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Combining Methods to Estimate Ecosystem Integrity and Ecosystem Service Potentials and Flows for Crop Production in Schleswig-Holstein, Germany

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Abstract

Human well-being is highly dependent on nature, especially with respect to 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 ecosystem services. The ecosystem service *potential* is assessed based upon a Bayesian belief network and the study area's soil fertility. The respective service *flow* is estimated from official regional statistics, and is represented by the total harvested biomass for food, fodder and energy. The spatial distribution of six different ecological integrity variables and the crop production *potentials* and *flows* are compared and interpreted with respect to the characteristics of the main landscape regions within the study area. The results indicate a trade-off between the actual crop production and the underlying ecological integrity and service *potentials*. This trade-off is strongest in case of croplands, while it gradually diminishes in grasslands and forests. Based on the results, conclusions about the relation between ecosystem services and ecological integrity are drawn. 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.

Research highlights

- Comprehensive ecosystem assessment on 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 arable land-, grassland and forests with respect to selected ecological integrity variables.

Keywords
ecological indicators, Bayesian Belief Network, remote sensing, regional statistics, correlation analysis

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 generally 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; Müller & Kroll 2011; Müller & Burkhard 2012; Kandziora et al. 2013; Hou et al. 2014; 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 EI as a fundament of ES provision, there are knowledge gaps with respect to the specific interactions among the conceptions (Erhard et al. 2017; Laurila-Pant et al. 2015; Liquete 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 efficiency (see Figure 1).

We assume that by looking at ES alone, one can get an incomplete perspective only for the sustainable management concerning ecosystem efficiency and thus desirability. Therefore, the aim of this study is not only to provide a comprehensive spatial 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 selected to represent EI and ES 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 a 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) are useful to visualize natural assets and 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 additional 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 mismatches and multiple uncertainties concerning data aggregation, representation, integration and interpretation. The combination and aggregation of multiple data sources, converted to a common format and resolution, are highly relevant approaches to resolve the problem of data scarcity (Hou et al. 2013; 2014). Such transformations are, naturally, bound to a whole array of uncertainties. However, 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 EI and ES.

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 EI 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 EI

(Schneider & Kay 1994; Müller 2005; Parrot 2010). Integrity consequently stands in a contradiction to human influences, also referred to as hemeroby (Hill et al. 2002), which usually introduces stress to ecosystems. In this fashion, Barkman et al. (2001) have defined EI 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 (for a definition of concepts used withing this text and related concepts, see Table 1).

Frameworks on landscape-scale integrity assessments have occasionally emerged, suggesting an index of regional integrity (Slocombe 1992; Andreasen et al. 2001; Reza & Abdullah 2011). EI 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 ES (Revenga 2005; Kandziora et al. 2013; Menzel et al. 2013; European Commission 2016; Roche & Campagne 2018). Different studies define ecosystem condition as the sum of biophysical properties that support the effective capacity of an ecosystem to provide services (MEA 2005; Schröter et al. 2006; European Commision 2016; Erhard et al. 2016).

A prominent approach to assess a landscape’s ecosystem integrity 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 EI indicators are strongly connected 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 EI 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), based e.g. on the concept of Schneider & Kay (1994). Also, vegetation complexity can be quantified using remote sensing either as a 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).

Table 1: A summary of the different concepts used within the text and other terms related to ecological integrity.

Concept	**Description**	**Literature source**
Ecological integrity	Distance from a natural reference – relatively unaffected by human influence	Karr & Dudley 1981; Karr 1993; Westra et al. 2000
Ecosystem integrity	Ecosystem capacity to dissipate energy gradients and maintain complex organization	Kay & Schneider 1992; Müller 2005; Jørgensen et al. 2007
Ecosystem health	The overall well-being, productivity, resilience and resistance of an anthropogenic ecosystem	Rapport et al. 1998; Costanza 2012
Ecosystem condition	The capacity of an ecosystem to provide services, relative to its potential capacity arising from the ecosystem´s state	European Commission 2014, p. 78
Resilience	The capacity to retain or restore a state of organization after suffering from a disturbance	Holling 1973; Pimm 1984
Resistance	Ability to mitigate the negative effects of stress or disturbance	Millar et al. 2007; Ramsfield 2016
Biophysical structures	The architecture of an ecosystem as a result of the interactions within the system	European Commission