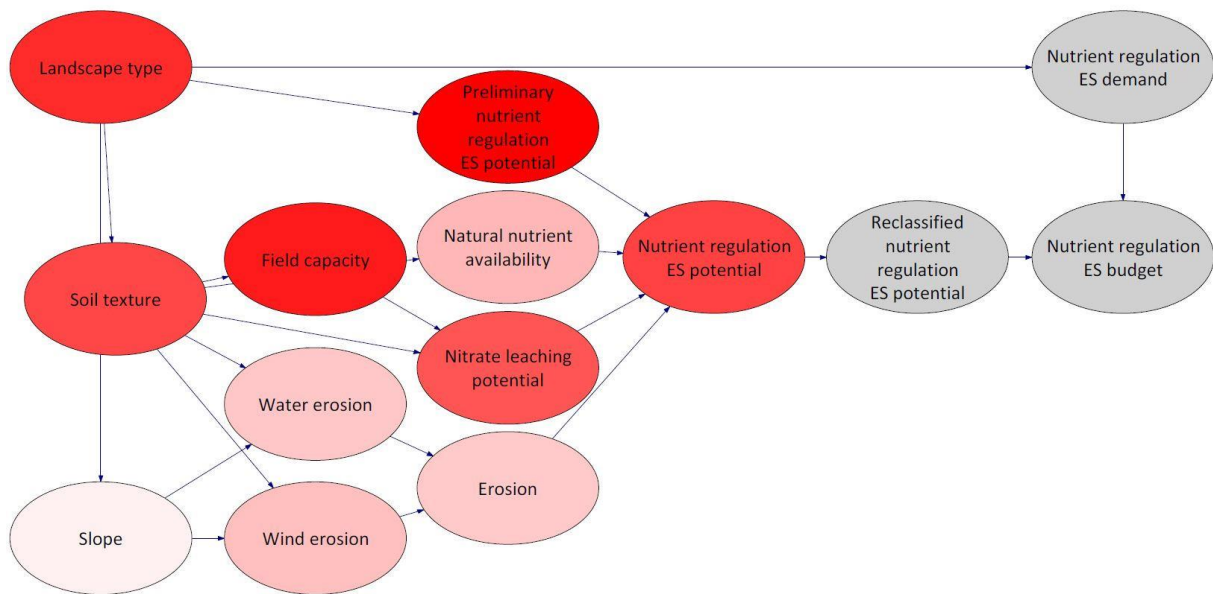


Fig 4. Sensitivity analysis for the node nutrient regulation ES potential in Schleswig-Holstein (intensity/strength of red colour indicates strength of influence).

When learning and evaluating a model with the same data set, cross-validation is an appropriate evaluation method (21). Cross-validation divides the data set into subsets for training and testing. The k -fold cross-validation, which is included in GeNIe, divides the data set into k -parts. Each data set is of equal size. $k - 1$ subsets are used for training and last k th subset is used for testing. This procedure is repeated k times (21). The performance measure of the model is the average of all individual performances (63). Thus, the whole data set can and has been used for training and testing (63).

3.2 Input data for the BBN

The quality of the input data is key for the applicability of BBN-based assessments. Data sets for the two study areas were collected in the form of digital maps (ArcGIS shape files). The data were extracted from the shape files using a pre-defined grid in the ArcMap 10.3 GIS software. The grid size was approximately 200 m, resulting in more than 300'000 data points for the study area of Schleswig-Holstein and around 1'500 data points for the Bornhöved Lakes District area. Table 2 gives an overview of the data sets which were used for this research in both study areas. The data sets have been cleaned, processed and discretized in order to fulfil the input requirements of the BBN.

Table 2. Input data.

Data set	Description	Resolution/ Scale	Source
CORINE LULC	Vector	10 ha	Bundesamt für Kartographie und Geodäsie (BKG, eng.: Federal Agency for Cartography and Geodesy) (http://www.geodatenzentrum.de/); European Environment Agency/ Copernicus (https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012/)
Nitrate leaching potential	Vector	1:250 000	Landesamt für Landwirtschaft, Umwelt und ländliche Räume (LLUR, eng.: State Agency for Agriculture, the Environment and Rural Areas) (http://www.umweltdaten.landsh.de)
Nutrient availability in the effective root zone	Vector	1:250 000	LLUR (http://www.umweltdaten.landsh.de)
Field capacity in the effective root zone	Vector	1:250 000	LLUR (http://www.umweltdaten.landsh.de)
DEM	Raster	200 m	BKG (http://www.geodatenzentrum.de/)
Soil texture	Vector	1:250 000	LLUR
Landscape Types	Vector	-	LLUR (http://www.umweltdaten.landsh.de)
Water erosion	Vector	1:250 000	LLUR (http://www.umweltdaten.landsh.de)

Wind erosion	Vector	1:250 000	LLUR (http://www.umweltdaten.landsh.de)
<i>Nutrient regulation</i> ES demand – Schleswig-Holstein	Vector	Municipalities	(14)
<i>Nutrient regulation</i> ES demand – Schleswig-Holstein	Vector	See CORINE data set	(14)

In addition to these data sets, the values for the *nutrient regulation* ES potential published in the ES matrix by Burkhard et al. (10) were adopted. The values range from 0 (no relevant ES potential) to 5 (highest ES potential) and were joined to the CORINE LULC data set using ArcMap 10.3 in order to come up with the corresponding distribution of the *nutrient regulation* ES potential within the study areas.

The colours of the nodes within the BBN were selected in order to support the understanding of the BBN structure. The nodes of all data sets which were used to predict the *nutrient regulation* ES potential are blue, with the exception of the grey-coloured node landscape types. The predicted node *nutrient regulation* ES potential as well as the reclassified *nutrient regulation* ES potential are greenish in order to visually represent the supply side of the ES, whereas the *nutrient regulation* ES demand is red in order to represent the opposite. The *nutrient regulation* ES budget is orange.

4 Results

4.1 Nutrient regulating ecosystem services in Schleswig-Holstein

From the BBN assessment, the following structure and corresponding probability distributions resulted for Schleswig-Holstein (Fig 5): The states *no relevant*, *low relevant* and *relevant* of the variable *nutrient regulation* ES potential share a probability of more than 80 %, whereby *no relevant* and *low relevant* make a contribution of 32% and 35%, respectively. The figure also depicts the overall probability

distributions of the nodes depicting further environmental characteristics of the study area as well as the *nutrient regulation* ES demand and budget nodes. With regard to the *nutrient regulation* ES budget, the state *sustainable* is most probable (more than 50%). The width of the arcs distinguishes the influence of the parent node on the corresponding child node. The influence between the landscape types on the preliminary *nutrient regulation* ES potential node is notably weak. Contrary to that, strong influences can be detected between landscape types and natural circumstances such as soil texture and slope.

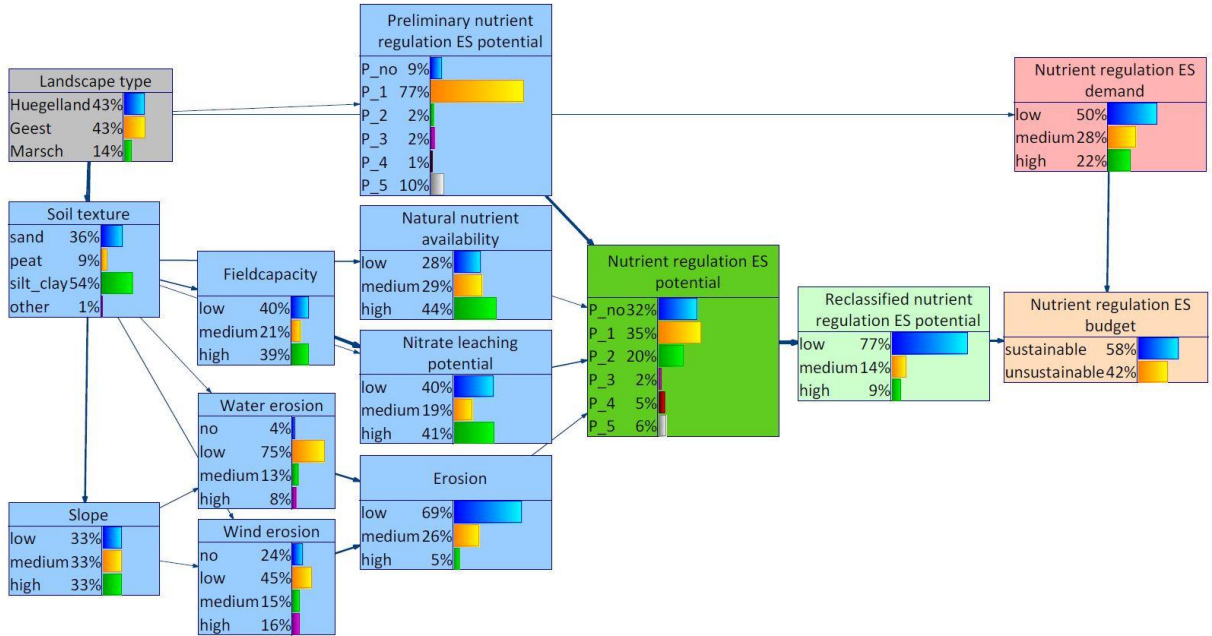


Fig 5. BBN for Schleswig-Holstein. The width of the arcs indicates strength of influence.

4.1.2 Altered distribution

Through the integration of additional data into the assessment of the *nutrient regulation* ES potentials, the probability distribution became diffused. Fig 6 presents this alteration for the former *low relevant* (left) and *high relevant* (right) *nutrient regulation* ES potentials. The shifted probability distributions still peaked at the corresponding former state, but only with around 40 percent. The probability was scattered among neighbouring states.

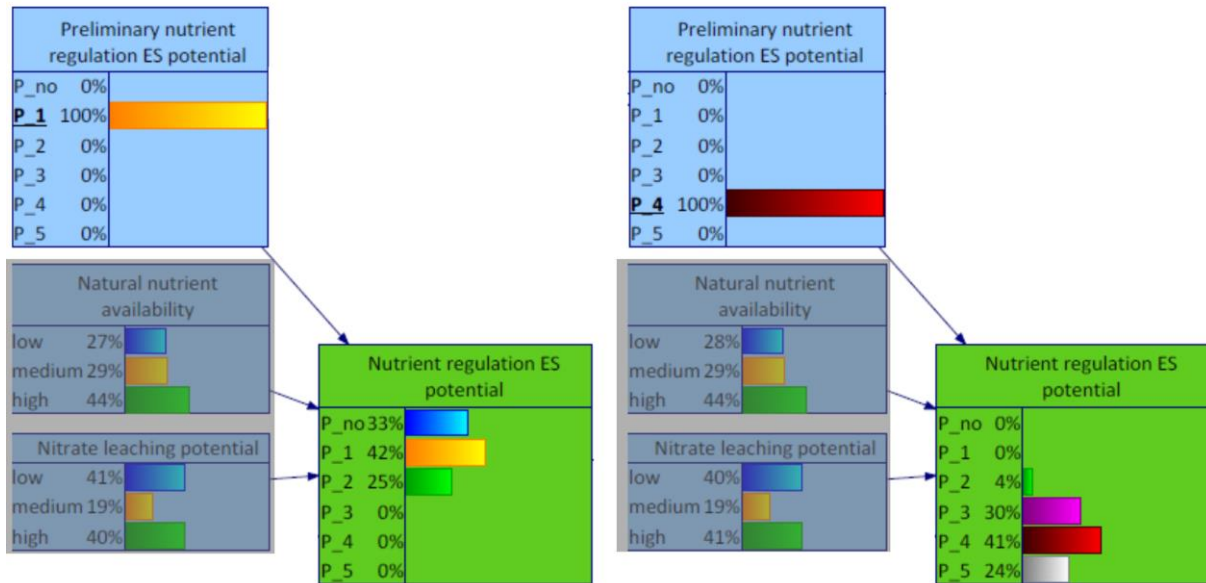


Fig 6. Excerpt of the BBN for Schleswig-Holstein focusing on changing nutrient regulation ES potential level, exemplarily for original low potential (1, left) and high potential (4, right).

4.1.3 Regional differentiation

Both, the *Hügelland* and the *Marsch* (Figs 7 and 8), were featured with highest probabilities for silty/clayey soils. This distribution was also reflected in the probability distributions of the other site-specific characteristics, in particular natural nutrient availability, field capacity and nitrate leaching potential. As a result, the probability distribution of the *nutrient regulation* ES potential is highest for *low relevant nutrient regulation* ES potential. Also the class *relevant nutrient regulation* ES potential scores a relatively high probability. The probability distribution of the node slope differs most between the *Hügelland* and the *Marsch* (Figs 7 and 8). While the *Marsch* was characterized with lower than average slopes, the opposite was true for the *Hügelland*. This difference was also reflected in the probability distributions of the child node water erosion.

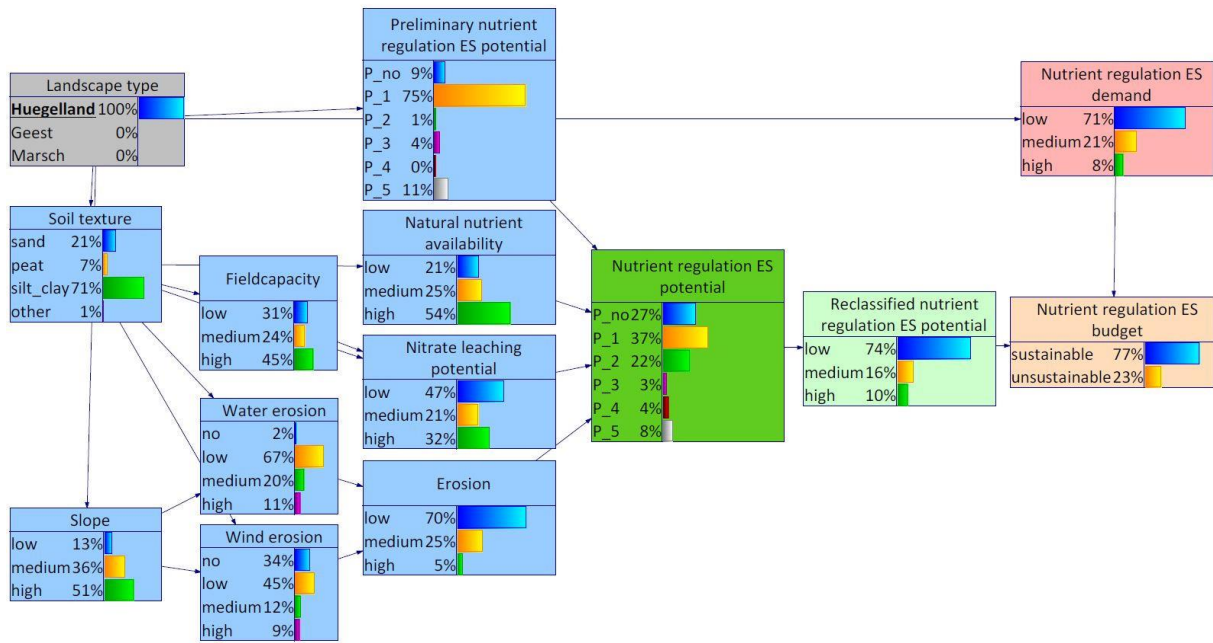


Fig 7. BBN for Schleswig-Holstein, landscape type Hügelland set as evidence.

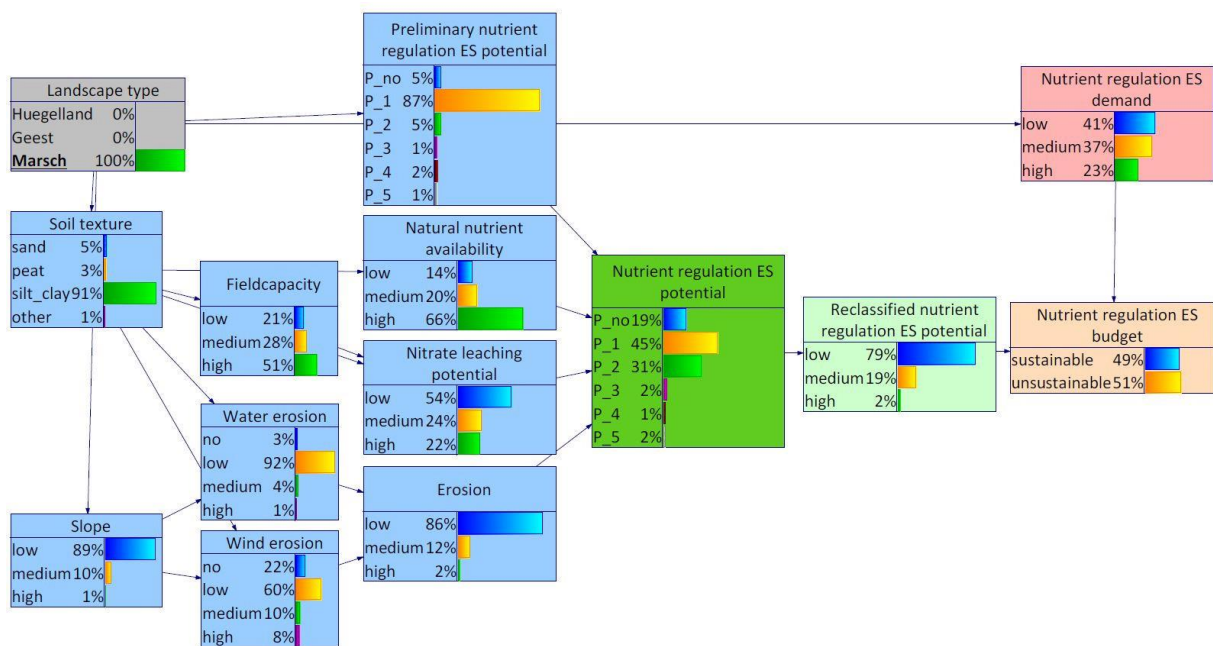


Fig 8. BBN for Schleswig-Holstein, landscape type Marsch set as evidence.

For the *Geest*, the BBN indicated highest probabilities for sandy soils which was in turn also reflected in the probability distributions of the other site-specific characteristics (Fig 9). The probability distributions of the nodes slope and water erosion roughly resembled the average distributions for Schleswig-Holstein. In contrast to that, the probability distribution of the node wind erosion indicated

higher wind erosion risks in the *Geest* than in the rest of the study area. Altogether, the probability distribution of the node (overall) erosion indicated highest risks for erosion in the *Geest*. Furthermore, the probability distributions indicated generally lower natural nutrient availability and higher nitrate leaching potentials in the *Geest* compared to the other landscape types. Altogether, this resulted in a probability distribution for the node *nutrient regulation* ES potential which indicates a lower than average potential *nutrient regulation* in the *Geest* area. In addition, the *nutrient regulation* ES demand in the area was higher than average. With regard to the *nutrient regulation* ES budget, *unsustainability* was more probable in the *Geest* than for the other two landscape types.

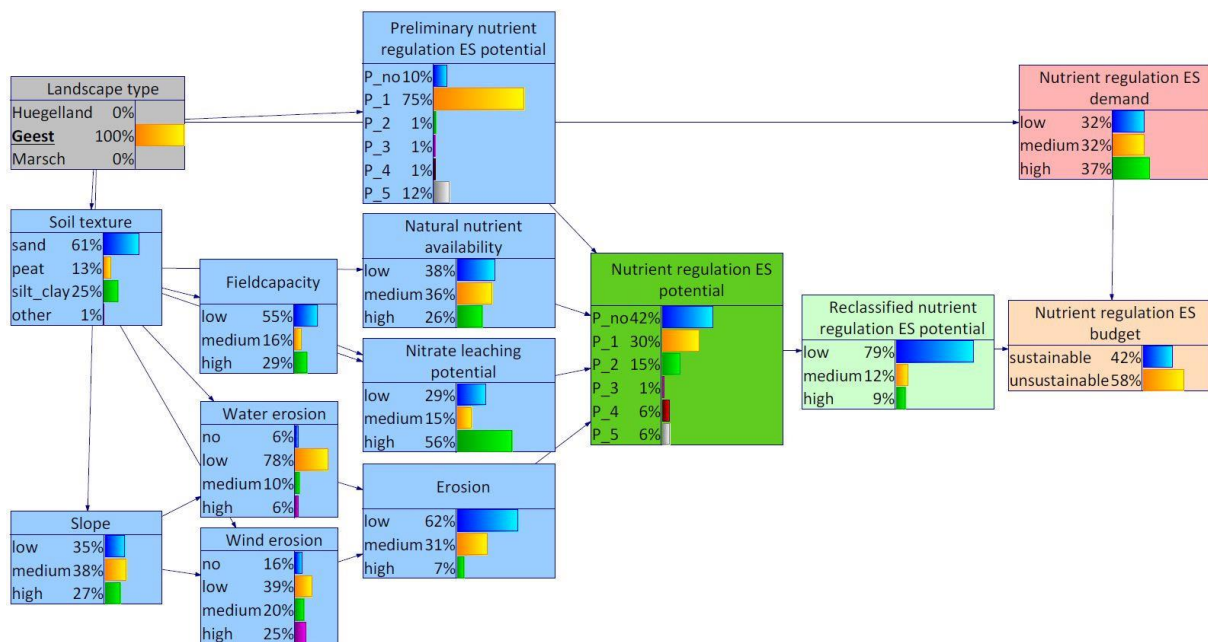


Fig 9. BBN for Schleswig-Holstein, landscape type *Geest* set as evidence.

4.2 *Nutrient regulation* in the Bornhöved Lakes District

The results from the assessment of the Bornhöved Lakes District scale resemble the outcomes on the scale of the federal state. As described in section 2.1.2, the Bornhöved Lakes District is located at the border of the two landscape types *Hügelland* and *Geest*. The *Marsch* area is not part of the Bornhöved Lakes District which can be recognized in the probability distribution of the corresponding states of the variable landscape types.

In the Bornhöved Lakes District, the probability distribution for the variable slope differed from the distribution for Schleswig-Holstein (Fig 10). Higher probabilities could be found for the states *medium* and *high*. The probability distribution of the *nutrient regulation* ES demand differed most from the distribution for Schleswig-Holstein. The highest probability was attributed to the state *medium* instead of *low*. As consequence, the probability distribution of the *nutrient regulation* ES budget shifted somewhat resulting in a share of 51% for the state *unsustainability* (Fig 10).

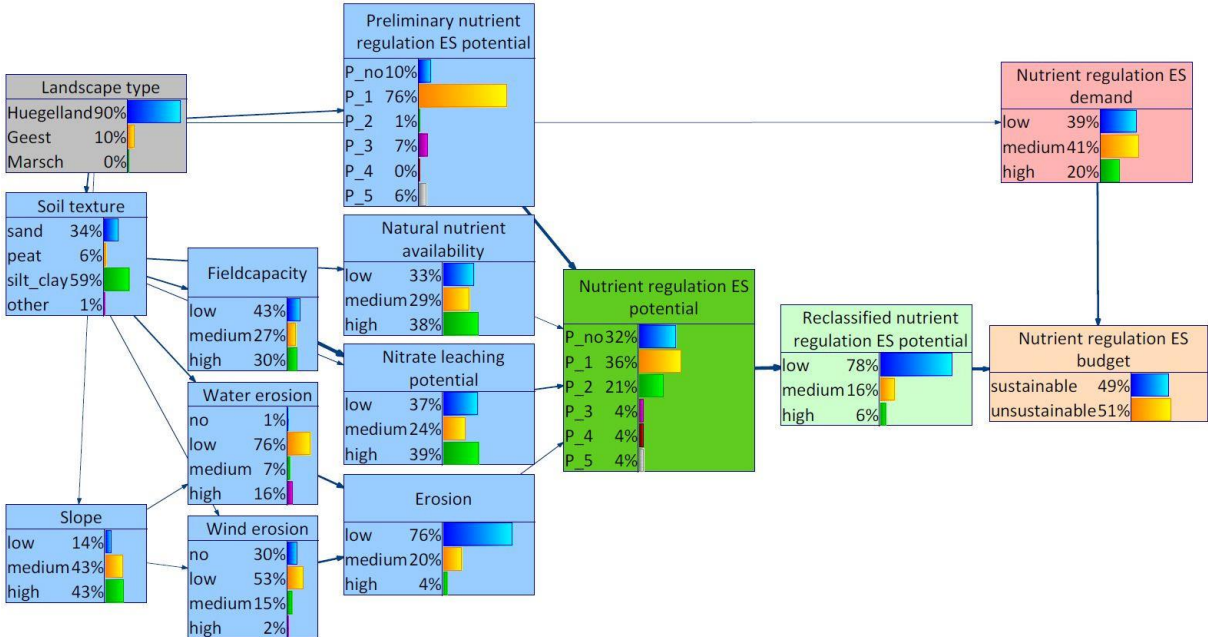


Fig 10. BBN for Bornhöved Lakes District. The width of the arcs indicates strength of influence.

When differentiating between the landscape types *Geest* and *Hügelland* within the Bornhöved Lakes District, differences were found with regard to the demand as well as the supply side of the *nutrient regulation* ES (Figs 11 and 12). Selecting *Geest* as evidence, the states *medium* and *high* both featured probabilities of 37%. In combination with a somewhat lower *nutrient regulation* ES potential, the state *unsustainable* of the variable *nutrient regulation* ES budget reached 70%. The shift on the supply side resulted from many marginal differences in the probability distributions of the environmental conditions, notably soil texture and dependent child variables.

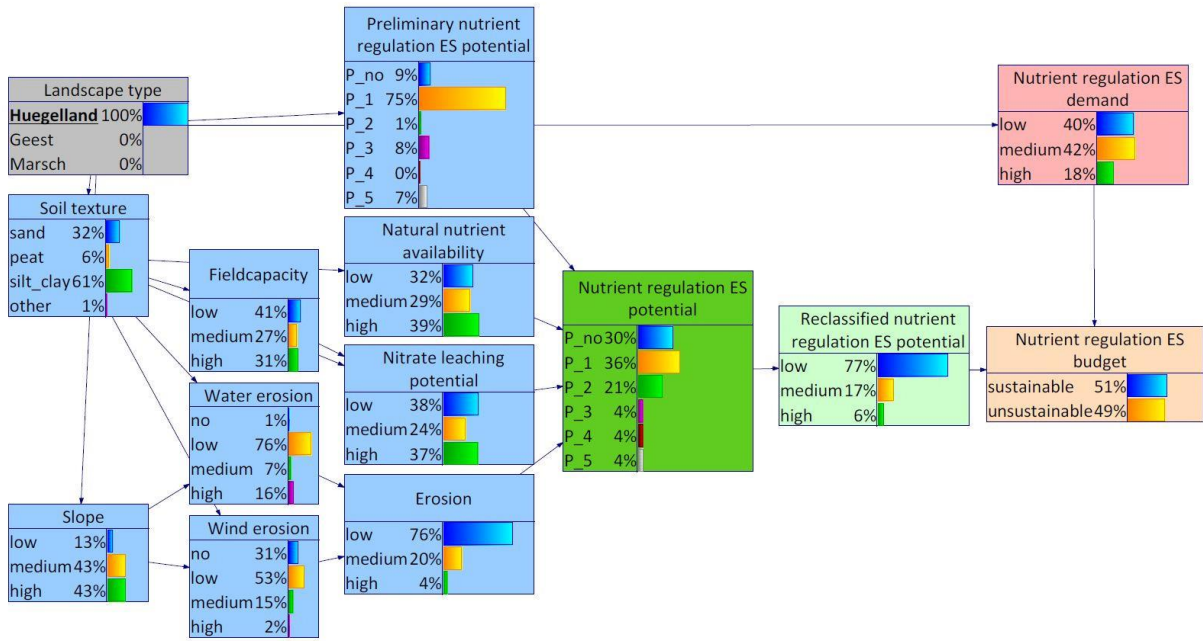


Fig 11. BBN for Bornhöved Lakes District, landscape type Hügelland set as evidence.

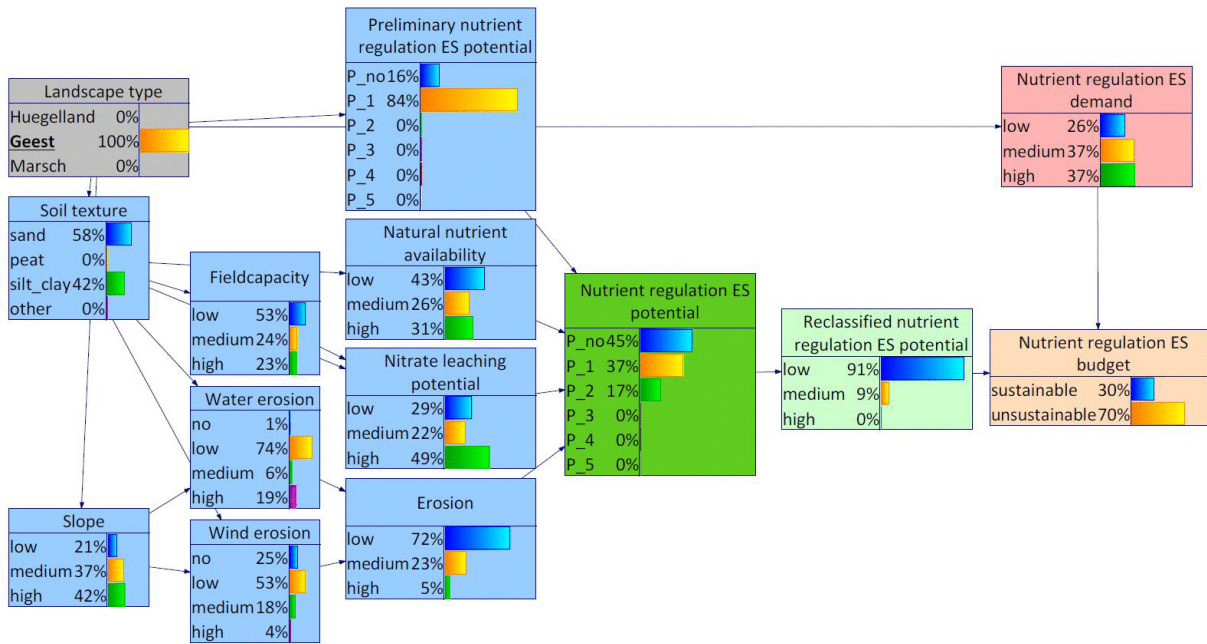


Fig 12. BBN for Bornhöved Lakes District, landscape type Geest set as evidence.

5 Discussion

5.1 Findings

According to the outcomes of the BBN, around one third of Schleswig-Holstein had *no relevant nutrient regulation* ES potential. More than 50% of the area was characterised by (*low*) *relevant* ES potentials. The remaining portion was distributed between *medium*, *high* and *very high relevant* ES potentials. Comparing these values with the original distribution of *nutrient regulation* ES potential based on the matrix values provided in the ES matrix by Burkhard et al. (10), a broader distribution could be identified (Fig 13). The original distribution peaked more extremely at *low relevant* ES potentials (with more than 70%). This alteration was also demonstrated for the distribution of *low* and *high relevant* *nutrient regulation* ES potentials separately (Fig 6).

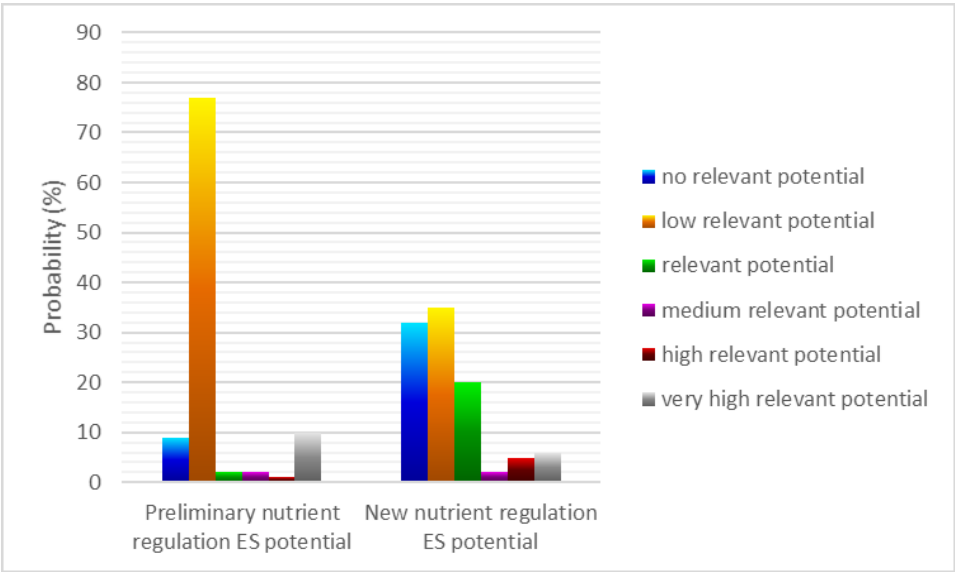


Fig 13. Probability distribution of the preliminary and new nutrient regulation ES potential.

The study revealed a regional differentiation of *nutrient regulation* ES potentials in Schleswig-Holstein. While the areas of the *Hügelland* and *Marsch* obtained higher probabilities for higher ES potentials compared to the whole federal state, the results for the *Geest* turned out to be considerably lower. The incorporation of the data on site-specific properties was reflected in the outcomes. Regional differences with regard to the probability distributions of the environmental conditions such as slope

and soil texture corresponded to the background information of the study areas. For instance, the area of the *Geest* was characterized by poor, sandy soils (see study area for more information) which are susceptible to wind erosion and nitrate leaching. These soils have relatively low field capacities and natural nutrient availability rates. These circumstances led to the obtained outcomes.

Considering the *nutrient regulation* ES budget, the results highlighted this regional issue. The *Geest* obtained high probabilities for an unsustainable *nutrient regulation* ES budget, as the area is featured by a low potential ES supply and a relatively high ES demand. The *Hügelland* obtained highest probabilities for a balanced ES budget as the area is featured by an average potential supply and a relatively low *nutrient regulation* ES demand.

Setting up the BBN for both study areas, the following conclusions can be made with regard to the issue of spatial scales: The time used for setting up the BBN for the study areas did not depend on the size of the study area. While training the BBN nodes, the elapsed time differed for the two different data sets in relation to the amount of data points. This difference can, however, be summed up to minutes only. In our case, different resolution input data had the greatest chance to provoke differences related to the issue of scale. This was the case in our BBN for the node *nutrient regulation* ES demand. The underlying data sets, which were adopted from Bicking et al. (14), differ in resolution. For Schleswig-Holstein, the demand was specified on the level of municipalities. The data set for the Bornhöved Lakes District was spatially more explicit, based on the polygons of the CORINE LULC shape file. As result, the probability distribution of the variable *nutrient regulation* ES budget differed considerably from the results on the Schleswig-Holstein scale. This alteration became even more distinct when the BBN for the Bornhöved Lakes District was assessed for the different landscape types. These findings indicate that the analysis on a larger scale and with a lower resolution underestimated the issue.

5.2 Strengths vs. limitations and uncertainties

Within this research, we combined quantitative data sets with information from expert evaluation in order to include as much valuable information as possible into the BBN. Only four out of the fourteen

nodes (the CPTs) have been filled in manually based on expert knowledge. For the remaining ten nodes, the BBN was trained by input data from other sources. Thus, more than 70% of the nodes in the BBN were based upon spatial data sets. However, the target node (*nutrient regulation* ES potential) can be found under the four nodes with expert-based constructed CPTs. Expert evaluation generally comes along with a range of uncertainties (12,72). Experts tend to base their evaluations strongly on their personal experience, knowledge, living conditions and attitude (11,12). As proposed in recent literature (11,73), we aimed to limit the uncertainties with regard to the expert evaluation as we consulted experts from different relevant research fields. However, the number of experts was limited and contributed considerably to the uncertainties of this study.

We assessed the *nutrient regulation* ES potential exemplarily for the nutrient nitrogen. As different nutrients vary with regard to chemical as well as physical properties, the processes in the environment differ and thus the structure of the BBN as well as its relations need to be adapted in order to obtain realistic results. Besides, the nodes included in a BBN contain a limited number of states. The data which served as model input were reclassified in order to fit this requirement. Defining different states and/or using a different reclassification scheme alters the distribution of the data, which in turn could result in the delivery of different outcomes with regard to the *nutrient regulation* ES potential analysis and eventually shift the sustainability decision. One needs to keep in mind that the ES budget node has been included into the network in order to allow for a rough estimation with regard to the balance of the ES demand and supply. That was why the resulting probability distributions should not be over-interpreted but only be regarded as a rough approximation.

The focal objective of the study was to test the application of a BBN as an integrative modelling approach combining the information from the ES matrix with additional data sets. The BBN model did not attempt to compile a complete network resembling complex reality as elaborately as possible. Altogether, we only used a limited number of variables to describe the *nutrient regulation* ES potential. The complexity of the environmental system was not entirely reflected in the constructed BBN which can be seen as a basic overview. On the one hand, we chose to keep it simple, as it fitted the target of

our study. On the other hand, data availability could be identified as major constraint. If an environmental system is to be simulated as much as possible, further site-specific characteristics, such as information on soil organic matter content, landscape structures and precipitation, should be included in the BBN.

According to Hou et al. (72), ecosystem services evaluation on the landscape scale involves various uncertainties. These uncertainties can be associated with issues concerning the initial data and the preferences of respondents (regarding expert evaluation), technical problems, methodological uncertainties and the general complexity of natural systems. All of these issues represent constraints identified in ecosystem service research (72,74) and are valid for the practical implementation of this study. A further constraint arises from the implementation of a rather abstract concept to a specific approach involving particular methodologies and data sets.

6 Conclusions

6.1 General conclusions

Summing up the outcomes obtained from this study, the hypotheses put forward in the introduction were evaluated:

- I. **The inclusion of data on site-specific properties for the assessment of the *nutrient regulation* ES potential results in a more scattered distribution of the ES potentials compared to the ES matrix values provided by Burkhard et al. (10).**

Yes, the probability distribution for the *nutrient regulation* ES potential based on the BBN was found to be wider than the original distribution based on the ES matrix values, which evaluated the *nutrient regulation* ES potentials for CORINE LULC types. The inclusion of more data on site-specific properties resulted in a more diverse pattern in regard to the probabilities of the *nutrient regulation* ES potentials.

II. The assessment of the *nutrient regulation* ES potentials results in a regional differentiation in Schleswig-Holstein.

Incorporating site-specific properties into the *nutrient regulation* ES potential assessment revealed the different potentials of the three main landscape types. The probability distribution of the *Hügelland* and *Marsch* peaked for low relevant potentials, whereas the *Geest* was featured with the highest probability for no relevant ES potentials. This regional differentiation became even more obvious concerning the estimated *nutrient regulation* ES budget (potential supply vs. demand). The area of the *Geest* unified relatively high probabilities for low *nutrient regulation* ES potentials and remarkably higher probabilities for high demand for *nutrient regulation* ES.

III. The probability distribution of the *nutrient regulation* ES potential in the Bornhöved Lakes District resembles the distribution for Schleswig-Holstein.

In general, the two BBNs delivered similar probability distributions. The greatest difference existed between the *nutrient regulation* ES demand. The Bornhöved Lakes District was characterized by higher demands compared to Schleswig-Holstein. This was reflected in the probability distribution of the *nutrient regulation* ES budget which identified higher probabilities for an unsustainable ES budget in the Bornhöved Lakes District. Similar to the BBN for Schleswig-Holstein, the BBN for the Bornhöved Lakes District also identified the *Geest* as an area with high probabilities for relatively low *nutrient regulation* ES potentials and relatively high *nutrient regulation* ES demand. However, minor differences became apparent with regard to the magnitude of the mismatch. The mismatch at the scale of the Bornhöved Lakes District depicted an even clearer picture.

It is striking that in spite of the distinct spatially varying distribution of the environmental conditions, land management with regard to agricultural practices has not been adapted to these circumstances. Land management aiming to adjust practices in accordance with the regional environmental conditions

would result in more sustainable agriculture. Such a site-specific agriculture would help to save resources while at the same time safeguard the environmental conditions and biodiversity of our ecosystems.

In summary, it can be stated that the BBN is an appropriate method in order to integrate additional data to the spreadsheet matrix approach for assessing ecosystem services. The possibility to include both qualitative and quantitative data to the network emphasizes the convenience of the approach. After the execution of this study, we share the belief that the use of BBNs to model ecosystem services using both empirical data and expert knowledge is promising (20,62).

This fact increases the value of the BBN for ES research as data from the different research domains (environmental, socio-cultural and economic) can easily be integrated. In our case, the integration of further spatially explicit data resulted in a distinct regional pattern with regard to the ES *nutrient regulation*. Outcomes which are based on higher resolution input data emphasised the unsustainable situation with regard to agricultural practices.

6.2 Future research

If data on cultivated crop types and their properties in the study areas would be incorporated into the BBN, more elaborate conclusions could be drawn on sustainability with regard to the *nutrient regulation* ES potential. In this context, the integration of land management options into the BBN would be an interesting approach. Land management options such as tillage are crucial for the determination of the *nutrient regulation* ES potential of agricultural grounds. The timing as well as the tillage technique employed influence the potential for soil loss through erosion and simultaneously the potential for nutrient loss in the system. Especially in combination with scenario assessments, this integration could deliver highly interesting results. In the future, it would be interesting to include further ES into the BBN. We find it exciting to assess whether one can come up with one pervasive network which could be applied for ES assessments on top of the matrix approach by Burkhard et al. (10).

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6

Comprehensive assessment of the ES crop production

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Combining methods to estimate ecosystem integrity and ecosystem service potentials and flow for crop production in Schleswig-Holstein, Germany

Zeleny, J., S. Bicking, K.B. Dang and F. Müller

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This paper delivers a comprehensive assessment of selected ecological integrity variables as well as the crop production ES potential and flow in the federal state of Schleswig-Holstein. Thereby, the study focuses on the evaluation of ecological integrity as the base for the capacity of an ecosystem to provide the ES crop production.

COMBINING METHODS TO ESTIMATE ECOSYSTEM INTEGRITY AND ECOSYSTEM SERVICE POTENTIALS AND FLOWS FOR CROP PRODUCTION IN SCHLESWIG-HOLSTEIN, GERMANY

Jakub Zelený¹, Sabine Bicking², Kinh Bac Dang^{2,3}, Felix Müller²

(1) Charles University, Faculty of Humanities, U Kříže 8, 158 00 Prague 5, Czech Republic

(2) Kiel University, Institute for Natural Resource Conservation, Olshausenstr. 75, 24118 Kiel, Germany; Corresponding Author: sbicking@ecology.uni-kiel.de

(3) Faculty of Geography, VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

Abstract

Human well-being is strongly dependent on the benefits supplied by ecosystems, especially for food provision. This study has been developed in the ecosystem service framework and focuses on the evaluation of ecological integrity as a base for the capacity of Schleswig-Holstein to provide the ecosystem service crop production. We hypothesize that ecological integrity itself is the base for the natural *potential* of a selected region, but both low *potential* and integrity can be substituted by artificial inputs like fertilizers. The *potential* of an ecosystem to provide the service crop production is assessed based upon two different approaches; a Bayesian belief network (semi-qualitative) and the qualitative ecosystem service matrix. The service *flow* is estimated based upon official regional statistics. The spatial distribution of six different ecological integrity variables, the crop production *potential* and

*Corresponding author. Email: name@emailaddress.xy

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flow are compared and interpreted with respect to the characteristics of the main landscape regions within the study area. The results indicate a decoupling of the actual crop production from the ecosystem conditions and respective service *potentials*. The findings of the study can be used to support the development of sustainable land management strategies, which aim to harmonize agricultural production and environmental conditions.

KEY WORDS: Ecosystem research, quantification and mapping, indicators, Bayesian Belief Network, remote sensing, regional statistics, expert evaluation, interrelation analysis

Research highlights

- Comprehensive ecosystem assessment at the level of the federal state of Schleswig-Holstein.
- Quantification and mapping of ecological integrity and ecosystem services.
- Evaluation of spatial interrelations between ecological integrity and ecosystem services.
- Identification of spatial mismatches between ecological integrity and intensive crop production.
- Regional comparison of the performance of crop-, grassland and forests with respect to selected ecological integrity variables.

1 Introduction

Ecosystem services (ES) are defined as the goods and benefits that people obtain from ecosystems (De Groot et al. 2002; Burkhard et al. 2009, 2012; Ash et al. 2010; Syrbe & Grunewald 2017). More precisely, “ecosystem services are the contributions of ecosystem structure and function – in combination with other inputs – to human well-being” (Burkhard et al. 2012, p.2). The concept of ES articulates the importance of the biosphere to humanity in the broadest sense.

The ecosystems’ structures, processes and functions are fundamentals for the capacity of an ecosystem to provide ES (Paetzold 2010; Burkhard et al. 2010; Kandziora et al. 2013; Hou et al. 2014, Müller & Kroll 2011; Müller & Burkhard 2012; Syrbe et al. 2017; Maes et al. 2018). The functions of an ecosystem are commonly referred to as ecosystem conditions and can be indicated using ecological integrity (EI) variables (Müller & Burkhard 2012; Schneiders & Müller 2017). Even though, there is a general scientific acceptance of the basic role of ecological integrity as a fundament of ES provision, there are knowledge gaps with respect to their specific interactions and influences (Erhard et al. 2017; Laurila-Pant et al. 2015; Liqueste et al. 2016). Since landscape features such as climatic, soil and biological conditions are arguably co-dependent to a large degree, seeing them as an interacting network should yield a more complete understanding of the factors determining production and its efficiency (see Figure 1).

We assume that by looking at ES alone, one can get an incomplete perspective on the management concerning ecosystem efficiency and thus desirability. Therefore, the aim of this study is not only to provide a comprehensive ecosystem assessment by applying a combination of multiple data sources and methodological approaches, but also to shed some light on the relationships and dependencies between the assessed variables of ecological integrity and ecosystem services in the landscape context.

A sustainable utilization of ES can be facilitated by a better understanding of the complexity of landscapes. Although progress in this field has been difficult due to historical lack of spatially explicit and statistically comparable data, modern technologies like remote sensing and probabilistic modelling open up new possibilities, which can successfully be used to quantify ecologically relevant features (Niemi & McDonald 2003; Müller & Burkhard 2012; Kandziora et al. 2013; Nielsen & Jørgensen 2013). Spatial analysis and representation (mapping) is useful to visualize natural assets, trade-offs between different interests and to promote efficient management strategies (Hou et al. 2013; Burkhard et al. 2013). Furthermore, spatial analyses

can be performed in order to create knowledge on human-environmental interactions (Burkhard et al. 2012; Schröter et al. 2014; Burkhard & Maes 2017b).

The common drawbacks of spatial analyses are related to data scarcity, scale and resolution mismatches and multiple uncertainties concerning data aggregation, representation, integration and interpretation. Therefore, the combination and aggregation of multiple data sources is one of the approaches to resolve the commonly appearing problem of data scarcity, because data is converted to a common format and resolution (Hou et al. 2013; 2014). Such transformations are, naturally, bound to a whole array of uncertainties. However, on the other hand, they gain the advantage of comparability by statistical analyses. Next to the quantification of EI and ES in the study area, mapping and spatial analysis of the variables has been key for this study. In the following sections, further information is provided on the general concepts of ecological integrity and ecosystem services.

1.1 *Ecological integrity*

The common understanding of the word “integrity” is wholeness or, an undisturbed state of being (Cambridge dictionary, 2019). In ecological terms, integrity can be understood as the proximity from a natural reference (Karr & Dudley 1981; Karr, 1993; Westra et al 2000; Andreasen et al. 2001) or as the degree of ecosystem maturity (Kay & Schneider 1992; Jørgensen et al. 2007). This study incorporates the understanding of ecological integrity as the degree of self-organization determining certain holistic system features. Since ecological systems are capable of oriented development without external influences (autopoiesis, Maturana & Varela 1998), the degree of self-organization can be used to measure and represent ecosystem integrity (Schneider & Kay 1994; Müller 2005; Parrot 2010). Integrity consequently stands in a contradiction to negative human influences, also referred to as hemeroby (Hill et al. 2002), which usually introduces disturbances or stress to ecosystems. In this fashion, Barkman et al. (2001) have defined ecological integrity as “a political target for the preservation against non-specific ecological risks, that are general disturbances of the self-organizing capacity of ecological systems” (Müller 2005, p. 283). Kay and Schneider (1992, p. 159) have argued for integrity in a similar fashion: “Integrity of an ecosystem refers to its ability to maintain its organization,” emphasizing the capacity of integer ecosystems to remain in a highly organized state despite being influenced by disturbances and gradual changes.

Frameworks suggesting landscape scale integrity assessments have occasionally emerged, suggesting an index of regional integrity (Slocombe 1992; Andreasen et al. 2001; Reza & Abdullah 2011). Ecological integrity variables are also good proxies to assess ecosystem conditions. They aim to maintain fundamental ecological functions and are the basis for the

sustainable provision of ecosystem services (Roche & Campagne 2018; Revenga 2005; Kandziora et al. 2013; Menzel et al. 2013; European Commission 2016). Different studies define ecosystem condition as the sum of biophysical properties that underpin services or as the effective capacity of an ecosystem to provide services (Schröter et al. 2006; MEA 2005).

A prominent approach is to combine different data from different methods to assemble comprehensive information about the focal socio-ecological system (Burkhard et al. 2009; Vihervaara 2010; Nedkov & Burkhard 2012). The omnipresent dilemma of data scarcity can be resolved by relying on expert knowledge and valuing different land use patterns and their potentials to support integrity and subsequent services, e.g. by using the ES matrix approach (Burkhard et al. 2010, 2012, 2014; Jacobs et al. 2015). Today, possibilities to derive ecological integrity indicators are strongly connected to digital technology, namely simulation models of ecosystems and spatial analyses of remotely sensed data (Hou et al. 2013). For instance Fraser et al. (2005, 2009 and 2011) have used remote sensing to represent ecological integrity changes by a temporal comparison of measurements of the Normalized Difference Vegetation Index (NDVI) and fragmentation metrics in Canadian national parks. A variety of indicators quantifying patterns of vegetation surface temperature gradients have also been proposed to represent integrity (Vargas et al. 2017; for a review see Maes et al. 2011), basing e.g. on the concept of Schneider & Kay (1994). Also vegetation complexity can be quantified using remote sensing either as representation of texture complexity (Parrott 2010) or by an assessment of patch and landscape heterogeneity (Walz 2014; for a review see Uuemaa et al. 2009). Therefore, this study embraces a comprehensive assessment of the ecological integrity including amongst others remote sensing analysis.

1.2 *Ecosystem services*

The interdisciplinary ES concept is of highly integrative nature, considering ecosystems and human-environmental interactions (Burkhard 2017; De Groot et al. 2017). Ecosystem services are understood as “[...] those products and outcomes from complex ecological interrelations which are useful and necessary for human wellbeing, thus providing societal benefits” (Müller et al. 2015, p. 8).

Generally, ES can be divided into three categories: provisioning, regulating and cultural ES (Kandziora et al. 2013; Burkhard et al. 2014; Sohel et al. 2015; Stoll et al. 2015; Haines-Young & Potschin 2017; Schneiders & Müller 2017). Direct products, such as crops and freshwater, are defined as provisioning ES (De Groot et al. 2010; Haines-Young & Potschin-Young 2010a; Kandziora et al. 2013; Haines-Young & Potschin 2017). The benefits which people obtain from ecosystems through the ecosystems’ regulation of natural processes are considered as

regulating ES (Kandziora et al. 2013; Haines-Young & Potschin 2017). Cultural ES refer to the intangible benefits that people obtain such as non-material inspirational and educational experiences (De Groot et al. 2010; Kandziora et al. 2013; Haines-Young & Potschin 2017).

The relevance of the ES concept is embedded into European policy, as the EU Biodiversity Strategy to 2020 (Target 2¹, Action 5) asked EU Member States to map and assess their ecosystems' states and respective services with assistance of the European Commission (Maes et al. 2012; Teller 2017). The mapping of ES supports a variety of purposes, amongst which the generation of knowledge in terms of ecosystem assessments, ecosystem accounting, decision support and awareness rising (Jacobs et al. 2017). Current applications of ES mapping focus on quantitative ES valuation and accounting (Syrbe et al. 2017). These maps can be used to indicate for instance risks for the state of ecosystems, unsustainable land management and utilization of ES. In that sense, the target of this study is to assess the sustainability of the current land management in the study area with regard to the ES utilization. Therefore, a lot of emphasize lies on the spatial assessment and mapping of relevant variables.

Within this study, we focus on the ES crop production, which falls into the category provisioning ES. The ES crop production refers to the cultivation of plants and harvests of these plants on agricultural fields and pastures, which are used for human nutrition, as fodder or for the creation of energy. Besides, ecosystem services can be divided into *potentials*, *flows* and *demands*. The *potentials* of an ES describe the hypothetical maximum yield of selected ES (Burkhard et al. 2014). On the other hand, the *flow* refers to the ES that are actually utilized (Syrbe et al. 2017), usually in a certain spatial and temporal scope. An aspect which is uncovered to be highly interesting and worthwhile of assessing is the spatial mismatch between ES *potential* and actual ES *flow* (Guerra et al. 2017). The ES demand is independent from ES supply (*potential* and *flow*) and is driven by the consumers' benefits, utilities or welfare (Villamagna et al. 2013; Burkhard et al. 2014; Brander & Crossman 2017). The demand is temporal and spatial dependent and directs the ES *flow*. This means, in case there is no demand for a certain service, there would be no ES *flow*. Nevertheless, also situations of unmet demand can occur, i.e. the demand for a certain ES is higher than the ES *flow* (Syrbe et al. 2017; Dang et al. 2018).

¹http://ec.europa.eu/environment/nature/biodiversity/strategy/target2/index_en.htm

The following box highlights the key essences extracted from the literature review on ecological integrity and ecosystem services:

<p>Ecological integrity</p> <ul style="list-style-type: none">● Ecological integrity represents the degree of self-organization of ecosystems. It can be regulated by different amounts of external inputs.● Ecological integrity determines the general capacity of ecosystems to provide ecosystem services. <p>Ecosystem services</p> <ul style="list-style-type: none">● Ecosystem services are the contributions in the form of goods and benefits that people obtain from ecosystems.● Ecosystem services can be distinguished referring to their <i>potentials, flows</i> and demands.

Figure 1, which is based upon the cascade model after Haines-Young and Potschin (2010b), demonstrates the relations between all items outlined above. The ecosystems and biodiversity are characterized by biophysical structures, processes and functions. The structures and processes can be bundled into certain functions and functional groups. Their performance is often indicated by parameters of ecological integrity or ecosystem health. Those functions are the fundamentals of ES *potentials*. They can be turned into ES *flows* if they are really activated and if they contribute to human well-being. In that case they are featured by certain values, which demonstrate the relative significance of the services. Benefits and values jointly are the basic components of the demands for ecosystem services. The social-economic system may introduce changes with respect to the utilization of ES and management. These activities can influence the potentials for future delivery of services. In case of unsustainable resource utilization, the chances are high that the future potentials will be reduced.

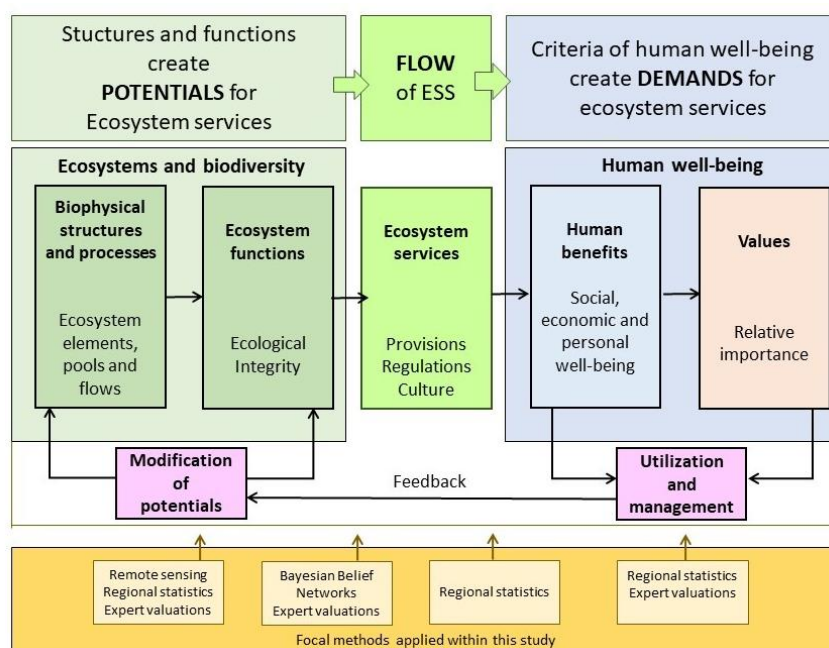


Figure 1: A schematic representation of the different components and feedback loops, which are interacting in the landscape system. The ecosystem structures and functions, including ecological integrity, are the base for the capacity of an ecosystem to provide ecosystem services, which subsequently create benefits, affecting human well-being. Focal methods used for representing each component are listed in the lower part of the figure.

1.3 Aim of the study

We assume that ecosystem services emerge at the interface between cultural and natural elements of a landscape, and that they are therefore important drivers of landscape organization. Thus, it is important to represent both the ecological integrity and ecosystem services in a simplified and comparable format, in order to provide comprehensive information for current management and methodological improvement. To be successful, diverse data sources have to be employed and properly modified realizing the many uncertainties (Hou et al. 2013), which can emerge from representing and aggregating landscape features. We aim at providing an extended interpretation of how ecological integrity relates to the production of ecosystem services in context of variable human land management and agricultural practices.

Consequently, the objective of the study is to deliver a basic, holistically oriented ecosystem assessment in Schleswig-Holstein. The study focuses on the evaluation of ecological integrity as a base for the capacity of the study area to provide the ES crop production. Different methodological approaches are applied in order to assess and map the diverse ecological integrity variables and the crop production ES *potential* and *flow*. Subsequently, the spatial distribution of the different ecological integrity variables, the crop production ES *potential* and

flow are compared and interpreted with respect to the characteristics of the main landscape types within the study area.

In order to reach these objectives, three research questions have been formulated:

- I. Does the spatial distribution of the assessed ecological integrity variables reveal a distinct regional pattern?
- II. Does the spatial distribution of ecosystem service crop production reveal a distinct regional pattern?
- III. What is the relation between the assessed ecological integrity variables and the crop production ES *potential* and *flow*?

The proximate section outlines the materials and methods utilized within this study. At first, the study area is described. Subsequently, the methodological approaches and input data sets used to assess the selected ecological integrity variables and the crop production ES *potential* and *flow* are enumerated. While the ecological integrity variables are mainly quantified on the base of remote sensing data, the ecosystem service *potential* is modelled using a Bayesian belief network approach. Some ecological integrity variables and the ES *flow* are indicated by regional statistical data. In addition to that, the ecological integrity variables and the ES *potential* are assessed using expert evaluation. In the third section, the results of the comprehensive assessment are presented. Subsequently, the main findings are compared and discussed with regard to the spatial distribution of maize production in the study area. Consequences of these land management and agricultural practices on the environment are delineated (example: nitrogen surplus). A detailed ecological integrity survey in arable lands and grasslands is conducted during a vegetation period to show management deficiencies in different landscape regions. Subsequently, the different methodological approaches and the respective findings are compared using spider diagrams. The comparison includes the differentiation of the results related to respective landscape types. Based upon these findings, some general conclusions are drawn concerning landscape related land management aiming to reduce the negative impact caused by modern agricultural practices. Finally, the research questions outlined in here are revised and answered.

2 Materials and methods

2.1 Study area

The study area, Schleswig-Holstein, is the northernmost federal state of Germany, surrounded by the North Sea to the West and the Baltic Sea to the East (Figure 2). Due to this position, the study area is featured by maritime and humid climatic conditions. The annual averages of the mean temperature and precipitation are around 8°C and 840 mm, respectively (Climate Data Center 2018). The spatial extent of the study area is approximately 15'802 km² (Statistische Ämter des Bundes und der Länder Deutschland 2018). Arable land and pastures are predominant land use types (Figure 2b).

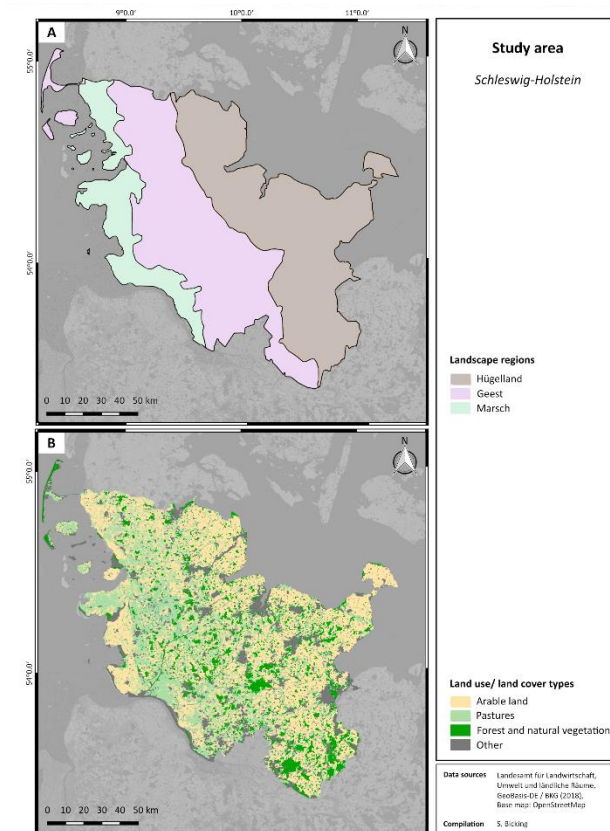


Figure 2: Overview of the study area incl. a) classification of main landscape regions and b) distribution of land use/ land cover types based upon CORINE 2012².

²http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=22&gdz_user_id=0

The study area can be subdivided into three main landscape regions (Stewig 1982; Bähr & Kortum 1987): Hügelland, Geest and Marsch (Figure 2). The different characteristics of the three regions can be attributed to the geological development of the area, during the Pleistocene and Holocene periods. The landscape regions Hügelland and Geest originate from the Pleistocene, whereas the Marsch dates back to the Holocene and is thus the youngest of the three landscape regions (Stewig 1982; Hoffmann 2004). The differences between the Geest and Hügelland arise from the varying expansions of the last two glaciations during the Pleistocene (Schott 1956; Stewig 1982). The Saalian glaciers covered both the Geest and the Hügelland. During the Weichselian glaciation, only the Eastern part of the study area was covered by the glaciers. The rolling hills of the Hügelland as well as the fertile soils, several lakes and embayments are remains from the impact of the Weichselian glaciation on the landscape (Schott 1956; Stewig 1982; Bähr & Kortum 1987). Contrary to that, during the respected period, Geest served as outwash plains of the glacial melting waters. As a result, the old moraines from the Saalian glaciation were extensively degraded. Today, the area of the Geest is characterized by rather poor, sandy soils (Schott 1956; Bähr & Kortum 1987) and due to the erosion by only little relief. The Marsch is located along the North Sea coast of Schleswig-Holstein and originates from post-glacial processes as sea level rise and deposition of tidal, fluvial and organic sediments (LLUR 2012). It is a low lying area (LLUR 2012), characterized by fertile soils, where drainage predominates the landscape (Hoffmann 2004). The regional differentiation of the study area is of great relevance for this research, as it partly determines the spatial patterns of ecological integrity and ES.

2.2 *Methodological approaches used in the study*

Next to the ES crop production *potential* and *flow*, six ecological integrity variables have been assessed, namely exergy capture, entropy production, abiotic heterogeneity, biotic water flows, storage capacity and reduction of nutrient loss. The selected indicators used to represent the ecological integrity variables (see Table 1 and 2) are following approaches proposed by Schneider & Kay (1994), Müller (2005), Maes et al. (2011) and Kandziora et al. (2013). Four methods, spanning from purely quantitative to qualitative, have been employed to deliver spatially comparable information on ecological integrity, ecosystem service *flows*, *potentials* and management.

We have used a probabilistic inference model integrated in a Bayesian Belief Network to estimate the likelihood of high crop production based on information on soil and climatic conditions. The modelled natural *potential* data set serves as a reference information on the hypothetical crop production, which would be obtained if the system would be mainly

dependent on abiotic factors. The contribution of biotic factors to ecosystem processes in Schleswig-Holstein were explored as ecological integrity using remote sensing and official regional data, such as statistics. The results serve as measured biotic potentials, represented as the capacities to bind solar energy in photosynthesis, capture it during evapotranspiration to drive vertical water flows, metabolize it efficiently, convert it into biomass and store it in soil. Actual *flows* of the focal provisioning service were calculated based on the official regional statistics and comprise food, fodder and biomass for energy production in Schleswig-Holstein. Finally, a qualitative expert derived matrix approach was applied, depicting land-use potentials with regard to ecological integrity and ecosystem services.

The results from these approaches were aggregated at the administrative level of the municipalities in Schleswig-Holstein, enabling statistical analyses and visual comparisons of spatial patterns of the integrity and service variables. All data sources were selected based on the criteria of good comparability. This included data preferably from the same year (2016 for remote sensing and 2010 in case of official statistics) and in comparable resolutions. The common scale of aggregation for all data was the level of municipalities (1176 municipalities).

2.2.1 Remote sensing procedures

Remote sensing measurements were taken from Landsat 8 TIRS (USGS³), Sentinel-2 MSI (ESA⁴) and MODIS (NASA⁵). Landsat 8 senses both multispectral and thermal images at moderate resolutions (30 and 100 m) and provides complementary information to Sentinel-2 with respect to vegetation performances (Roy et al. 2014; Castaldi et al. 2016; van der Werff & van der Meer 2016; Chrysafis et al. 2017). Since Sentinel-2 measures reflected light with a higher resolution (10, 20 and 60 m), sensitivity and temporal frequency, multispectral products were selected from Sentinel-2 instead of Landsat 8. Landsat 8 nevertheless, served to provide a vital measure of Land Surface Temperature (LST), which is missing in Sentinel-2. The data source with the lowest spatial (1 km) but highest temporal (8-day composites) resolution was obtained from MODIS in order to represent photosynthetic productivity and respiration.

³<https://earthexplorer.usgs.gov/>

⁴<https://scihub.copernicus.eu/>

⁵<https://earthdata.nasa.gov/>

2.2.1.1 Aggregation and image processing

Individual images of Schleswig-Holstein, obtained from remote sensing data sets available on the different respective geoportals, were selected for the year 2016, and were aggregated to represent the sum of the individual increments per day of the subject year for each variable. Also, relevant land-use classes were considered during the aggregation. For that matter, the European 2012 CORINE land cover data set was used. All sea and water surfaces were removed prior to the analysis, since the approach is based on representing vegetation only. Since most emphasis was given to variables related to croplands, followed by grassland and forests, only relevant areas were included. The 8-day calculations of net primary production (NPP) and respiration from MOD17 were first aggregated into monthly composites and further aggregated for the whole year by simple summation. The remaining three variables, normalized difference vegetation index (NDVI), temperature difference (TD) and texture heterogeneity (HG) were summed up across the year 2016 using the area under curve (AUC) calculation. The AUC corresponds to the integral, thus the volume of space under each time curve (summation of squares between each measurement point in the respective time period). The downloaded data sets were processed in QGIS (Quantum GIS) and aggregated at municipality level using the zonal statistic algorithm, to obtain median values for each municipality polygon.

Table 1: Indicators, respective units, resolutions and instruments derived from remote sensing data to deliver representations of selected ecological integrity variables.

No.	EI variable	Indicator	Unit	Resolution	Satellite	Source
1	Biotic water flows	Temperature difference (TD)	[°C]	30 m (100 m) ⁶	Landsat 8	www.earthexplorer.usgs.gov
2	Exergy capture	NDVI	[-]	10 m	Sentinel-2	www.scihub.copernicus.eu
3	Abiotic heterogeneity	Edge density (ED)	[-]	10 m	Sentinel-2	www.scihub.copernicus.eu
4	Entropy export	Metabolic respiration	[g C/m ² y ⁻¹]	1 km	MODIS (MOD17)	www.modis.gsfc.nasa.gov
5	Net primary production	Net primary production	[g C/m ² y ⁻¹]	1 km	MODIS (MOD17)	www.modis.gsfc.nasa.gov

2.2.1.2 Indicating abiotic heterogeneity

In the present study, ecosystem abiotic heterogeneity was quantified based on the Sentinel-2 bands 4 and 8 and it represents the intensity of the difference between every individual cell of a raster relative to its adjacent cells. Specifically, the algorithm used to calculate heterogeneity is quantifying intensities of linear gradients between cells. The calculation was designed to represent vegetation surface complexity of natural areas like for forests, in contrast to typically homogeneous agricultural areas. The heterogeneity variable quantifies the complexity of vegetation, which is of direct relevance to the capacity to self-organize and provide rich habitat for biodiversity and thus, ecological integrity (Parrot, 2010).

Abiotic heterogeneity was quantified as Edge Density (ED) and produced in the Sentinel Application Platform (SNAP by ESA) software using Diagonal Compass Edge Detector filter algorithm. The filter applies a predefined operation on a selected raster, which in this case quantifies the presence of linear shapes. The function is based on calculations of the parameters of a cell in a raster, with respect to surrounding cells. Images from Sentinel-2 band

⁶ Resampled to 30 m from 100 m

4 and 8 were used in the process. Band 4 represents reflected light without vegetation, while band 8 contains reflected light from both vegetated and non-vegetated areas. The product images were further processed by converting all values to absolute (positive) values and square root transformed to obtain near-normal data distribution (normality not tested). The conversion to positive values served to remove the factor representing orientation of the edge (represented as either + and -) as we were only interested in absolute values of edges. The two images were finally recalculated to a joint variable of heterogeneity by subtraction of the transformed band 4 from band 8. The heterogeneity variable contains information on vegetation only, therefore representing canopy surface texture complexity or heterogeneity.

2.2.1.3 Indicating exergy capture

Exergy capture is the capacity of vegetation to capture solar radiation, and was previously suggested to be readily measured as NDVI (Kandziora et al. 2013). NDVI is a 0 – 1 normalized ratio between reflected light in red (RED) and near infrared (NIR) part of the frequency spectrum (Eq. 1; Xu et al. 2012), and in the most general way, it represents the “greenness” of the vegetated surface or the fraction of red light absorbed by chlorophyll. Both parameters were obtained from band 4 and band 8 of the Sentinel-2 data.

Equation 1: Calculation of NDVI from Sentinel-2

$$NDVI [-] = \frac{NIR - RED}{NIR + RED}$$

or

$$= \frac{Band\ 8 - Band\ 4}{Band\ 8 + Band\ 4}$$

Where:

NDVI = Normalized Difference Vegetation Index

NIR = Near InfraRed

RED = Red part of the visible spectrum

2.2.1.4 Indicating biotic water flows

The potential evapotranspiration, measured as the distance between reference vegetation surface temperature and bare soil, represents the amount of water which is being moved in plant stems and solar energy used to evaporate the water from leaves. The intensity of evapotranspiration relates to the efficiency and intensity of the whole ecosystem metabolism and is thus of major importance for ecological integrity assessments (Schneider & Kay, 1994).

An estimate of biotic water flows was derived from the Thermal InfraRed Sensor (TIRS) instrument, which can be used to estimate Land Surface Temperature (LST). The respective band 10, containing thermal information, was recalculated into At-Satellite Brightness Temperature (see Equation 2) and used for further transformations.

The raster data was further processed to quantify the range in °C further referred to as temperature difference (TD), to represent the capacity to reduce the surface temperature. The temperature transformation exported the values between the 2% and 98% percentile (to remove outliers), multiplied it with -1 to make it an inverse value and set the lowest value to 0 (no capacity to reduce surface temperature – usually bare soil or urban surface). The parameter TD therefore, quantifies the absolute distance in °C between the lowest and highest 98% percentile in a given measurement and is a measure of the capacity of the vegetation to reduce surface temperature compared to bare soil in the given measurement context.

Equation 2: Calculation of At-Satellite Brightness Temperature

$$T = \frac{K2}{\ln\left(\frac{K1}{L\lambda} + 1\right)}$$

Where:

T = At-satellite brightness temperature (°C)

$L\lambda$ = Top of Atmosphere (TOA) spectral radiance $\left(\frac{\text{Watts}}{\text{m}^2 \cdot \text{srad} \cdot \mu\text{m}}\right)$

$K1$ = Band-specific thermal conversion constant from the meta-data

$K2$ = Band-specific thermal conversion constant from the meta-data

2.2.1.5 Indicating primary production and entropy export

Gross and net primary production (GPP, NPP respectively) are important to estimate the amount of photosynthetic energy, which is captured during photosynthesis (thus, GPP is hypothetically related to NDVI as a variable estimating exergy capture) and the proportion of it, which is stored in biomass (NPP). MODIS delivers data for further processing by a model calculation (exact name MOD17), which offers two parameters representing GPP and NPP (Zhao et al. 2005). The amount of respired energy was obtained for this study by substituting NPP from GPP in the year 2016 and is further referred to as the EI indicator entropy export. The method of data aggregation is described in section 2.2.1.1.

Equation 3: Calculation of respiration

$$\text{Respiration} = (NPP - GPP)$$

Where:

NPP = Net primary production

GPP = Gross primary production

2.2.2 Official regional data utilization

Data provided by official institutions such as the Statistical Agency North (2010) and the LLUR (2011) were consulted for this study. Table 2 gives an overview on all parameters of EI and ES that have been generated based upon these data sources. Primarily, the agricultural census from 2010 (Statistical Agency North 2010) served as data source for the quantification of several EI and ES indicators. In particular, the agricultural census served as the base for information on the spatial extent (in ha) of arable land and pastures as well as the cultivated crop types at the scale of the municipalities. Average values on the harvests (in dt/(ha*a)) of the different crop types was available at the scale of counties or the federal state of Schleswig-Holstein. This information has been processed in order to deliver the indicator for the crop production ES *flow*. In addition to that, the harvest of silage maize has been quantified and mapped as well. The plant residuals (in dt/ha) left to decompose on the field after harvest have been estimated as an indicator for the ecological integrity variable storage capacity. We assume that when more plant residues are left to decompose, there will be more organic matter and energy available for soil life to incorporate and build soil structures, which are fundamental for holding water and nutrients. The residuals commonly consist of the root biomass and further biomass from secondary products (e.g. straw) which remain on the field after harvest. The residual management was assumed to be crop dependent and identical throughout the whole study area. The residuals have been calculated based upon the statistical information on the cultivation (agricultural census 2010), average values on the product, secondary product and root biomass and average residual management values for the different assessed crop types including grasslands. The estimated residuals (in dt/(ha*a)) have been defined as the indicator for the EI attribute storage capacity.

As some data entries at the scale of the municipalities are missing in the regional statistics due to data privacy law, the information on the scale of municipalities has been compared to the information provided at the scale of counties. The calculated differences have been allocated to the municipalities with data gaps. The relative spatial extent of arable land and pastures within the affected municipalities served as weighting factor for the allocations. Next to these statistical data sets, spatial data on soil functions provided by the LLUR (2011) have been consulted, focusing on information on the nitrate leaching potential in the federal state. The LLUR (2011) calculated the nitrate leaching potential mainly based upon soil properties and

climatic conditions. This data set was defined as the indicator for the EI reduction of nutrient loss.

Table 2: Indicators, respective units and data sources of selected ecological integrity and ecosystem service variables.

No.	EI/ES variable	Indicator	Unit	Source
5	Reduction of nutrient loss (EI)	Nitrate leaching potential	Relative scale from 0 to 100	LLUR (2011)
6	Storage capacity (ES potential)	Residuals on crop- and grassland	dt/(ha*a)	Agricultural Census (Statistical Agency North 2010)
7	Crop production (ES flow)	Yield from crop- and grassland	dt/(ha*a)	Agricultural Census (Statistical Agency North 2010)
8	Silage maize production	Biomass production through silage maize cultivation	dt/(ha*a)	Agricultural Census (Statistical Agency North 2010)

2.2.3 Bayesian belief network applications

Bayesian Belief Networks (BBN) are based on Bayes's theorem (Bayes 1763) and represent posterior probabilities of output nodes under the changes in related input nodes (Ellison 2004). The approach of Bayesian Belief Networks (BBN) has been initiated from artificial intelligence comprehensions (Kleemann et al. 2017) that have become an increasingly popular method in environmental and ecosystem service studies (see e.g. Barton et al. 2008 and Pascual et al. 2016) to simulate uncertain and complex issues through a Directed Acyclic Graph (DAG) (Uusitalo 2007).

Adapted from various former BBN approaches (Dang et al. 2018; Ellison 2004; Kragt 2009; Kruschke 2014; Poppenborg & Koellner 2014), the authors have developed a new BBN that distinguishes abiotic variables, ecosystem functions, additional anthropogenic inputs and the crop production ES *potential* (Figure 1). The network has been developed in order to predict the suitability of agricultural regions based on the Bayesian probability approach under the changes of abiotic and anthropogenic factors. The two main factors which control the node "natural productivity" are: ecosystem functions and additional inputs from humans (or farming practices). The types of ecosystem functions in the ecosystems identified include: Photosynthesis potential, nutrient availability (in soil) and water availability (soil moisture). The natural sources of these functions are estimated from abiotic factors (such as soil radiation, temperature, soil texture, erosion etc.).

2.2.4 Expert assessment interpretations

In order to attain an overview of the ecosystem service *potentials* of the multiple ecosystem types of a landscape complex, an integrative documentation of expert opinions has been realized by creating and developing a so-called “ecosystem *potential* matrix” which has been elaborated throughout a sequence of steps (Burkhard et al. 2009, 2012, 2014; Stoll et al. 2015). In its recent basic form, this table assesses the probabilities to provide ecosystem services and integrity attributes of 28 terrestrial, 15 coastal and 18 marine ecosystem types (Müller et al in preparation). These systems were evaluated referring to 39 services or integrity indicators. The quantification actually was based on a scoping technique in a span of ecosystem service supply capacities between 0 and 100 ecosystem services *potential* scoring points. The focal question to the experts was “How big is the average *potential* of the ecosystem type “x” to provide the ecosystem service “y” – please quantify your assessment by a value between 0 and 100, focusing in this generalized form on values between 10 and 90” (thus enabling special parameter combinations above or below the average-based scopes)? In the terrestrial environment, the investigated systems are identical with the existing CORINE land cover types that can be found in Northern Germany, thus the matrix information can rather easily be translated into regional maps of ecosystem service *potential*.

Several authors have discussed the related uncertainties of expert based valuation schemes and the outcoming maps (e.g. Hou et al. (2013), Schulp et al. (2014), Jakobs et al. (2015), Campagne et al. (2017), Campagne & Roche (2018)), therefore before all the number of demanded experts has been optimized to 110 addresses within the last attempt. The average return quote was around 50%. The proposed corrections have been noted, checked and applied and the resulting scheme of uncertainties was documented (Müller et al. in preparation). In this paper, the resulting qualitative ES *potentials* have been aggregated to the areas of the municipalities and/ or landscape regions of Schleswig-Holstein.

3 Results

In the following section, the spatial distributions of the assessed ecological integrity variables and the crop production *ES potentials* and *flows* are presented as maps and are statistically compared at the municipality level.

3.1 Ecological integrity variables

Figure 3, 4 and 5 demonstrate that the spatial distributions of the ecological integrity variable form regional patterns following the distribution of the three main landscape regions. From an integrative point of view, the central part of the study area - Geest – received, with some exceptions, lower values in terms of ecological integrity compared to the other two regions (Figure 3 and Figure 4). One exception is exergy capture, which was highest in Geest, although in terms of NPP, the three regions are rather equal nevertheless. Thus, despite a relatively high level of photosynthetic potential in Geest, the resulting NPP is equivalent to areas with mediocre exergy capture. The missing piece to the story seems to be respiration, which also culminates in the Geest. At first glance, it is evident that a large part of the photosynthesis, which takes place in the Geest, is being inefficiently conserved within the system and is released, enhancing entropy production.

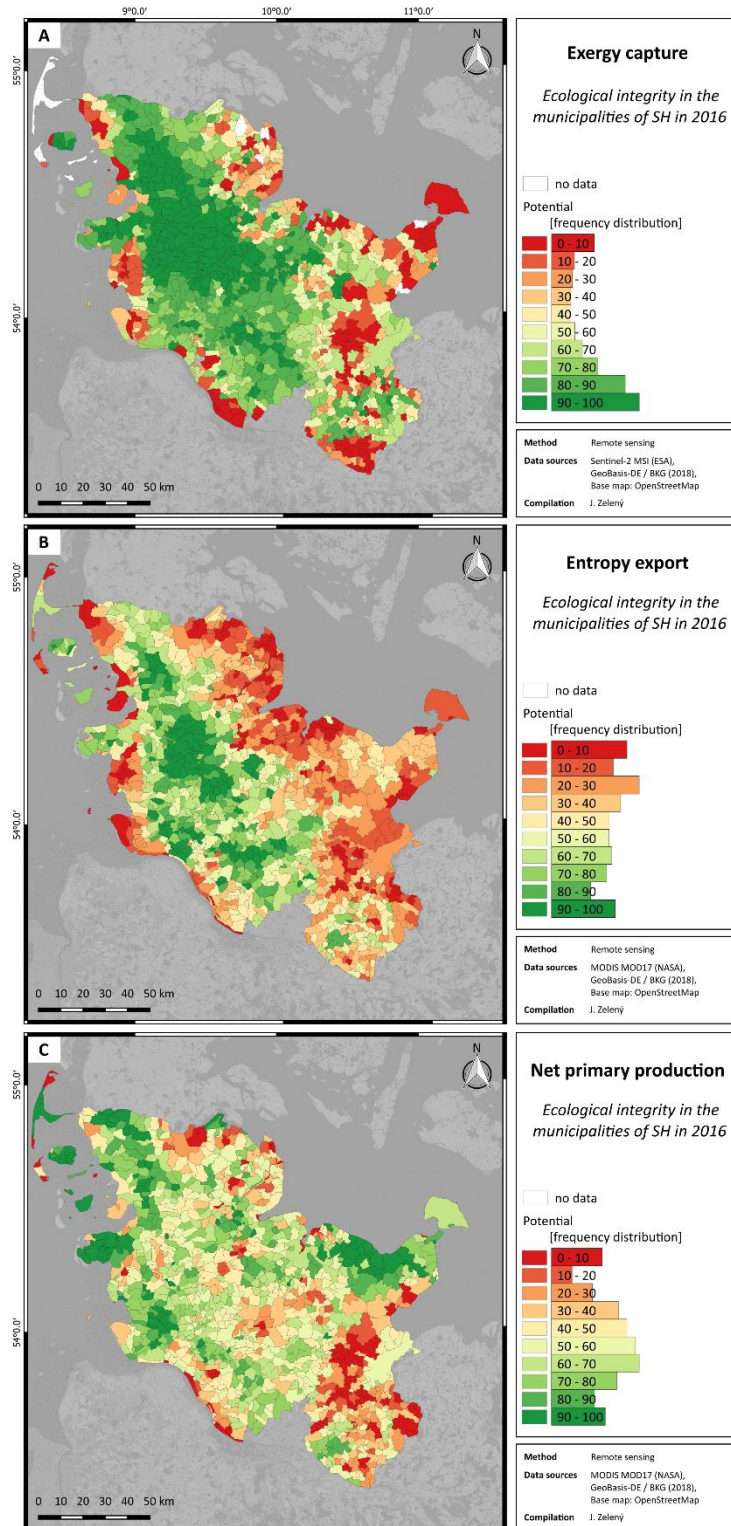


Figure 3: Ecological integrity variables in the municipalities of Schleswig-Holstein in 2016: a) exergy capture (NDVI), b) entropy export (respiration) and c) net primary production.

Further assessed variables, such as biotic water flow, reduction of nutrient loss and storage capacity, show clear trends according to the spatial distribution of the main landscape regions, too. The area of the Geest performs the worst of the three (Figure 4). The ecological integrity variable biotic water flows shows a sharp distinction between the eastern coast with fairly high values, and the western coast with moderate to low values. Lowest potentials for biotic water flows can be found in the centre of Schleswig-Holstein, most notably in the northern part of the Geest.

The storage capacity, the estimated potential to support soil structure, is considerably low in the Geest (Figure 4). In particular coastal communities score high potentials for the ecological integrity variable storage capacity. Besides, the Geest also performs lowest of the three landscape regions with respect to the capacity to retain nutrients (reduction of nutrient loss, Figure 4), which can be related to the poor soil conditions which foster easy drainage and do not contain sufficient amount of organic matter, facilitating nitrate leaching. The area of the Hügelland features on average highest reduction of nutrient loss potentials.

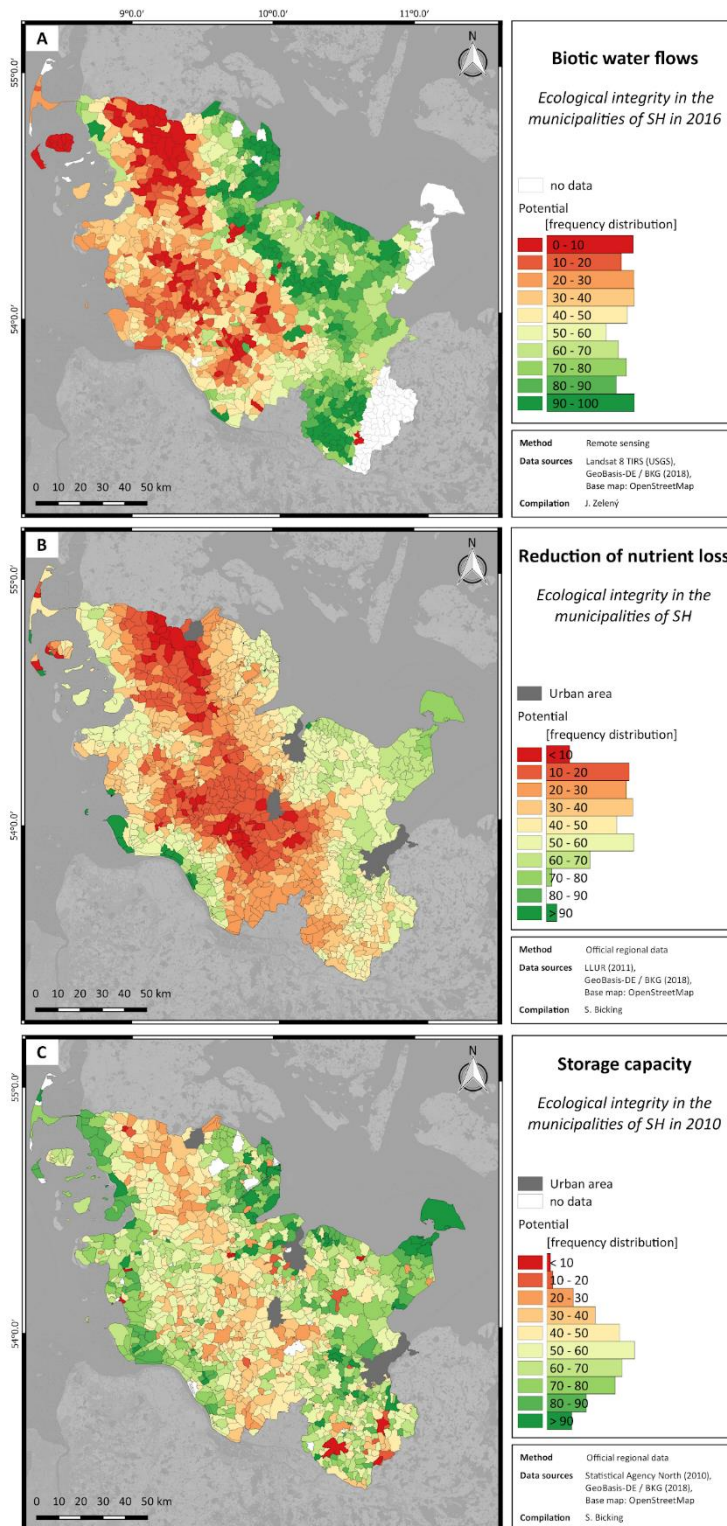


Figure 4: Ecological integrity variables in the municipalities of Schleswig-Holstein: a) biotic water flows (temperature difference) in 2016, b) reduction of nutrient loss (nitrate leaching potential) and c) storage capacity (residuals) in 2010.

Another variable, which scores high values in the area of the Geest alongside exergy capture, is abiotic heterogeneity (Figure 5). This spatial pattern originates from the historical land management and distinct land ownership in the study area, which caused smaller and more fragmented fields in the Geest in comparison to the Marsch and Hügelland areas, which are far more homogeneous. In addition to that, the Geest area is characterized by larger areas covered by grasslands compared to the other two regions (see Table 4). These aspects contribute to higher abiotic heterogeneity.

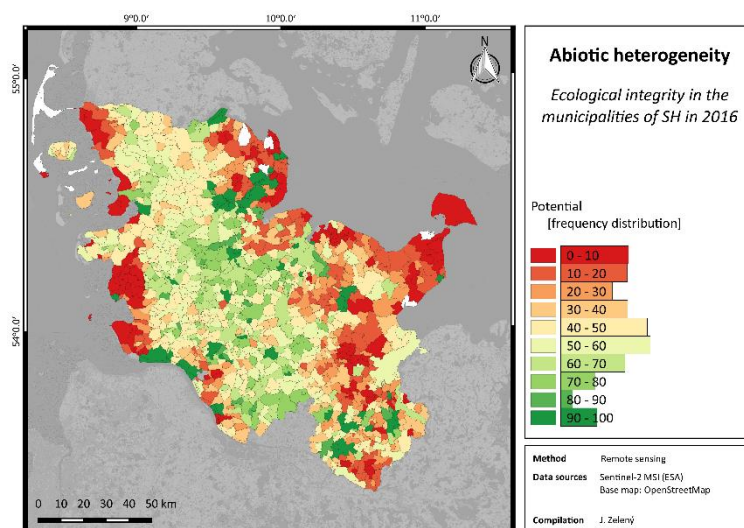


Figure 5: EI variable abiotic heterogeneity (edge density) in the municipalities of Schleswig-Holstein in 2016.

To sum up, the Geest area is featured by highest photosynthetic potentials and respiration rates and a mediocre abiotic heterogeneity, while all remaining ecological integrity variables score lowest compared to the other two landscape regions. The assessment indicates that the Marsch and Hügelland have a lower level of exergy capture, the resulting net primary production is, nevertheless, virtually equal in all three regions.

3.2 Provisioning ecosystem service variables

The spatial distribution of the crop production *ES potential* in Schleswig-Holstein (see Figure 6a) is roughly following the geomorphological development of the area and reflects the spatial pattern of the ecological integrity variables biotic water flow, storage capacity and reduction of nutrient loss. The landscape region Marsch is characterized by highest *ES potentials*, followed by the Hügelland. The lowest crop production *ES potential* can be found in the Geest area. This spatial pattern is strongly influenced by soil properties and other abiotic parameters in the landscape. The sandy and rather infertile soils of the Geest have a lower capacity to retain water and nutrients, which makes the grounds less favourable for agriculture. Within the BBN outcome map, some red spots with very low *potentials* for crops are related to big

forests in the South, semi-terrestrial, artificial lagoon areas at the North Sea coast and the dune areas on the islands. Contrary to the ES *potential*, the crop production ES *flow* (Figure 6b), which is indicated by the actual harvest values in the municipalities, scores highest in the Geest area. The landscape region Marsch is characterized by medium ES *flow* values and the Hügelland area exhibits the lowest ES *flows*. For some municipalities no values are presented, as consequence of data consistency and data availability. Besides, the urban areas of Schleswig-Holstein (Flensburg, Kiel, Lübeck and Neumünster) have been excluded from the assessment due to their disparities compared to the rural areas, which are exhibited in the underlying data sets.

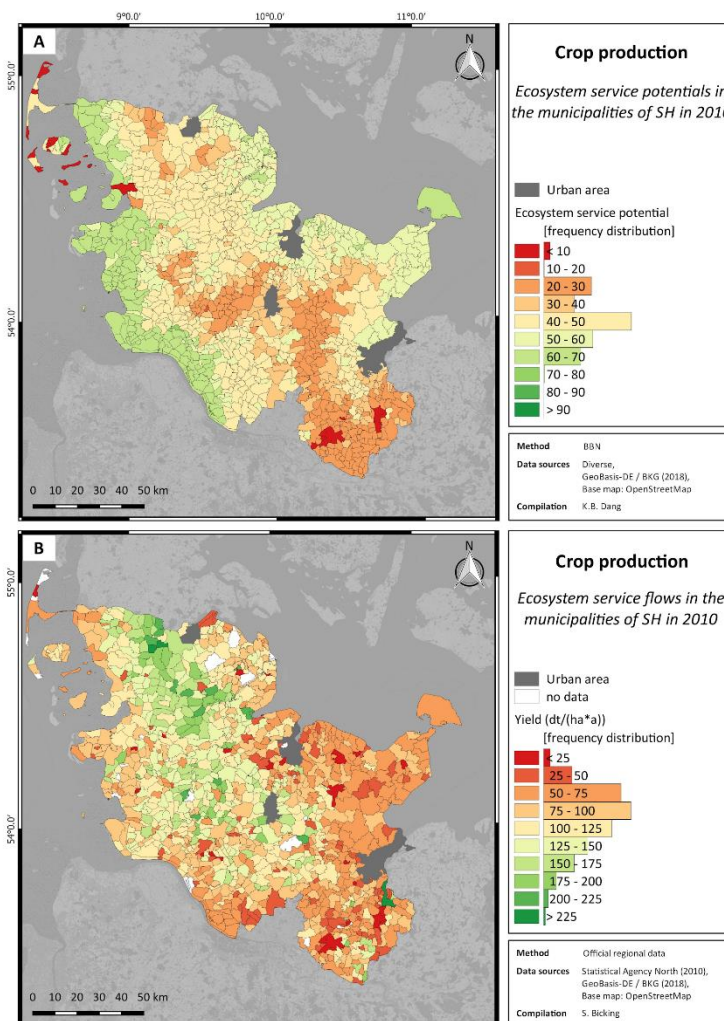


Figure 6: Crop production ecosystem service: a) *Potential* derived by BBN assessment and b) *flow* based upon regional statistics.

The correlations between the assessed ecological integrity variables and crop production ES *potential* and *flow* support the findings outlined above (Figure 7). There is a significant positive relation between the ecological integrity variables biotic water flows, reduction of nutrient loss, storage capacity and the crop production ES *potential*. The crop production ES *flow* is

positively correlated with the ecological integrity variables exergy capture and entropy production. On the other hand, the crop production ES *flow* is negatively related to the other integrity parameters like biotic water flows and reduction of nutrient loss. This means the highest actual crop production is taking place in conditions, which are unfavourable with respect to the soil nutrient and water retention potentials. A second point worth of notice is a positive relation between the actual crop production and entropy export. This in general means higher photosynthetic potentials happen at the cost of significant increases in respiration. Thus, although the ES crop production is higher in Geest, also the associated respiration of the system is much higher. This means, biomass is produced with lower efficiency compared to the Marsch and Hügelland.

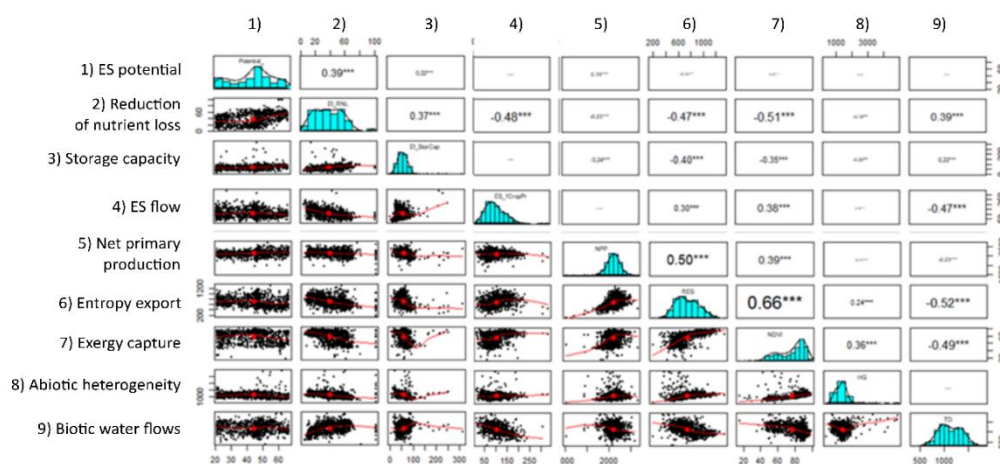


Figure 7: Correlation table presenting the statistical correlations between selected ecological integrity and ecosystem service variables. The remote sensing data sets were sampled for the whole study area excluding water and urban areas. A Pearson’s correlation was performed for: 1) Crop production ES *potential* (BBN approach), 2) EI variable reduction of nutrient loss (as nitrate leaching potential), 3) EI variable storage capacity (as residual biomass), 4) crop production ES *flow* (as actual yield), 6) EI variable entropy export (as respiration), 7) EI variable exergy capture (as NDVI), 8) EI variable Abiotic heterogeneity (as edge density) and 9) EI variable biotic water flows (as temperature difference).

4 Discussion

The results of the presented assessment offer several lines of potential interpretation, which we explore as: the general interplay between the assessed variables, the focus on silage maize cultivation in the Geest, a comparison between the performance of cropland and pasture and an overall comparison of the three landscape regions using a wide selection of variables.

An outstanding perspective for the assessment of ecological integrity alongside ecosystem services is the potential to deliver guidance to a more efficient type of management, possibly leaning towards sustainability. The findings of this study indicate a spatial mismatch between the intensive crop production (*ES flow*) on the one hand and the *ES potential* as well as ecological integrity on the other hand. The goal is to give as rich explanation of this obvious paradox as our data and methods allow.

One part of the statistical processing was the comparison between three major land use types, relevant for the study area: arable lands, pastures and forests. All tested variables were stronger correlated in arable lands, when compared to pastures and forests. These include integrity variables, mainly biotic water flows, reduction of nutrient loss and storage capacity, which are positively related, and stand in opposition to exergy capture, entropy export and the *ES flow* crop production. There is a clear relation between the photosynthetic production and ecological integrity here: the more exergy is captured, the more the system respire and thus the marginal increment of any increase in exergy captured leads to steeply rising entropy export. We suspect that the more a system is artificially pushed to greater performance above a certain level, the more gross energy is needed to capture and store additional units of exergy in biomass.

It is noticeable, that the trend between production and exergy capture is present, but decreasing in pastures, and virtually gone in forests (see Appendix 1 and 2). We assume that as the anthropogenic gradient decreases in ecosystems, which are used less intensively like pastures and forests, also the decoupling between material production and ecological integrity is reduced. Another assumption is that production in arable lands is accompanied with heavy artificial inputs, which are designed to substitute reduced ecological integrity and *ES potential*, as otherwise, there would be no reasonable explanation to the negative relation between actual production and photosynthetic potential (GPP and NDVI) on one side and the remaining integrity variables on the other side.

The high entropy export in Geest indicates that this region has a lower potential to convert solar energy into biomass when compared to the other two regions. This means that in order to maintain an equivalent NPP across Schleswig-Holstein and even higher production in Geest,

they produce by about $\frac{1}{3}$ more entropy along the way when compared to the rest of the study area. However, this does not account for the inputs, which are required and transformed into waste during the process. The entropy law dictates that every time energy is transferred between different forms, parts of the exergy are transformed and released as entropy (or waste, disorder etc.) and this can lead to a series of unwanted results like for e.g. enhanced CO₂ emissions, fostering climate change. In the context of Schleswig-Holstein, the production in Geest is achieved under conditions of heavy waste production, e.g. in the form of nutrient surpluses. Sandy soils contribute heavily to the overall low capacity to maintain nutrients; combined with low amount of residual biomass (storage capacity), the soil is not suited for holding soluble nutrients and they readily leach into the groundwater. Thus, in order for the production to be maintained as high as in the other regions, soluble nutrients need to be present in the root zone when production happens.

4.1 *It's all about the maize...*

The assessment reveals a distinct spatial pattern of the crop production ES *flow* (Figure 6b). As described above, highest harvest values (in dt/(ha*a)) can be found in the Geest area. Looking into the information from the regional statistics (Statistical Agency North 2010) on the individual crop types, the cultivation of silage maize stands out. Figure 8a presents the spatial distribution of the harvest from silage maize in the study area. Generally, the same trend presented in Figure 6b is shown. The regional pattern is even more distinct with no or very low harvest of silage maize (in dt/(ha*a)) in the areas of the Hügelland and Marsch, and very high (up to 75 dt/(ha*a) and more) harvest values in the Geest area.

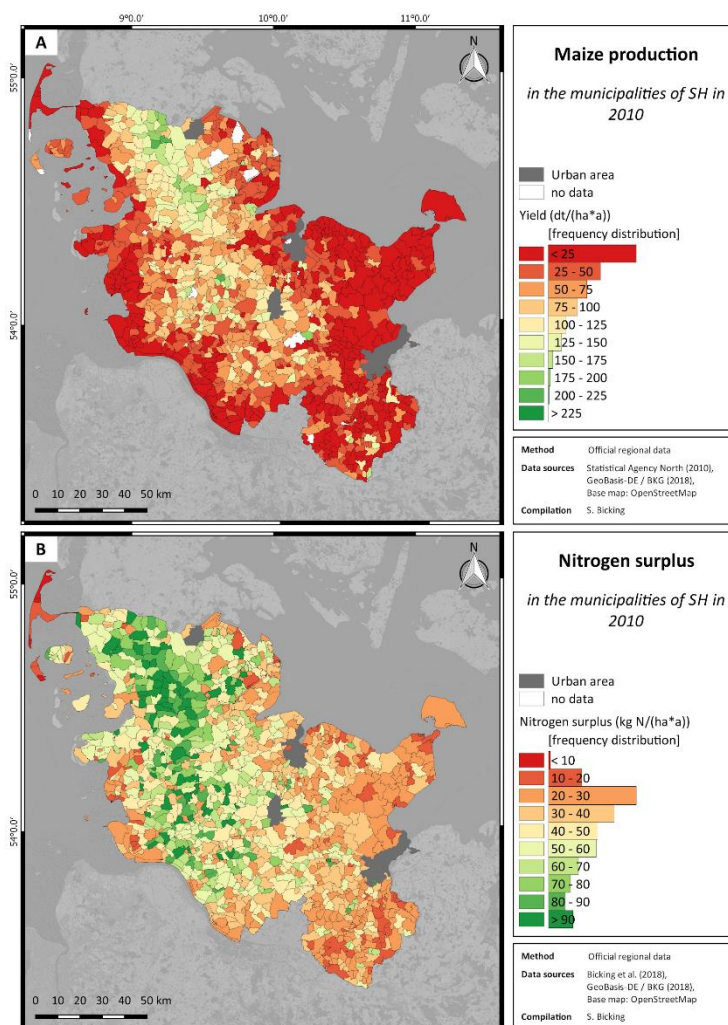


Figure 8: Silage maize harvest (a) and estimated nitrogen surplus (b) in the municipalities of Schleswig-Holstein in 2010.

The development of the silage maize cultivation in Schleswig-Holstein can be divided into two main steps. Generally, due to the relatively infertile soils in the Geest, the area has historically been relatively strongly used for livestock production, accompanied with pastures. The cultivation of pastures as fodder for the livestock has been supplemented with silage maize cultivation since the 1960's. The second step in the development of the silage maize cultivation evolved at the turn of the millennium and is related to the production of bioenergy. As the oil and gas prices increased, farmers started to become interested in the installation of biogas plants. The usage of silage maize as substrate increases the biogas yield in an optimal manner, compared to other energy crops. In 2004, the Renewable Energy Act (in German: Erneuerbare-Energien-Gesetz) provided strong incentives for farmers to install biogas plants (Appel et al. 2016). Amongst others, feed-in tariffs have been granted for a period of 20 years. Since then, the installation of biogas plants and cultivation of silage maize increased strongly (Appel et al. 2016). In particular, the areas, which have already had experience with silage

maize intensified the cultivation. Therefore, the observed strong regional differentiation arose. The regional pattern of the installed biogas plants in the study area (Table 3) is in line with the spatial distribution of the harvest of the silage maize (Figure 8a). The Geest area is characterized by the highest installed power per hectare.

Table 3: Installed electrical power per hectare (kW/ha) in the three main landscape types (based upon Bundesnetzagentur (2019)).

Landscape region	Installed power per hectare (kW/ha)
Hügelland	0.14
Geest	0.27
Marsch	0.1

Comparing these findings to the estimated nitrogen surplus (in kg N/(ha*a)) on agricultural grounds (Bicking et al. 2018), the following can be stated: Generally, the areas with high maize harvests are featured with high nitrogen surpluses. In combination with the assessed EI variable reduction of nutrient loss (Figure 8b) an ecologically harmful picture arises, as our study identifies that these areas exhibit a very low potential for the reduction of nutrient loss. In order to confirm these findings, a correlation analysis has been performed for relevant variables (Figure 9). As this analysis focuses on the silage maize cultivation, all data sets based upon remote sensing have been sampled for croplands before the assessment has been performed. There is a strong positive correlation between the maize harvest and the overall harvest (crop production ES *flow*) in the study area. This is not surprising as silage maize, with an average harvest of around 337 dt/ha (Statistical Agency North 2010), made up a large share of the total harvest in 2010 in Schleswig-Holstein. Further positive correlations have been found between the silage maize harvest and the ecological integrity variable exergy capture, entropy export and the nutrient surplus. Negative correlations arise between the maize harvest on the one side and the ecological integrity variables biotic water flows, reduction of nutrient loss and storage capacity on the other (Figure 9). The amount of maize harvested is not correlated to the crop production ES potential. All of these correlations highlight the detachment of the intensive silage maize cultivation from the environmental capacities in the form of ecological integrity and resultant crop production ES *potential*. The results indicate the presence of another, stronger factor maintaining production, which we suspect to be intensive human activity and artificial input overriding site-specific natural constraints and substituting the missing or diminished ecological integrity.

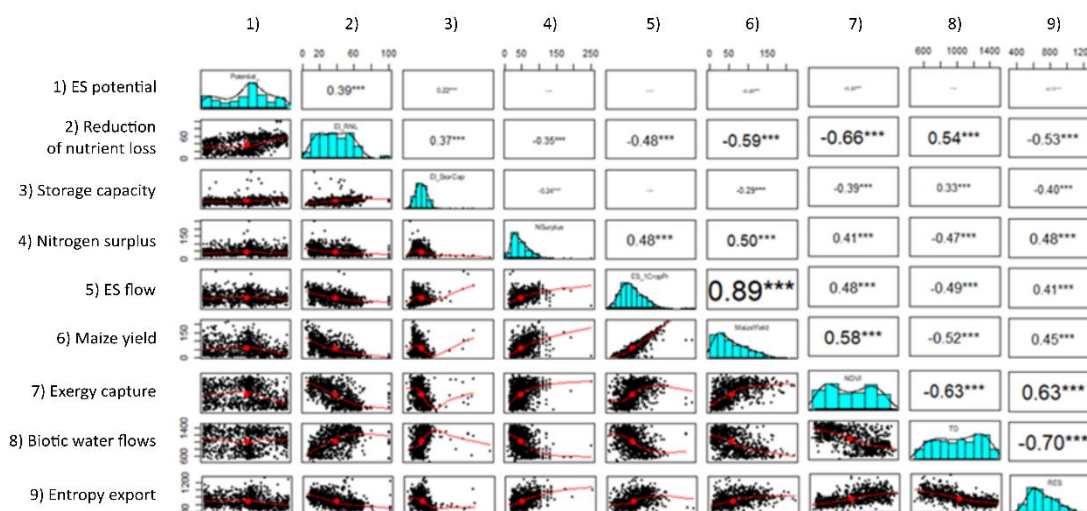


Figure 9: Correlation table presenting the statistical correlations between selected ecological integrity and ecosystem service variables. The remote sensing data sets were sampled in croplands. A Pearson's correlation was performed for: 1) Crop production ES *potential* (BBN approach), 2) EI variable reduction of nutrient loss (as nitrate leaching potential), 3) EI variable storage capacity (as residual biomass), 4) estimated nitrogen surplus (Bicking et al., 2018), 5) crop production ES *flow* (as actual yield), 6) silage maize yield, 7) EI variable exergy capture (as NDVI), 8) EI variable biotic water flows (as temperature difference) and 9) EI variable entropy export (as respiration).

4.2 Grass or Grain?

Differences in the three main landscape regions can be assessed in more detail looking at time developments throughout a vegetation period. Most importantly, the difference between continuous cultivation like pastures and discontinuous cultivation like arable lands shows additional information on ecosystem management, with possible suggestions about management efficiency.

Maize cultivation in Geest takes part in later periods of summer 2016, which produces the most significant difference in Figure 10 - in March and June, the Geest croplands seem to be unvegetated as the maize plants are still very small and cannot totally cover the soil surface with foliage. During this time, Marsch and Hügelland are peaking in NDVI, which reflects the physiological state of the cereal that is predominantly cultivated in these regions. Cereal plantations are already harvested in June or July. By that time, these fields are already uncovered, while maize is peaking in the Geest region. When NDVI values are summed across the number of days, the Geest region surpasses Hügelland and Marsch, possibly due to the vegetation period of maize cultivation extending into the late summer (Figure 10). Based on the correlation analysis performed for the selected variables in arable lands, the higher aggregated NDVI values in Geest can be related to higher gross primary production (GPP),

rather than production itself (GPP and NDVI correlation value = 0.58). Net primary production (NPP), a value used to represent the energy embodied biomass, does not differ significantly for any of the natural regions. Thus, higher exergy captured does not automatically mean more production, when this trend is bound with significantly increased levels of respiration (Figure 10e & f).

We assume that arable lands utilize solar energy more efficiently in Hügelland and Marsch because biotic water flows are much higher in these regions, thus more heat energy is consumed during evapotranspiration. These results are linked to lower intensities of evapotranspiration by vegetation and thus, lower volumes of water transported. This distribution relates to lower metabolic rates and ecosystem efficiencies. The results are consistent with the regional diverging soil properties for each of the three major land-use types in Schleswig-Holstein. This can be an effect of the poor, sandy soils in the Geest, incapable of holding moisture. The biotic water flows of arable lands in Geest are significantly lower when compared to the other regions, but also compared to other land uses like pastures and forests within the area of the Geest (Figure 10c & d). This strong decrease of biotic water flows, along with a strong increase of respiration in the arable lands in the Geest in comparison to other landscape regions and land uses signals that greater pressures are applied and greater losses are accompanying the production in this region. We assume that these are the costs associated with highly industrialized production conditions in remarkably unfavourable conditions, which reveal themselves as sharp decreases of ecological integrity while maintaining production. The net primary production is not significantly higher. Thus, the disadvantages might outweigh the benefits of such practices.

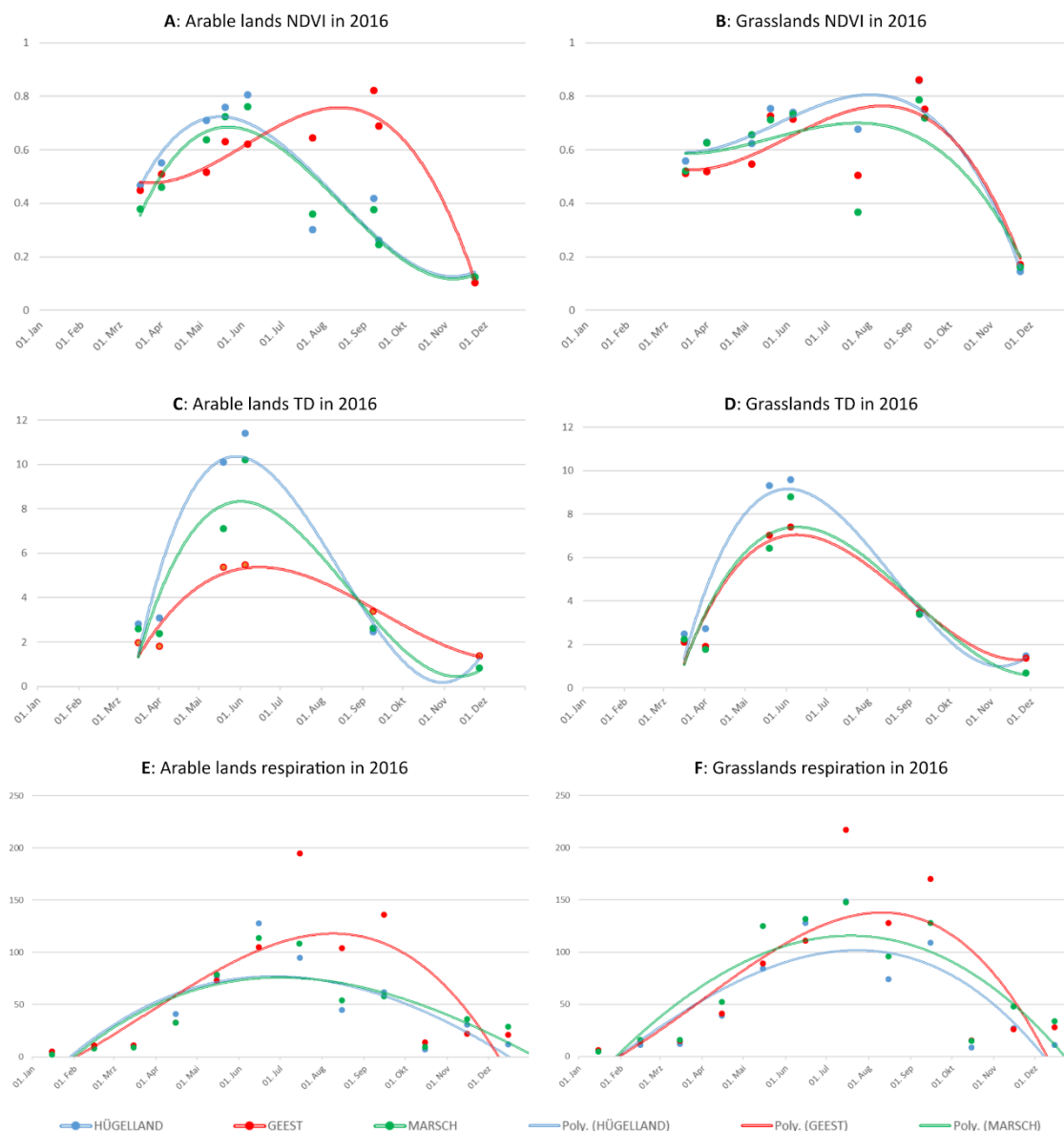


Figure 10: Performances of selected ecological integrity variables in arable lands and grasslands in the three main landscape regions Hügelland, Geest and Marsch throughout the year in 2016: a) Exergy capture (NDVI) in arable lands, b) exergy capture (NDVI) in grasslands, c) biotic water flows (temperature differences) in arable lands, d) biotic water flows (temperature differences) in grasslands, e) entropy export (respiration) in arable lands and f) entropy export (respiration) in grasslands. The points correspond to the actual data assessed by means of remote sensing. The curves correspond to a predicted trend line from each point data set, using a polynomial function calculation (x3; third level).

4.3 Methods, landscape regions and an integrative solution?

In the following section, selected results delivered by the qualitative (ES matrix) and semi-qualitative and quantitative assessments are compared. The comparison is performed at the scale of the main landscape regions Hügelland, Geest and Marsch. The individual results of

the diverse assessment approaches for the EI variables storage capacity, reduction of nutrient loss, exergy capture, biotic water flows, abiotic heterogeneity and the ES crop production are compared. Subsequently, the results from the different approaches are combined in order to come up with an integrated assessment of a selected EI variable on the scale of the three main landscape regions.

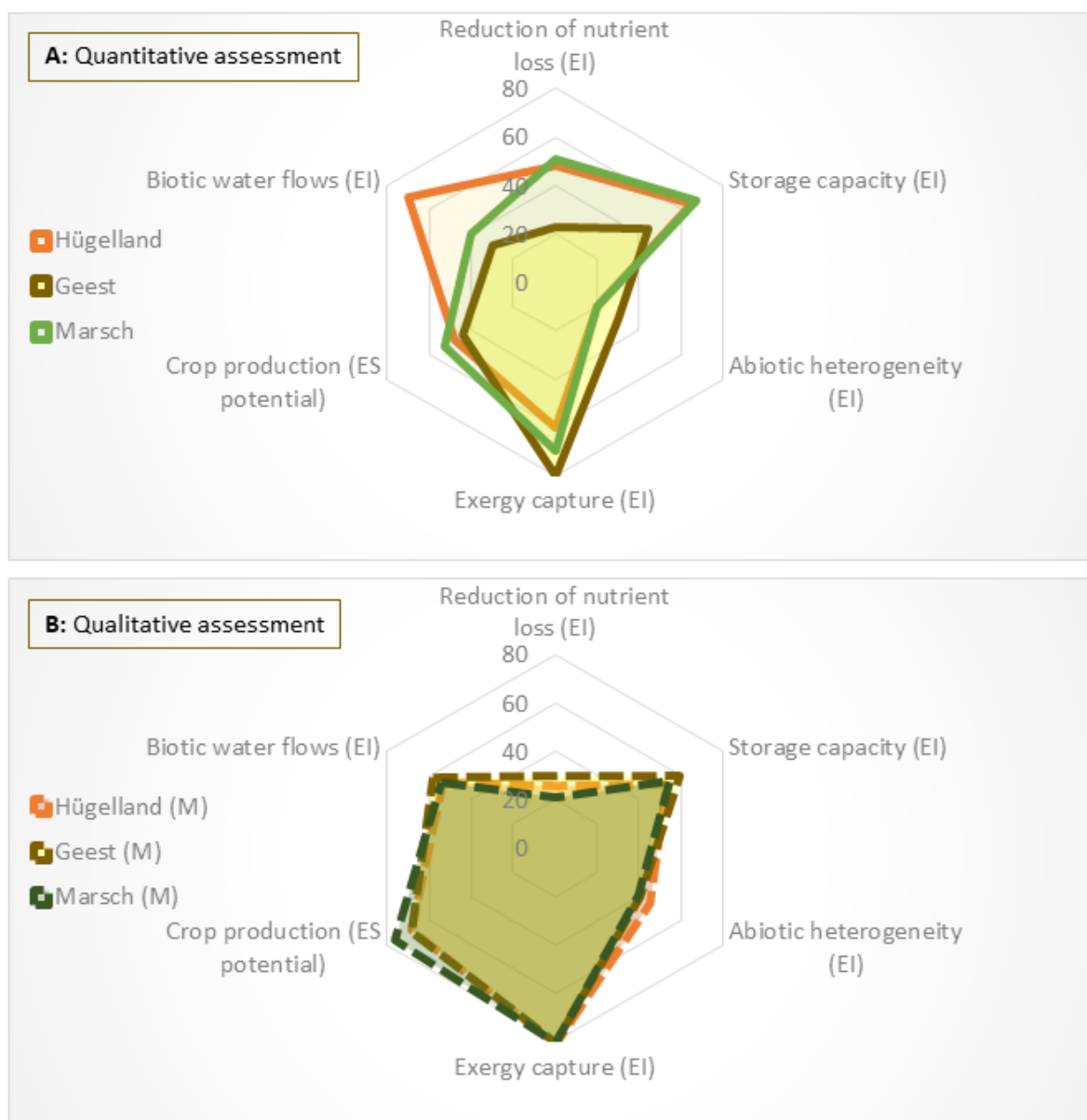


Figure 11: Comparison of selected mean EI and ES *potential* in the main landscape types: A) Aggregated findings from quantitative assessment (biotic water flows, abiotic heterogeneity and exergy capture - remote sensing; crop production – BBN (semi-qualitative); reduction of nutrient loss - official geodata; storage capacity - regional statistics) and B) aggregated findings from qualitative assessment (ES matrix).

Generally, the quantitative assessment results in larger variations among the landscape regions compared to the qualitative matrix based approaches (Figure 11). According to the quantitative assessment, the Geest area scores highest in the exergy capture and the abiotic

heterogeneity. For all other variables the Hügelland and Marsch score high, whereas the Geest provided lowest values. The qualitative assessment delivers contrary results, only little variability between the landscapes regions with a reversed order. Thus, the qualitative assessment indicates highest biotic water flows, reduction of nutrient loss and storage capacity values in the Geest area, and lower than average values for abiotic heterogeneity and the crop production ES potential. The qualitative approach on the basis of the ES matrix, designates expert-based valuations onto land cover types. The respective assessment relies on land cover, only. Thus, for a regional assessment the relative occurrence of the respective land cover types in the area of interest is crucial for the findings (see Figure 2b). Table 4 presents the relative occurrence of the types non-irrigated arable land, pastures and other in the three main landscape regions, based upon the CORINE 2012 land use land cover (LULC) data set. The portion of non-irrigated arable land is highest in Hügelland, followed by the Marsch region. Thus, the relative share of pastures and other LULC classes is highest in the Geest area.

Table 4: Distribution of selected land cover classes in the main landscape regions (based upon BKG, 2012).

Landscape region	non-irrigated arable land	pastures	other
Hügelland	56%	16%	28%
Geest	36%	37%	27%
Marsch	49%	38%	13%

The ES matrix values for instance storage capacity and reduction of nutrient loss in non-irrigated arable land relatively low. Thus, the mean capacities for these EI variables in landscape regions with large non-irrigated arable land areas is relatively low. The quantitative assessments include a different set of indicators to identify the respective capacities. In the case of the EI storage capacity the estimated biomass remaining on the fields after harvest serves as an indicator. The estimation is based upon regional statistics, which identify the agricultural crops, which are grown in the municipalities, and assumptions on the remnant practices per crop type. For the EI reduction of nutrient loss, the official nitrate leaching potential, which has been calculated by the LLUR (2011) based upon soil properties and further site-specific characteristics, serves as a base. Thus, the scope and level of information from the quantitative and qualitative assessment differ. This aspect is supported by the findings on the spatial distribution of the EI and ES in the study area described above.

The assessment of the main landscape types illustrates the discrepancies related to the different approaches. In order to guarantee a comprehensive EI and/or ES assessment, all

relevant and substantial information on the study areas should be integrated. Therefore, we make an attempt to combine the findings from the qualitative and quantitative assessment exemplarily for the EI reduction of nutrient loss. The average of the values from the two approaches have been calculated for each municipality. Thus, both approaches have been weighted evenly. Figure 12 presents the spatially explicit findings of that integrative assessment at the scale of the municipalities. The regional differentiation identified above can be seen at that spatial scale as well.

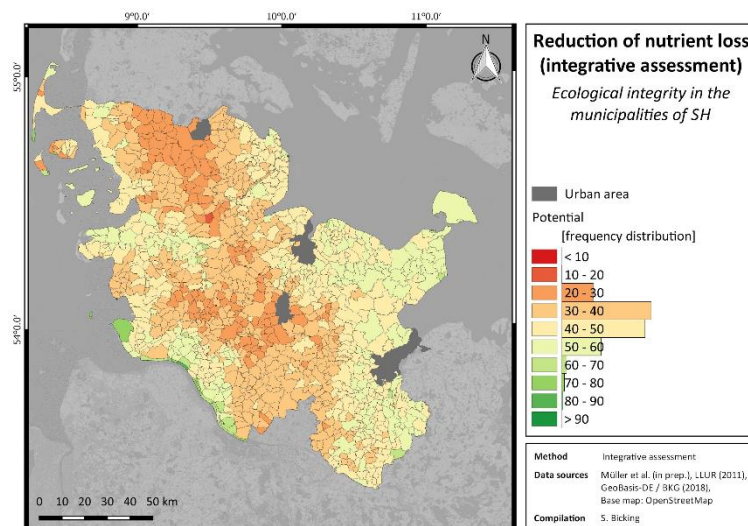


Figure 12: EI variable reduction of nutrient loss in Schleswig-Holstein, based upon the integrative assessment, combining the official regional data on soil properties with the ES matrix approach.

Figure 13 presents the aggregated reduction of nutrient values based upon the three different approaches at the scale of the main landscape types. Through the integrative approach, the differences between the landscape regions are softent. Nevertheless, the integrative assessment still results in lowest values for the reduction of nutrient loss in the Geest region and consequently relatively high reduction of nutrient loss values in the area of the Hügelland and Marsch.

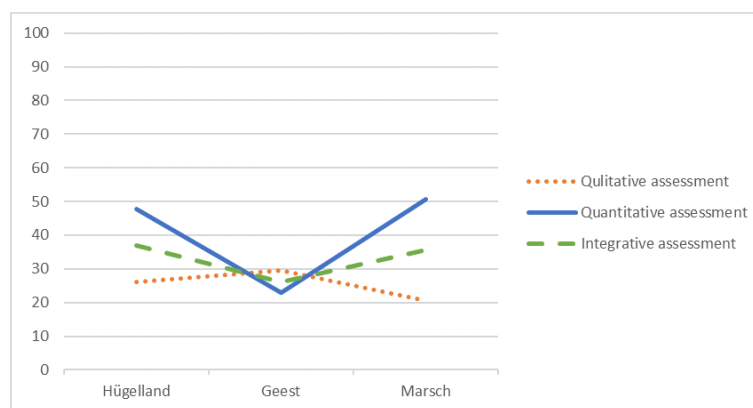


Figure 13: Comparison of mean EI reduction of nutrient loss using different assessment methods (qualitative - ES matrix; quantitative - official geodata; integrative - combined approach) in the main landscape regions.

4.4 Uncertainties and limitations

One innovative feature of this paper is the attempt to illustrate socio-ecological interrelations on the base of the spatial patterns of respective indicators. Besides some interesting outcomes, this concept is also linked with several sources of uncertainties, which could create insecurity related to the evidence of the complex results. Such methodological sources of vagueness, inexactness and failures have been discussed in several books and papers. Concerning the working steps of this article, uncertainties due to remote sensing and GIS procedures have been described e.g. by Alexander et al. (2017), Foody and Atkinson (2003), Hunaker et al. (2013), Lu (2006), Shao and Wu (2008), Stritih et al. (2019) or Woodcock (2002). In this study, the availability of cloud-free images covering the whole extent of the study area and their irregularity within the reference year have been prominent issues. Through gaps in the remote sensing data sets during the peak vegetation period, important plant dynamics may remain unconsidered which would lead to inconsistencies in the results. Our solution was the combination of multiple data sources to cover for these gaps (described in detail in section 2.2.1). Although we have given some suggestions about the state of the three landscape regions of Schleswig-Holstein, the assessment of their ecological integrity is only relative, given the conditions of the study area. The contemporary agricultural practices are almost exclusively based upon spending resources to diminish ecological integrity (self-organization or succession). Thus, although our results indicate “better” conditions on agricultural grounds in Marsch and Hügelland in comparison to the Geest area, this does not mean farming is done optimally or sustainably there. An issue is that there are no references to the optimal landscape region specific potentials and thus sustainable agricultural production system, where provision of crops is fully in line with ecological integrity.

The generally appearing uncertainties of ecosystem service assessments have been discussed e.g. by Boerema et al. (2017), Dong et al. (2015), Grêt-Regamey et al. (2013), Hamel & Bryant (2017), Schulp et al. (2014) or Seppelt et al. (2011), and special uncertainties referring to the application of Bayesian networks were e.g. analyzed by Ahmadi et al (2015), Ascough II et al. (2008), Pollino et al. (2007) and Regan et al. (2002). Finally, the comprehensive uncertainties related to expert-based approaches like the matrix applications, have been objects e.g. in Burkhard & Maes (2017a), Campagne & Roche (2017), Dong et al. (2015), Hou et al. (2013), Jakobs et al. (2015) or Schägner et al. (2013). Already the high number of references may indicate the important role of uncertainties in recent ES assessments and their significance for ES sciences.

Referring to spatial ES approaches, Stritih et al. (2019) have listed 7 different types of uncertainties which have to be considered, e.g. in Bayesian network applications within ecosystem services assessments: the natural variability, classification errors, measurement errors, empirical and process-based model variabilities, uncertainties of the applied expert knowledge and linguistic uncertainty. Schulp et al. (2014) are discussing further sources for unsecure analyses. For instance:

- the uncertain definition of the ecosystem service indicators might not be consistent,
- the variable level of process understanding can cause uncertainty in quantification and mapping,
- the different aims of mapping influences can lead to diverse directions of regional distinctions,
- the potentially biased selection of the most relevant indicators influences parameter comparability,
- the failures and inaccuracies of the data sources themselves can be enormous, and
- the inherent challenges of different methodologies for mapping ES can also have significant influences on the result accuracies.

Besides these relatively concrete items, Hou et al. (2013) have discussed a long list of sources for uncertainties in spatial ES matrix applications. Some additional points are:

- uncertainties due to ecosystem and landscape dynamics (e.g. uncertain dynamics of land-use or climate, temporal shifts in comparable data sets),
- uncertainties due to modelling methodologies (e.g. assumptions, input data, missing influences, model inexactness),

- uncertainties due to landscape analytical methods (e.g. heterogeneities, classification ambiguity, non-checked accordance of satellite images and ground truth, inexactness appearing due to image processing and interpretation analyses, potential inaccuracies within delivering institutions such as EEA, ESA, NASA or USGS),
- uncertainties due to incompatible indicator – indicandum relations (e.g. chosen empirical parameters from regional analyses do not always completely comply with the selected indicators, semi-suitable target values),
- uncertainties due to natural service supply (e.g. due to limited regional knowledge or uncertain dynamics),
- uncertainties due to preference settings (e.g. valuation strategies of individual participants, biased expert judgements in matrix surveys),
- uncertainties due to technical problems (e.g. methodological weaknesses, de-compatibilities of methods, data scarcity),
- uncertainties due to scaling mismatches (e.g. neglecting additive (emergent) effects of ecosystem complexes or neglecting the effects of landscape boundaries or punctual landscape elements, transfer from CORINE land cover resolution to municipality scales, information loss due to distinct resolutions of initial data sets),
- uncertainties due to insufficient parameter inclusion (e.g. concentrating on land cover without considering soils, elevations, land use intensities, etc.),
- uncertainties due to lack of processual knowledge (e.g. working with lack of information on carbon sequestration potentials or nutrient retention capacities inexact data on production, yields, nutrient balances),
- uncertainties due to non-regarded interactions (e.g. influences from neighbouring ecosystems), and
- uncertainties due to loose distinctions between *potentials*, *supplies*, *flows* of and demands for ecosystem services (e.g. confusion of *potentials* and demands concerning cultural ecosystem service).

In spite of this long list of potential failures, it is assumed that the focal results of this study are realistic and significant outcomes. But the high amount of potential uncertainties also demonstrates that there is still a lot of work necessary to continue developing the described ecosystem service assessment conceptions and techniques.

5 Conclusions

This study contributes to the theoretical assessment of the relation between ecological integrity and the provision of ecosystem services. Nevertheless, the assessment also has a strong applied focus on land management and agricultural practices. Besides, the assessment reveals the strengths, scopes and limitations of the different methodological approaches. Striving for comprehensive ecosystem assessments, different approaches have been combined in order to increase the informative value of the analysis, exemplarily for the EI variable reduction of nutrient loss. Summing up the knowledge obtained from the study, the research questions are revised and answered accordingly:

- I. Does the spatial distribution of the assessed ecological integrity variables reveal a distinct regional pattern?

Yes, generally the assessed ecological integrity variables can be divided into two different groups with reference to their spatial pattern. The ecological integrity variables which have a strong relation to the production of biomass show highest values in the area of the Geest. This is the case for the ecological integrity variables entropy export and exergy capture. The landscape regions Hügelland and Marsch are characterized by lower values for both of these ecological integrity variables. The spatial assessment of the ecological integrity variables which indicate the functionality of the ecosystem apart from the simple biomass production indicated a reversed regional pattern. The area of the Geest is featured by lowest values for the ecological integrity variables reduction of nutrient loss, biotic water flows and storage capacity. The assessment reveals that both, the Hügelland and Marsch, deliver higher ecological integrity with respect to these variables.

The spatial pattern of the abiotic heterogeneity follows the regional distribution of the biomass related integrity variables. However, the abiotic heterogeneity needs to be regarded on its own as this distinct regional pattern originates to a large extent from the historic land management rather than from the fundamental environmental characteristics of the region. The distribution reveals the landscape structure with regard fragmentation and the sizes of the agricultural fields.

- II. Does the spatial distribution of ecosystem service crop production reveal a distinct regional pattern?

Yes, the assessment identifies regional differentiations with regard to the ecosystem service crop production. Interestingly, the regional pattern of the ecosystem service

potential and the actual ecosystem service *flow* don't coincide. The assessment of the crop production *potential* identifies the Hügelland and Marsch as the regions with highest ecosystem service *potentials*. In contrast to that, these areas are characterized by rather low ecosystem service *flow* values. Highest values for actual crop production (*ES flow*) can be found in the Geest area.

III. What is the relation between the assessed ecological integrity variables and the crop production *ES potential* and *flow*?

The crop production ecosystem service *potential* is strongly related with the spatial distribution of the ecological integrity variables reduction of nutrient loss, storage capacity and biotic water flows. Nevertheless, this spatial pattern is opponent to the regional distribution of the ecosystem service *flow* in terms of actual harvest. The assessment revealed a strong correlation between the crop production *ES flow* and the ecological integrity variables, which are strongly related to biomass production, i.e. exergy capture and entropy export. Thus, this study revealed a detachment of intensive agricultural production from the fundamental environmental functions.

This supports the assumption that land management and agricultural practices are not directed towards sustainable development. The more historic land management practices (smaller more fragmented fields in the Geest and a greater share of pastures compared to arable land) were more in line with the natural circumstances of the respective landscape region. The recent development in the Geest with intensive maize cultivation for fodder and biomass production contradicts these circumstances. The political agenda on energy production from biomass, more precisely the financial incentives for biogas production, which aimed at increasing the sustainability of the energy sector came with unexpected unsustainable side effects. The comparison of the performance of the grass- and croplands in the three main landscape regions supports these assumptions. Overall, the lower natural productivity in the Geest should result in larger areas covered by pastures, which perform far better concerning most EI indicators. Strong advice to import more organic matter into the soils to help retain water and nutrients. Generally, intensive crop production in the Geest area should be reduced.

Using landscape scale measures and combining methods has yielded evidence suitable for testing theoretical presuppositions present in contemporary scientific discourse. These included the notion of EI being the foundation for ES provision, yet our results indicate an opposite trend where agricultural production is clearly traded-off against ecological integrity. This is the influence of human management and the input, which serves to suppress self-organization and substitute integrity by providing nutrients, removing competition and

preventing pest damage. Not only is this activity very energy and material demanding, it also produces a whole array of unwanted by-products like CO₂, entropy and nitrate leaching leading to more unexpected costs.

The inverse relation between integrity and service provision and the accompanying costs give us evidence of unsustainability; the production regime, in which costs exceed the benefits. But since the costs are not accounted for due to methodological or theoretical constraints, such practices appear profitable or even worth of political support as in the case of maize cultivation in Geest. To conclude upon the apparent paradox, we fully support the premise, that all ecosystem services are founded on ecological integrity and are thus fully in concordance with it. Thus, sustainable agriculture is founded upon maintaining high ecological integrity supporting an array of ecosystem services throughout the whole vegetation season, and stands in contrast to current agriculture, prioritizing a single service at the expense of all other services including the underlying ecological integrity.

We would like to argue for the conceptual progression towards continuous-cover crops, polycultures, agroforestry and permaculture as a basis for landscape management. With regard to agricultural practices, high levels of integrity relate mostly to specific soil communities. Soil communities undergo succession just like plant or water communities, and will have to start over if disturbed by for e.g. tillage and pesticide leakage into the soil. Soil biodiversity is what makes nutrients available for plants, keeps the soil aerated and resistant to compaction by building structure (capillary system) and helps decompose organic matter which then increases the capacity to retain water and nitrogen. By continually tilling, the soil is being forcefully homogenized and loses structure, by application of pesticides the rich biota which is normally responsible for unlocking nutrients to plants in untilled land is diminished. Now, fertilizers need to be applied if any plants are to grow on such soil, but not because the fertilizers improve growth, but because the ecological integrity is thoroughly suppressed and does not contribute in the provision of the ecosystem services anymore.

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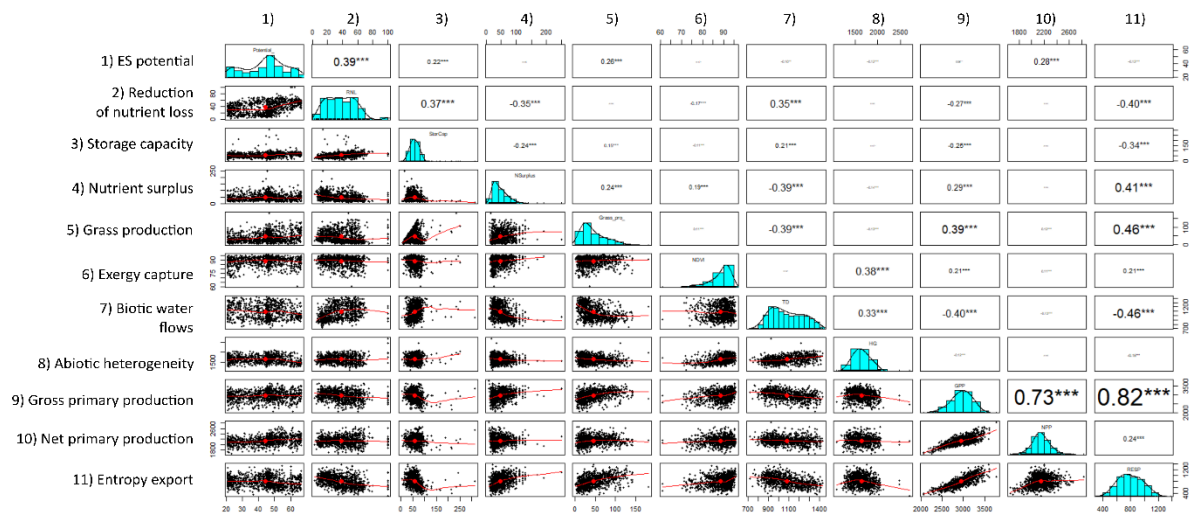
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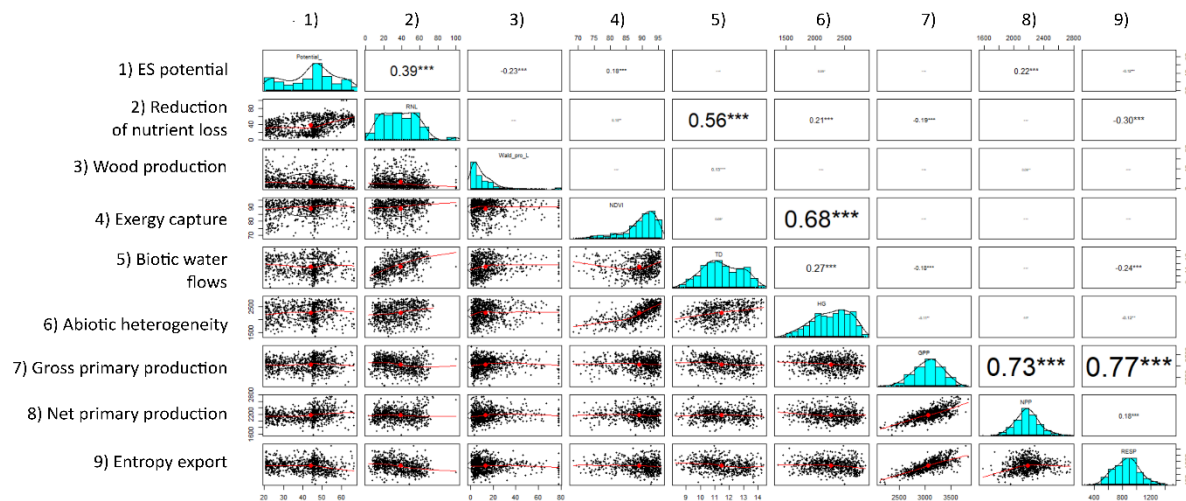
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Appendix



Appendix 1: Correlation table presenting the statistical correlations between selected ecological integrity and ecosystem service variables. The remote sensing data sets were sampled in grasslands. A Pearson’s correlation was performed for: 1) Crop production ES potential (BBN approach), 2) EI variable reduction of nutrient loss (as nitrate leaching potential), 3) EI variable storage capacity (as residual biomass), 4) estimated nitrogen surplus (Bicking et al., 2018), 5) grass production (as grass yield), 6) EI variable exergy capture (as NDVI), 7) EI variable biotic water flows (as temperature difference) and 8) Abiotic heterogeneity (as edge density), 9) Gross primary production, 10) Net primary production and 11) EI variable entropy export (as respiration).



Appendix 2: Correlation table presenting the statistical correlations between selected ecological integrity and ecosystem service variables. The remote sensing data sets were sampled in forests. A Pearson’s correlation was performed for: 1) Crop production ES potential (BBN approach), 2) EI variable reduction of nutrient loss (as nitrate leaching potential), 3) Wood production (as timber growth), 4) EI variable exergy capture (as NDVI), 5) EI variable biotic water flows (as temperature difference), 6) Abiotic heterogeneity (as edge density), 7) Gross primary production, 8) Net primary production and 9) EI variable entropy export (as respiration).

7

Synthesis

Within the synthesis, the main results from the individual chapters are brought together. The chapter includes a discussion of the findings and underlying approaches, including an elaboration of the strengths and limitations of the approaches. In addition, general uncertainties related to ecosystem research and the conceptual ES framework are discussed. Thereby, the issue of spatial scale is considered and a theoretical thinking experiment is performed on the issue of scale in relation to the ES concept. Based upon the collection of the findings and the discussion, an outlook on relevant future research opportunities is provided. Finally, in the conclusions, the main findings of the individual studies are used in order to answer the main research question and to draw conclusions related the main objectives of the thesis.

7 Synthesis

7.1 Discussion of main results

In this chapter, the findings of the individual papers are compared to contemporary literature and are put into relation to the objectives of the thesis and the conceptual framework, which have been introduced in chapters 1 and 2. Table 3, lists the research questions raised in the individual papers (chapters 3-6). The table also highlights the respective integral elements of the individual chapters, which were essential for answering the research questions.

Table 3: Individual research questions and corresponding relevant elements from chapters 3-6.

Chapter	Individual research questions	Integral elements
3	<ul style="list-style-type: none"> • Do nutrient regulation ES potentials and demands coincide in Schleswig-Holstein and the Bornhöved Lakes District? • Is it possible to statistically prove the influence of the ES nutrient regulation on the nutrient status of the ecosystems? • Does an assessment on a higher spatial resolution result in more valid outcomes? 	<ul style="list-style-type: none"> • Application of ES matrix for assessing nutrient regulation ES potential in the study areas • Development of an approach to calculate the nutrient surplus as an indicator for the nutrient regulation ES demand • Calculation of the nutrient surplus on different spatial scales in the study areas • Comparison of the spatial distribution of the nutrient regulation ES demand and potential to the nitrate leaching potential
4	<ul style="list-style-type: none"> • Does the calculated nutrient regulation ES demand in the case study area Eversen resemble the nutrient regulation ES demand on the scale of the municipalities in the county of Höxter? • Do the calculated nitrogen budgets depend on agricultural practices such as crop rotation, the establishment of flower strips and fellow land? 	<ul style="list-style-type: none"> • Refinement of the approach to calculate the nutrient surplus as an indicator for the nutrient regulation ES demand • Calculation of the nutrient surplus on different spatial scales in the study areas • Comparison of the spatial distribution of the nutrient regulation ES demand to the nitrate leaching potential and the

	<ul style="list-style-type: none"> • How can nitrate leaching and denitrification potentials be used in the assessment of the nutrient regulation ES? 	denitrification potential in the form of a vulnerability evaluation
5	<ul style="list-style-type: none"> • Does the inclusion of data on ecosystem properties and conditions for the assessment of the nutrient regulation ES potential result in a more scattered distribution of the ES potentials compared to the distribution based upon the ES matrix values provided by Burkhard et al. (2014)? • Does the assessment of the nutrient regulation ES potential indicate regional differences in Schleswig-Holstein? • Does the probability distribution of the nutrient regulation ES potential in the Bornhöved Lakes District resemble the distribution in Schleswig-Holstein? 	<ul style="list-style-type: none"> • Proposition of an integrative assessment in order to assess the nutrient regulation ES potential based on the ES matrix approach • Implementation of the proposed approach through the development of a BBN to assess the nutrient regulation ES potential under consideration of selected ecosystem properties and conditions • Application of the BBN on different spatial scales in the study areas • Analyses of regional differences based upon main landscape regions • Evaluation of sustainability through comparison of nutrient regulation ES potential and demand
6	<ul style="list-style-type: none"> • Does the spatial distribution of the assessed ecological integrity variables reveal a distinct regional pattern? • Does the spatial distribution of ES crop production reveal a distinct regional pattern? • What is the relation between the assessed ecological integrity variables and the crop production ES potential and flow? 	<ul style="list-style-type: none"> • Holistic regional ES assessment of the ES crop production integrating fundamental EI variables • Application of different quantitative and qualitative methodologies to assess relevant EI variables and ES • Comparison of different methodological approaches • Analyses of regional differences based upon main landscape regions • Interpretation of findings based upon land management and agricultural practices

7.1.1 Assessing the nutrient regulation ES demand and potential

Within these compartments, the thesis focuses on issues related to land management and agricultural practices by applying an interdisciplinary ES approach. A lot of emphasis was placed on the assessment of the nutrient regulation ES. Both the demand and supply side of the ES were assessed. The rationale for the strong emphasis on this ES originates in its high contemporary relevance, as explained in the introduction (chapter 1.1). The results of this thesis contribute to the debate on the topic of nutrient management. Generally, the results revealed an unsustainable nutrient management as depicted by other research and monitoring projects (Heidecke et al. 2014; LLUR 2014a; Taube et al. 2015; Trepel 2016). The findings highlight the regional component in terms of variations of the nutrient situation (Taube et al. 2015). Moreover, the general results and conclusions of the nutrient situation in the federal state of Schleswig-Holstein in this study are conform to the findings of the LLUR (2014a). Concerning the nitrate concentration of the groundwater bodies of Schleswig-Holstein, the LLUR (2014a) detected that in particular the area of the Geest has high values and hence has to be evaluated negatively in regard to the respective environmental condition (LLUR 2014a). The findings of this thesis consequently detected a high demand for the nutrient regulation ES in that area, indicated by high nutrient surpluses.

The LLUR (LLUR 2014a) identified that denitrification plays a major role in decreasing the nitrate concentration in anoxic conditions. The LLUR assumes that for a large share of the areas with relatively low nitrate concentrations in the groundwater bodies, the nutrient surplus is still too high but denitrification compensates for the high values (LLUR 2014a). In order to enable denitrification, further substances, for example pyrite, are required for the chemical reactions to take place (Torrentó et al. 2010; LLUR 2014a). These substances occur in a finite amount and therefore limit the potential for the process of denitrification. The LLUR already monitored incomplete denitrification and therefore increasing nitrate concentrations in some humus-scarce, sandy groundwater bodies of the Geest (LLUR 2014a). Thus, it can be assumed that the nitrate concentrations in these respective groundwater bodies will increase in the future.

As indicated above, the findings of this thesis are in line with the monitoring results of the state government and highlight the need for adaptations in land management and agricultural practices in order to achieve sustainable conditions. Furthermore, the findings give insights from the perspective of an integrative ecosystem research approach. The application of an ES assessment, focusing on the quantification and mapping of the regulating ES nutrient regulation granted access into the complex issue and revealed spatial patterns and regional differences based upon ecosystem properties and conditions and anthropogenic factors.

7.1.2 Refining the quantification of the nutrient regulation ES demand

Striving for a spatially even more explicit understanding of the nutrient issue, the study was executed on a finer scale. The demand for nutrient regulation was assessed on the scale of an individual farm, located in the federal state of Nordrhein-Westfalen. The study included the influence of other agricultural practices such as crop rotation systems and flower strips on the nutrient situation. As a side effect of the research on the farm-scale, the revised German Fertilizer Ordinance (dt: Düngeverordnung, DüV) was critically assessed. The study revealed nitrogen oversupply situations in the whole study area. Nevertheless, consistent with the literature (European Commission – DG ENV 2010; PAN Germany 2010; Bruns 2012; VALERIE 2017), the assessment highlighted the reducing effect of increased crop rotation on the nitrogen surplus. Through the cultivation of flower strips and the inclusion of fallow land, the diversity of the agricultural grounds can be enhanced (Tschumi et al. 2015). The results highlight the positive effects of these measures as they decrease the local nutrient surplus. Functionally diverse systems are generally more effective in retaining nutrients (Hooper and Vitousek 1997; Hooper and Vitousek 1998). Thus, they have a higher nutrient regulation ES potential (Fu et al. 2012; Burkhard et al. 2014). In order to increase the informative power of the study, the nitrate leaching potential was calculated for all field parcels that were assessed. In combination with the denitrification potential, the nitrogen surplus and the nitrate leaching potential were used in order to assess the relative vulnerability to nutrient oversupply. Relative vulnerability assessments enable the identification of hotspots (Weißhuhn et al. 2018). The assessment in the case study area Eversen detected hotspots of vulnerability, which originated from disadvantageous spatial mismatches of the nitrogen surplus and the nitrate leaching and denitrification potential.

7.1.3 Refining the assessment of the nutrient regulation ES potential

The spatially explicit results from the assessment of the nutrient regulation ES demand indicating regional differences support the assumption that a more holistic and integrative assessment of the nutrient regulation ES potential is necessary. In this context, the ES matrix approach was critically discussed. In particular the aspect that the applied ES matrix approach evaluates ES solely based upon the distribution of land use/land cover provided space for criticism (for more information see chapter 7.3.1). The conclusion was drawn that in order to guarantee a comprehensive understanding of the potential of ecosystems to provide the ES nutrient regulation, more environmental information should be integrated. In order to enable the incorporation of additional data but still harness the applicability of the ES matrix approach and corresponding evaluation of the ES potential, a BBN was developed. On the one hand, the ability of the BBN approach to serve as an integrative assessment model for comprehensive ES assessments was tested. On the other hand, the influence of incorporating further selected spatially explicit environmental data on the nutrient regulation ES potential was assessed. The

BBN assessment identified that Schleswig-Holstein is for the most part featured by no and low relevant nutrient regulation ES potential. Compared to the spatial distribution of the nutrient regulation ES potential solely based upon the ES matrix assessment, a broader distribution resulted. Besides, the results of the BBN demonstrate regional differences in the assessed ES potential. The main landscape regions Hügelland and Marsch attained generally higher nutrient regulation ES potentials compared to the Geest area. This spatial distribution reflects the regional patterns of the environmental input datasets, such as information on slope and soil properties, which were incorporated in the assessment. The Geest area, which is characterized by rather poor, sandy (Schott 1956; Bähr and Kortum 1987), which have relatively low field capacities and natural nutrient availability rates, is subject to e.g. wind erosion and nitrate leaching (LLUR 2011; LLUR 2014b). These natural circumstances led to the obtained outcomes. A comparison of the findings on the distribution of the nutrient regulation ES potential and demand revealed a detrimental situation as a spatial mismatch between the distribution of the nutrient regulation ES potential and demand was detected. In particular, the Geest area seems to be unbalanced as the area is featured by a low potential ES supply and a relatively high ES demand.

7.1.4 Comprehensive assessment of the ES crop production

As discussed throughout the whole thesis, the agricultural sector is tightly linked to many ES (Power 2010). The original aim of agricultural practices was the provision of food products for human nutrition and animal fodder (Johansson et al. 2010). Nowadays, agricultural practices also aim at producing fibers and biomass for energy production (Johansson et al. 2010; Bruns 2012). In the framework of the ES concept, this corresponds to the provisioning ES crop production. This ES is directly linked to human-wellbeing (McMichael et al. 2005; Haines-Young and Potschin 2010), in particular to the constituents basic material for good life and health (Haines-Young and Potschin 2010). This connection highlights the high importance of the ES and served as additional argument to include the ES in this thesis. Considering the lessons learned from the preceding ES assessments, the ES crop production was assessed applying an integrative approach. The ecosystem condition, represented in the form of ecological integrity, was considered as a foundation for the provision of the ES crop production. Different methodologies were applied in order to facilitate the comprehensive assessment. Next to the ecological integrity, both ES potentials and flows were considered. The study examined the general spatial distribution and the interrelation between the different ecological integrity variables, ES potentials and ES flows. Spatial differences were evaluated in order to draw conclusions on specific regional characteristics and patterns. Furthermore, the applied methodologies and respective results were compared.

The study indicates that the assessed ecological integrity variables can be divided into two main groups. The ecological integrity variables, which have a strong relation to biomass production are

exergy capture and entropy export (Schneiders and Müller 2017). Biotic water flows, storage capacities and reduction of nutrient loss belong to the second group. The study revealed a strong discrepancy of the regional pattern between these groups. Both exergy capture and entropy production exhibited highest values in the Geest region. In contrary to that, the ecological integrity variables from the second group were rather low in the Geest area. The regions of the Marsch and Hügelland surpass the Geest with regard to biotic water flows, storage capacity and reduction of nutrient loss. The potential of the ES crop production followed this spatial trend. Nevertheless, the crop production ES flow, indicated by actual harvest values, exhibits the reversed spatial pattern, only correlating positively with exergy capture and entropy production. The results indicated that decoupling between EI and ES flow occurs in intensively managed agricultural areas with the aim to increase the exploitation of an ecosystem with regard to one specific ES (Schneiders and Müller 2017).

Thus, even though there are distinct regional differences with regard to the ecosystem properties and conditions, land management and agricultural practices are not well adapted to these circumstances. The findings from this thesis can in particular be used in order to increase the understanding between EI, which represents the ecosystem condition, and ES. The findings support the assumption that an assessment of the ecosystem condition is fundamental and needs to be performed in order to guarantee a holistic and meaningful ES assessment as proposed in contemporary ES research (Müller et al. in prep.; Müller and Kroll 2011; Burkhard et al. 2012b; Erhard et al. 2017; Maes et al. 2018).

7.2 Answers to individual research questions

Aiming to answer the main research question of the thesis, individual research questions were developed in chapters 3-6. The results of these chapters were used to answer the research questions individually. Table 4 summarizes these questions and the corresponding answers.

Table 4: Individual research questions and corresponding answers from chapters 3-6.

Chapter	Individual research questions	Derived answers
3	<ul style="list-style-type: none"> Do nutrient regulation ES potentials and demands coincide in Schleswig-Holstein and the Bornhöved Lakes District? Is it possible to statistically prove the influence of the ES nutrient regulation on the 	<ul style="list-style-type: none"> No, in both study areas, relatively high demands for nutrient regulation coincide with low potential supplies of this ecosystem service. Yes, in the Bornhöved Lakes District the statistical evaluation revealed a correlation between nutrient regulation ES potential and the nutrient status defined as the groundwater nitrate concentration.

	<p>nutrient status of the ecosystems?</p> <ul style="list-style-type: none"> • Does an assessment on a higher spatial resolution result in more valid outcomes? 	<ul style="list-style-type: none"> • Yes, the evaluation of the results showed that by increasing the resolution of data, the results become more appropriate and applicable.
4	<ul style="list-style-type: none"> • Does the calculated nutrient regulation ES demand in the case study area Eversen resemble the nutrient regulation ES demand on the scale of the municipalities in the county of Höxter? • Do the calculated nitrogen budgets depend on agricultural practices such as crop rotation, the establishment of flower strips and fellow land? • How can nitrate leaching and denitrification potentials be used in the assessment of the nutrient regulation ES? 	<ul style="list-style-type: none"> • Both assessments indicate high nitrogen budgets in the respective study areas. The calculation based on the municipalities scored higher surplus values for both the ecological and agricultural calculation. The assessment on both spatial scales revealed discrepancies between the agricultural and ecological nitrogen budget calculation. Thereby, the discrepancy between the agricultural and ecological calculation was even larger on the individual field scale. • The assessment identified the effects of different agricultural practices on the nutrient regulation ES demand. Next to the effects of enlarged cropping systems, the effect of additional agricultural measurements aiming to reduce surface runoff, prevent erosion and increase nutrient regulation on the nutrient regulation ES demand have been identified. • The combination of the nutrient regulation ES demand with the nitrate leaching and denitrification potential has been used in order to estimate the relative vulnerability to nutrient excess. The assessment identified hot- and cold spots of vulnerability in the study area and can, therefore, be used in order to support sustainable land management and agricultural practices concerning fertilization practices.
5	<ul style="list-style-type: none"> • Does the inclusion of data on ecosystem properties and 	<ul style="list-style-type: none"> • Yes, the probability distribution for the nutrient regulation ES potential based on the BBN was

	<p>conditions for the assessment of the nutrient regulation ES potential result in a more scattered distribution of the ES potentials compared to the distribution based upon the ES matrix values provided by Burkhard et al. (2014)?</p> <ul style="list-style-type: none"> • Does the assessment of the nutrient regulation ES potential indicate regional differences in Schleswig-Holstein? • Does the probability distribution of the nutrient regulation ES potential in the Bornhöved Lakes District resemble the distribution in Schleswig-Holstein? 	<p>found to be wider than the original distribution based on the ES matrix approach. The inclusion of more environmental data resulted in a more diverse pattern with regard to the probability distribution of the nutrient regulation ES potentials.</p> <ul style="list-style-type: none"> • Yes, incorporating site-specific environmental data into the nutrient regulation ES potential assessment revealed regional differences for the main landscape types. The probability distribution of the Hügelland and Marsch peaked for low relevant potentials, whereas the Geest showed the highest probability for no relevant ES potentials. This regional difference became even more obvious concerning the estimated nutrient regulation ES budget (ES potential vs. demand), as the Geest unified relatively high probabilities for low nutrient regulation ES potentials and high probabilities for high ES demand. • Yes, the two BBNs delivered similar probability distributions. The greatest difference was found for nutrient regulation ES demand, with relatively higher values in the Bornhöved Lakes District compared to Schleswig-Holstein. The BBN for the Bornhöved Lakes District indicated the same general regional trend with regard to the ES potential and ES budget identified for Schleswig-Holstein. The mismatch at the scale of the Bornhöved Lakes District showed an even clearer picture.
6	<ul style="list-style-type: none"> • Does the spatial distribution of the assessed ecological integrity variables reveal a distinct regional pattern? 	<ul style="list-style-type: none"> • Yes, generally the assessed ecological integrity variables can be divided into two different groups with reference to their spatial pattern. The ecological integrity variables which have a

<ul style="list-style-type: none"> • Does the spatial distribution of ES crop production reveal a distinct regional pattern? • What is the relation between the assessed ecological integrity variables and the crop production ES potential and flow? 	<p>strong relation to the production of biomass show the highest values in the area of the Geest. The spatial assessment of the ecological integrity variables which indicate the functionality of the ecosystem apart from the simple biomass production indicated a reversed regional pattern, as the area of the Geest has the lowest values for the ecological integrity variables reduction of nutrient loss, biotic water flows and storage capacity.</p> <ul style="list-style-type: none"> • Yes, the assessment identifies regional differences with regard to the ES crop production. Interestingly, the regional pattern of the ecosystem service potential and the actual ecosystem service flow do not coincide. The assessment of the crop production potential identifies the Hügelland and Marsch as the regions with highest ecosystem service potentials. In contrast to that, these areas are characterized by relatively low ecosystem service flow values. • The crop production ES potential is strongly related to the spatial distribution of the ecological integrity variables reduction of nutrient loss, storage capacity and biotic water flows. Nevertheless, this spatial pattern is contrary to the regional distribution of the ecosystem service flow in terms of actual harvest. The assessment revealed a strong correlation between the crop production ES flow and the ecological integrity variables which are strongly related to biomass production, i.e. exergy capture and entropy export. Thus, this study revealed a detachment of intensive
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		agricultural production from fundamental environmental functions.
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The insights from the individual chapters and the general findings of the thesis are brought together and summarized in chapter 7.5.

7.3 Strengths, challenges and uncertainties

This section deals with general aspects that concern the applied approaches and methodologies. Chapter 7.3.1 covers the identification of strengths and limitations of the utilized approaches, chapter 7.3.2 addresses common issues related to the concept of ES and chapter 7.3.3 subsequently discusses the issue of scale in relation to ES and ES assessments.

7.3.1 Methodological strengths and limitations

Generally, distinct strengths and limitations can be allocated to the different methods and data that were applied. For instance, the ES matrix approach which was applied in chapters 3, 5 and 6, stands out due to its flexibility and applicability to different levels of complexity (Burkhard 2017b; Dunford et al. 2017b). The approach merges ES mapping and modelling, as it is a combination of GIS and spreadsheets analysis (Dunford et al. 2017b). The approach allows for fast implementation on various spatial scales (Burkhard et al. 2014; Burkhard 2017b; Campagne and Roche 2018). For this thesis, the ES matrix from Burkhard et al. (2014) was adopted for the assessments in chapters 3 and 5. For the assessment in chapter 6, the newly developed ES matrix by Müller et al. (in prep.) was applied. Both ES matrices link specific ES potentials to specific land use/land cover classes, whereas the CORINE LULC dataset (Müller et al. in prep.; Burkhard et al. 2014) serves as foundation. Simple GIS analyses allowed for the application of the ES matrices based upon the CORINE LULC dataset in the respective study areas and generated spatially explicit distributions of the ES potentials. The ES matrices were originally developed based upon for example statistics, model outcomes and primarily on expert evaluation (Müller et al. in prep.; Burkhard et al. 2014). The inclusion of expert evaluation into an assessment is usually accompanied by a range of uncertainties (Hou et al. 2013; Campagne and Roche 2018). Experts generally base their evaluations on their personal background including their experience, education, living conditions, beliefs and attitudes (Jacobs et al. 2015; Campagne and Roche 2018). Through the involvement of experts from different relevant research fields, the uncertainties of the expert evaluation can be reduced (Jacobs et al. 2015; Schulp and Landuyt 2017).

In chapter 5, a BBN was developed in order to assess the nutrient regulation ES potential in more detail. The possibility of integrating quantitative and qualitative data from the different research domains (environmental, socio-cultural and economic) into BBNs is a great advantage (Dunford et al. 2017b). This enables the incorporation of field data, results delivered from other models and possibly

information based on expert evaluation (Dunford et al. 2017b; Landuyt et al. 2017). This aspect increases the convenience and practicability of BBNs in regions with data scarcity and scientific fields where the available data base does not fulfill the requirements for empirical or process-based models (Landuyt et al. 2017). Of course, BBNs are accompanied by a simplification of the reflected systems, which leads to increased uncertainties related to the model outputs. Nevertheless, uncertainties are taken into account in BBN-applications (McCann et al. 2006), as the realized value of a particular variable can be allocated to multiple states using probabilistic methods. Besides, through its graphical nature, model transparency is enhanced (Landuyt et al. 2017). Last but not least, an advantage of BBNs is the good suitability into the ES cascade (Landuyt et al. 2017). With respect to the implementation of the BBN in this thesis, the focal objective of the application needs to be kept in mind when interpreting the findings of the assessments. The respective study aimed to test the application of a BBN as an integrative model, incorporating the ES matrix approach and further environmental data. Even next to the ES matrix, expert evaluation was an essential base for the BBN development. Therefore, the general limitations, which come along with expert evaluation, described above are applicable. Furthermore, structural limitations arose from the general BBN outline. Only a limited amount of nodes and thus environmental parameters was incorporated into the BBN, partly due to the objective of the study and partly due to limited data availability. As proposed by the literature (Landuyt et al. 2012; Landuyt et al. 2017), the BBN did not reflect the actual complexity of the ecosystem but only represented a simplification. In addition to that, the incorporated nodes only featured a limited number of states. The input data was reclassified according to these defined states. Modification of the defined states and the reclassification of the input data could potentially alter the results.

When taking official regional statistic data as base for the ES assessment, certain strengths and limitations occur. The quantification of the nutrient regulation ES demands in chapters 3 and 4 and the assessment of the ES crop production in chapter 6 used information from the regional statistic data. They are easily accessible and available for a broad variety of topics. Even though data privacy law prevents some data to be published, they provide a well-managed pool of official governmental information. However, certain aspects decrease the quality of this type of data for spatially and temporally explicit ES assessments. Firstly, the data is usually provided on the scale of administrative units, such as municipalities and counties. An accurate spatially explicit allocation of information within these units is not possible (Burkhard and Kruse, 2017). Furthermore, the spatial extent of these units often does not correspond to any meaningful biophysical area. Besides, the statistical information is usually only available for low temporal resolutions, hindering detailed temporal explicit assessments such as incorporating seasonal aspects (Burkhard and Kruse, 2017). The quantification of the nutrient regulation ES demand on the field scale (chapter 4) was primarily based on the data and information from the field record system of the farmer. The field record system contains information on cultivated

crop types and specifies the fertilizer applications (von Ruschkowski 2018). However, no data on the field-specific harvest was recorded; only rough estimates were provided by the farmer. The fact that the harvest data was based on average estimations without temporal and spatial variations increased the uncertainties of the approach.

For all methods that were applied, the following issues must be addressed for a scientifically sound interpretation of the results. For the interpretation of the findings, the applied approach and utilized input data needs to be considered. The strengths and limitations of both are reflected in the corresponding results, thus, they should be kept in mind when interpreting the results. Concerning the input data, quality and resolution needs to be taken into account. In ES research, there is a lack of specific data and therefore proxy indicators are often employed (Erhard et al. 2017). If so, also this needs to be considered when describing and interpreting the results. Generally, it can be stated that there is a lack of spatially explicit data on ecosystem condition and therefore there is an insufficient base for appropriate ecosystem condition mapping and assessment (Erhard et al. 2017). This aspect highlights the necessity to use proxy indicators for certain aspects of ecosystem condition. The findings of this thesis highlight the potential of data derived from remote sensing as a foundations for the spatial assessment of ecosystem condition.

As indicated in chapter 2.2.1, the thesis excluded the quantification and mapping of cultural ES. This exclusion is due to the fact that the dependence between environmental conditions and cultural ES differs compared to the other two ES classes. Cultural ES are strongly influenced by prevailing social values, norms and personal experiences amongst others (Kopperoinen et al., 2017). Thus, perceptions, attitudes and beliefs are subjective and differ between individuals (Pyhälä et al. 2016). Strong discrepancies can also be found between different areas and cultures. Thus, the assessment of cultural ES is highly dependent on the socio-cultural context and cannot be readily transferred to other case study areas (Kopperoinen et al., 2017). This partial detachment from environmental conditions led to the exclusion of cultural ES from this thesis, which aimed to assess the influence of environmental conditions on the spatial distribution of ES. Therefore, all statements and conclusions pertaining to ES only referring to provisioning and regulating ES.

7.3.2 General challenges and uncertainties of the ES concept

The complexity of ecosystems infers great challenges to the domain of ecosystem research. This thesis focused on human-environmental interactions, employing the ES concept. The concept is of multi-, inter- and transdisciplinary nature (Burkhard 2017a; Maes 2017). It encompasses the complexity of ecology but also includes the socio-economic research domain. The evaluation of ES on the landscape scale involve various uncertainties (Hou et al. 2013). These uncertainties are of different nature, for instance originating from the input data, study design, technical problems, general methodological

uncertainties and the complexity of natural system sand are constraints in ES research (Hou et al. 2013; Schulp et al. 2014) and apply to this thesis. Figure 5 presents an overview of typical uncertainties, which accompany ES assessments.

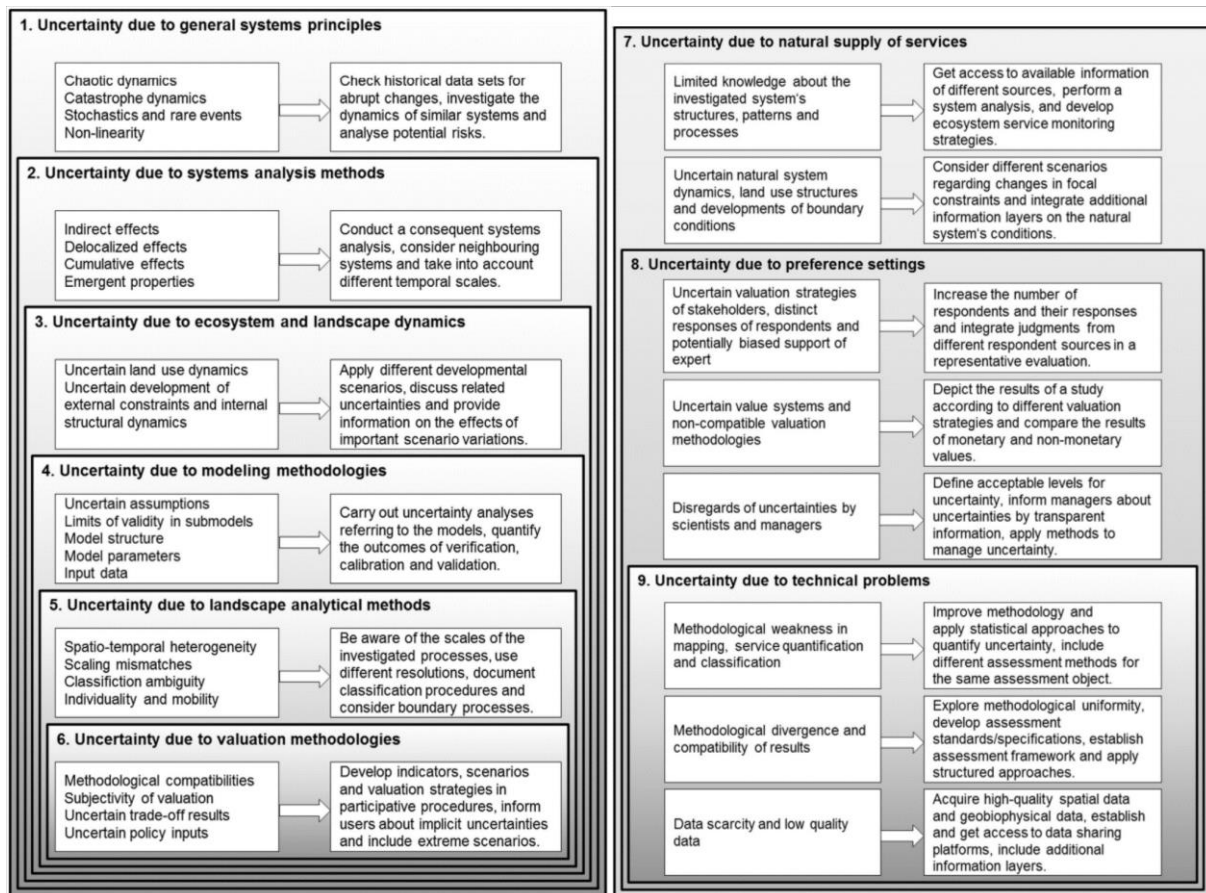


Figure 5: Overview of typical system based and ecosystem service assessment related uncertainties and potential actions for uncertainty reduction (Hou et al. 2013).

Besides, the sometimes unclear terminology within the ES concept may be a pitfall. A consistent employment of the correct terminology is essential in order to guarantee the relevance of the contribution to contemporary ES research. Thereby for instance, one needs to consider the differences between ES potential, flow and demand (Burkhard et al. 2012b; Burkhard et al. 2014; Schröter et al. 2014a; Dunford et al. 2017b; Bicking et al. 2018; Dang et al. 2018). Careful consideration is essential for the interpretation of the findings from ES assessments in order to ensure the comprehension of the results (Dunford et al. 2017b). For the evaluation of the results, the input data and applied methodologies need to be considered. This is of primary importance when proxy indicators are used for the assessment. In the scientific ES community, a highly debated issue occurred with reference to the "value" of ES (Dunford et al. 2017b). The debates included discussions on diverse output units, e.g. biophysical, monetary or sentimental valuation, but also general issues such as the comparability of different ES. Generally, values are not static but context-dependent (Dunford et al. 2017b). Changes in the environmental, socio-economic or political framework might influence the valuation. As a result,

challenges and uncertainties arise for the assessment of ES. The numerous specific issues, which come up with reference to cultural ES, are not considered in this thesis.

7.3.3 The issue of scale

The issue of scale is a consistently occurring challenge in the ES assessment and mapping domain (De Groot et al. 2010a; Power 2010; Bastian et al. 2012; Burkhard et al. 2012b; Kandziora et al. 2013c; Stoll et al. 2015). The issue is multidimensional and occurs in relation to different aspects (Bastian et al. 2012). Firstly, scale is highly relevant for the general development of an appropriate ES mapping and assessment approach, because it must match the spatial and temporal extent as well as the overall aim of the study. On different spatial and temporal scales, different mapping and assessment methods must be applied, e.g. the requirements for producing an ES map, which serves as overview on a national scale are different from the requirements of a detailed study investigating ES on a local scale. Consequently, also the conditions for the input datasets differ. In the applied part of this thesis, the scaling issue was considered with reference to its spatial dimension. In chapter 3, the nutrient regulation ES demand was assessed on the spatial scale of Schleswig-Holstein (regional scale) and the Bornhöved Lakes District (local scale). In the first step, the nutrient regulation ES demand was calculated and allocated to the individual municipalities. Subsequently, the nutrient regulation ES demand was allocated to the specific land use/land cover classes in the area of the Bornhöved Lakes District, thereby increasing the spatial explicitness of the assessment. Figure 6 presents findings from chapter 3, which indicate the dependency between the spatial scale and resolution of the assessment and the relative validity of the corresponding results. The evaluation was based upon literature research and a statistical analysis of the results in the two study areas on the different spatial scales. The relative validity of the outcomes was defined as the degree of conformity of the respective results with the expectations obtained from the literature review.

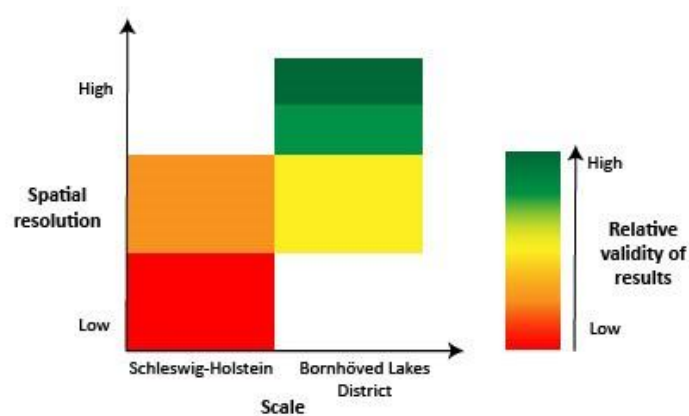


Figure 6: Relative dependency between validity of results, scale and spatial resolution.

The issue of scale was also considered in chapters 4 and 5. In chapter 4, the approach developed in chapter 3 for assessing the nutrient regulation ES demand was applied. Again, the demand was assessed on two different spatial scales. On the scale of the municipalities in the county of Hötter (regional scale) and on the scale of individual fields (local scale) which are operated by a family-owned farm. The approach, developed in chapter 3, was refined in regard to data availability. The results from the assessment on the local scale are of higher resolution and allow for further spatial explicit environmental analysis. In particular, with respect to advising land management and agricultural practices, the results from the assessment on the local scale have a higher quality.

In chapter 5, the BBN was set up for Schleswig-Holstein (regional scale) and the Bornhöved Lakes District (local scale). The input datasets were sampled individually for the two study areas. In total 300,000 and 1,500 data points were extracted for Schleswig-Holstein and the Bornhöved Lakes District, respectively. The elapse time for training the individual BBNs correlated to the amount of data points. In addition to that, the resolution of the input dataset for the nutrient regulation ES demand, which was adopted from the findings outlined in chapter 3, differed for the two study areas, as described above. This influenced the probability distribution of the nutrient regulation ES budget for the two different spatial scales and supports the assumption that the analysis on a larger scale and with a lower resolution underestimates the spatial mismatch between the ES potential and demand. Thus, again the relative validity of the results increased with an increasing spatial resolution (Figure 6).

However, there is another dimension concerning the issue of scale which arises from the ES concept. This issue concerns the scope of the ES as such, more precisely the assumption that different ES act on different spatial and temporal scales (Roth et al. 1996; Rodríguez et al. 2006; Constanza 2008; Vandewalle et al. 2009; Bastian et al. 2012; Kandziora et al. 2013b). Besides, also the underlying functions of the ecosystem are thought to operate on distinct spatial and temporal scales (Müller 1992). For that matter, a little thinking exercise was conducted, interlinking the individual ES to entities concerning their scope. To generate a complete picture, both, the spatial and temporal scale, and cultural ES and EI indicators were included. Figure 7 presents a conceptual allocation of the individual ES and EI variables to their spatial and temporal scale. Only a selection of ES from the three categories and EI variables are depicted in order to increase the lucidity of the visualization. Aiming to compare the three different ES categories (provisioning, regulating and cultural) and the EI variables, the ES and EI variables were colored according to their respective category.

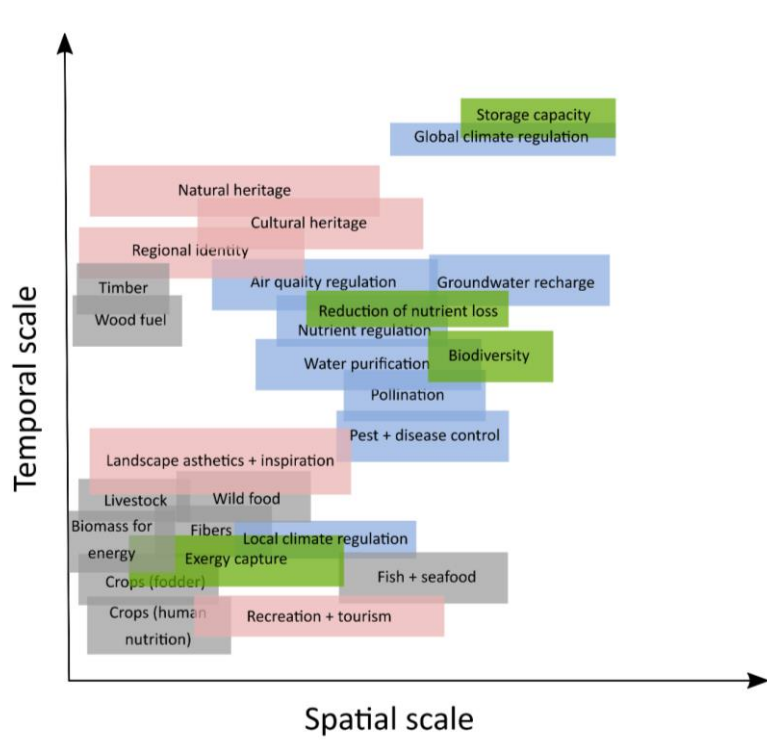


Figure 7: Spatial and temporal scopes of selected ES and EI variables. The colors indicate the category (green = EI; grey = provisioning ES; blue = regulating ES and red = cultural ES).

The patterns and trends illustrated in Figure 7 support the assumption that different ES and EI variables act on different spatial and temporal scales. In addition to that, the thinking exercise led to the assumption that the temporal and spatial scopes of the investigated ES and EI indicators correlate with their category (provisioning ES, regulating ES, cultural ES and EI). It seems that EI indicators generally act on the largest spatial and temporal scales, followed by the regulating ES. However, discrepancies in their scopes occur. For instance, an exception to the rather large temporal and spatial scope is the EI exergy capture, as it seems to act on rather small scales, resembling the general pattern of many provisioning ES. The strong relation between the EI variable exergy capture and several provisioning ES (Schneiders and Müller 2017) is in line with these findings. As indicated above, provisioning ES seem to act on smaller temporal and especially smaller spatial scales (Geijzendorffer and Roche 2013). Exceptions are provisioning ES, which are related to production in forests and marine systems, such as the ES timber production and the ES fish and seafood. Forest-related ES act on larger temporal scales compared to the average provisioning ES. Whereas, the ES fish and seafood acts on a higher than average spatial scale. The cultural ES seem a little detached from the general picture, as their scope is more diverse. They are associated with a rather low spatial but medium temporal scales. The medium temporal scale is due to the intergenerational propagation of knowledge, experiences and beliefs, which are influential for the evaluation of cultural ES. In general, the spatial and temporal scales, which can be attributed to the ES and EI, can be used as proxies to identify appropriate policy and decision-making levels. For instance, the ES global climate regulation acts on a large spatial and temporal scale,

thus the ES is of global importance and should be considered on the highest policy and decision-making level.

Of course, the exercise presented here is a rather simplistic approach. It was solely based on the author's personal and subjective opinions and is thus biased in many different ways. General aspects considering challenges and opportunities that arise from the issue of scale with reference to ES have been assessed before (a.o. De Groot et al. 2010a; Power 2010; Bastian et al. 2012; Burkhard et al. 2012b; Kandziora et al. 2013c; Stoll et al. 2015). The findings of the individual studies should be coherently assessed. Not only further knowledge from experts should be incorporated into the issue of scale assessment, but the assumptions should also be supported by statistical evaluations of measurements and observations in the real world. Another scale-related issue concerning ES comes from the fact that for some ES, the settings of the ecosystems in their surrounding are of high relevance, i.e. the ES emerge from a specific combination of ecosystems (Geijzendorffer and Roche 2013). In that sense, a single service would originate from the landscape rather than the individual ecosystem. Thus, landscape composition and pattern would need to be considered for the evaluation of the service (Müller et al. in prep.; Vandewalle et al. 2009; Brockerhoff et al. 2017). An example of this would be the ES landscape aesthetics & inspiration. The perceived inspiration may arise from the complete viewshed and may not be allocated to only one ecosystem, e.g. on observational platforms.

7.4 Conceptual consequences for land management and outlook

The results of the ES assessment in the federal state of Schleswig-Holstein and in Höxter highlight the relevance for including environmental characteristics into land management policies and agricultural planning. The DüV (2017) claims to consider these aspects. However, the findings of this research imply other estimations. Consistent with the evaluation of Taube (2018), the results of this thesis indicate that more measures should be implemented to increase the consideration of regional ecosystem properties and conditions in agricultural management. In addition to that, the DüV (2017) should prevent loopholes that allow violating general threshold values. Due to the general objective of the research as well as some methodological uncertainties (for more information see chapter 7.3.1) in the study, the research results should be used to examine the general picture rather than explicit results. Considering this, the results emphasize the necessity for strict regulations and detailed declarations with regard to the application of all kinds of fertilizers on farmland. A better harmonization of land management policies and agricultural practices with the regionally diverging distribution of environmental characteristics would result in more sustainable agriculture, saving resources while protecting the conditions and biodiversity of our ecosystems. Furthermore, the thesis generated knowledge on the interrelation between ecosystem properties and conditions, in the form of structures, processes and functions, and ES.

In this thesis, all assessments considering the ES nutrient regulation were executed exemplarily for the nutrient element nitrogen. Future investigations should incorporate an assessment of other nutrients such as phosphorous. The different biogeochemical properties of the nutrients underline the relevance to consider at least both nutrients in a joint assessment. The integration of further land management options and agricultural techniques, such as crop rotation and tillage/non-tillage practices, would increase the quality of the assessment and consequently allow for more elaborate conclusions on sustainability with regard to the ES nutrient regulation. Furthermore, the seasonal variability should be included in the analysis (Guerra et al. 2017). More detailed and precise information on vegetation periods, climatic conditions, etc. should be integrated in order to evaluate the nutrient situation in the investigated case study areas.

Another interesting approach concerning the nutrient regulation ES potential assessment would be the inclusion of the BBN into GIS software, as proposed by Landuyt (2014). This approach would provide spatially explicit outcomes. The BBN allows for an integration of scenarios, providing an opportunity to include stakeholders into the assessment (Dunford et al. 2017b). Besides, the BBN provides the opportunity to assess multiple ES. In doing so, also ES trade-offs and synergies could be assessed. The results from such an assessment could be generalized and applied in order to derive more universal findings and derive a catalog of measurements and thresholds. As the findings of the groundwater body monitoring project of the LLUR show, there are regional differences in the denitrification potential (LLUR 2014a). Thus, the spatial distribution of the denitrification potential should be included in an approximate assessment in order to ensure an integrative ecosystem research approach. Concerning the thinking experiment on the ES issue of scale, more research is required in order to be able to draw generally valid conclusions. Future research should incorporate further literature analysis, an expert evaluation that incorporates researchers from different scientific domains and empirical analyses focusing on the quantification of the theoretical framework.

This thesis can be considered as one of the first steps towards a holistic ES assessment of Schleswig-Holstein. Integrating the lessons learned and expanding the thematic scope, the attained results may be used as a foundation for the development of a comprehensive and holistic ES assessment on the scale of the federal state. Such a comprehensive assessment would integrate further research on ecosystem properties and conditions as well as an evaluation of a larger variety of ES from the different ES categories (provisioning, regulating and cultural). ES potential, flow and demand should be considered and quantified using different methodological approaches in order to enable an integrated ES assessment of the federal state. In that context, further contemporary drivers, derived from anthropogenic activities, should be incorporated.

7.5 Conclusions

The following section depicts the main findings of this thesis. The outcomes of chapters 3-6 are summarized and general conclusions concerning the main research objectives are drawn. The findings enable an elaborated response to the main research question: **How do ecosystem properties and conditions influence the spatial distribution of regulating and provisioning ES?**

The ES concept defines ecosystem properties and conditions as the fundamental base of an ecosystem to provide ES (Müller and Kroll 2011; Syrbe et al. 2017; Burkhard et al. 2018). Ecosystem condition thereby reflects the ecosystem state or health, which is often associated with the ecological integrity of a system. Integer ecosystems often also have a higher capacity to provide multiple ES. Thus, the potential of an ecosystem to provide ES is dependent on its ecological integrity. This causal relation can be supported by the findings of this thesis. The assessment of the spatial distribution of the EI and ES in the federal state of Schleswig-Holstein revealed strong correlations between EI variables and ES. In particular, the functional EI variables reduction of nutrient loss, biotic water flows and storage capacities positively correlated with the ES potential. In addition to the ecosystem condition, also the ecosystem properties are of relevance for the capacity of an ecosystem to provide ES. The spatial distribution of ecosystem properties, in terms of ecosystem structures and processes, affect the individual ES potentials. The quantification and mapping exercises of the regulating ES nutrient regulation within this thesis support this hypothesis. The spatial distribution of ecosystem properties, such as soil type and slope, influence the potential of the ES nutrient regulation.

Overall, it can be concluded that the influences of ecosystem condition and ecosystem properties on the potential of an ecosystem to provide regulating and provisioning ES can be proven. Thus, regional differences occur in the potential of ecosystems to provide ES. However, the thesis also emphasized the relative importance of human inputs. In particular, the results highlight the influence of human actions, pressures and flows aiming to maximize provisioning ES, such as crop production. By means of land management and agricultural practices such as the application of fertilizer, the supply of the specific individual ES is artificially increased. Thereby, the dependence on ecosystem properties and conditions can be bypassed. However, this unbalanced utilization of ES has negative side effects and the overall supply of ES bundles is reduced. Applying the example introduced above, intensive agricultural practices are used in order to increase the supply of the ES crop production. These practices usually include the application of fertilizers, herbicides and pesticides and probably exclude land management measures such as flower strips, diverse crop rotation systems and hedgerows. Thereby, other ES such as nutrient regulation, water purification and erosion regulation as well as biodiversity are negatively influenced (Power 2010; Bruns 2012). Of course, the intensity of the influences depends on the precise management, for example, the type, amount and timing of the

fertilizer, herbicide and pesticide applications. In the long run, the management options described above will influence the state of an ecosystem and thereby reduce the natural potential of an ecosystem to supply certain ES. The same general picture arises from the theoretical exercise concerning the issue of scale of ES. There seems to be a difference between the spatial and temporal extent of the individual ES impact levels. Roughly speaking, regulating ES act on comparably diverse spatial and medium temporal scales and seem to be closely linked to many EI variables. Provisioning ES seem to be acting on rather small spatial and temporal scales, whereas they seem to be closely related to the EI variable exergy capture.

It can be concluded that an integrative ES assessment should include a holistic examination of the respective ecosystems, as proposed by the ES concept (Müller and Kroll 2011; Müller and Burkhard 2012; Syrbe et al. 2017; Burkhard et al. 2018; Maes et al. 2018). Such a holistic research approach should include the evaluation of ecosystem properties and conditions and their connections to ES. Only then, can an integral understanding of ecosystems as parts of complex social-ecological systems be established. Site-specific agricultural practices, which incorporate regional information on relevant environmental characteristics would help to save resources while safeguarding the environmental conditions and biodiversity of our ecosystems.

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Appendices

List of publications

Bicking S, Burkhard B, Kruse M, Müller F (2018) Mapping of nutrient regulating ecosystem service supply and demand on different scales in Schleswig-Holstein, Germany. *One Ecosystem*. 2018;3:e22509

Bicking S, Burkhard B, Kruse M, Müller F (2019) Bayesian Belief Network-based assessment of nutrient regulating ecosystem services in Northern Germany. *PLOS ONE*.

Bicking S, Steinhoff-Knopp B, Burkhard B, Müller F (submitted) Quantification and mapping of the nutrient regulation ecosystem service demand on the regional and local scale. *Ecosystems and People*.

Burkhard *et al.* (2018) Mapping and assessing ecosystems services in the EU - Lessons from the ESMEERALDA approach of integration". *One Ecosystem* 3: e29153

Hou Y, Chen W, Bo L, Burkhard B, Bicking S, Müller F (in preparation) Ecosystem service potential, flow, demand and their spatial associations: A comparison of nutrient retention service between a human- and a nature-dominated watershed. Unpublished manuscript

Ma L, Bicking S, Müller F (2018) Mapping and comparing ecosystem service indicators of global climate regulation in Schleswig-Holstein, Northern Germany. *Science of The Total Environment*. 648

Müller *et al.* (in preparation) Assessing ecosystem service potentials to evaluate terrestrial, coastal and marine ecosystem types in Northern Germany – an expert-based matrix approach. Unpublished manuscript

Schumacher J, Inácio M, Bicking S, Schernewski G, Müller F (in preparation) Assessment of ecosystem services across the land and sea interface: approach and application in Baltic case studies.

Zeleny J, Bicking S, Dang BK, Müller F (submitted) Combining methods to estimate ecosystem integrity and ecosystem service potentials and flow for crop production in Schleswig-Holstein, Germany. *Landscape online*

List of conference contributions

Bicking S, Müller F (2018) A glimpse behind the scenes: Assessing ecosystem services based on statistical data and expert evaluation. Poster at SHE Conference 2018. Lisbon, Portugal

Bicking S, Müller F (2018) Ecosystem service assessments in a sequence of land- and seascapes in Northern Germany. Poster at EcoServ 2018. Poznań, Poland

Bicking S, Burkhard B, Kruse M, Müller F (2018) Ökosystemleistung (ÖSL) Nährstoffregulation in Schleswig-Holstein. Presentation at IALE-D 2018. Hannover

Zeleny J, Bicking S, Dang BK, Müller F (2018) Combining methods to estimate ecosystem service potentials for crop and fodder production in Schleswig-Holstein, Germany. Presentation at SHE Conference 2018. Lisbon, Portugal

Curriculum Vitae

Sabine Bicking

PERSONAL DETAILS

Tel. 0049/ 157 82587697
E-mail sbicking@ecology.uni-kiel.de
Birth day 28th July 1992
Nationality German
Family status unmarried



EDUCATIONAL BACKGROUND

01/2017 – 06/2019 **Kiel University, Faculty of Agricultural and Nutritional Sciences**
PhD Candidate: Agricultural Sciences - Ecology
Title: Quantification and mapping of regulating and provisioning ecosystem services in Schleswig-Holstein

10/2014 – 12/2016 **Kiel University**
Master of Science in ‚Environmental Management‘
Degree: M.Sc.

09/2011 – 08/2014 **Free University Amsterdam (Netherlands, Amsterdam)**
Bachelor of Science in ‚Aarde en Economie‘ (Earth Sciences and Economics)
Emphasis on: Earth surface, Spatial analysis
Degree: B.Sc.

08/2009 – 07/2011 **Georg-Büchner Gymnasium, Kaarst**
Emphasis on: Mathematics, English, Social sciences, Biology
Degree: Abitur

07/2008 – 07/2009 **Sunshine Beach State High School (Australia, Queensland)**
Emphasis on: Marine biology, Photography, Mathematics, English

07/2002 – 06/2008 **Georg-Büchner Gymnasium, Kaarst**

PROFESSIONAL EXPERIENCE

08/2018 – today **Kiel University, Researcher**
Quantification and mapping of ecosystem services in Schleswig-Holstein and the Baltic Sea

02/2017 – 07/2018 **Leibniz-Universität Hannover, Researcher**
Testing of biophysical quantification and mapping methods for ecosystem service assessments

04/2016 – 12/2016 **Kiel University in cooperation with the State Agency for Agriculture, the Environment and Rural Areas, Master thesis**
Title: Assessment of regulating ecosystem services in Schleswig-Holstein: From the development of scientific data to a vivid comprehensive presentation in the Agricultural and Environmental Atlas

11/2014 – 08/2016 **GEOMAR Helmholtz Centre for Ocean Research Kiel, Research assistant**

Assistance for the scientific coordination of the SFB 754
Climate-Biogeochemistry Interactions in the Tropical Ocean
04/2014 – 07/2014 **Free University Amsterdam in cooperation with Hoogheemraadschap
Hollands Noorderkwartier & Deltares (Netherlands), Bachelor thesis**
Title: The influence of coastal management on the distribution of sand,
mollusks and gravel along the North Sea coast of Texel and in the Slufter

ENGAGEMENT

10/2014 – 06/2018 **Volunteer at Greenpeace Kiel**
Public relations, project coordination and campaigning focusing on
awareness rising for environmental issues

FURTHER KNOWLEDGE

German	Native speaker
English	Fluent, spoken and written; Master in English
Dutch	Fluent, spoken and written; Bachelor in Dutch
EDP- Knowledge	MS Office, ArcGIS, QGIS, R, Photoshop
Interests	Kitesurfing, Surfing, Books and Travelling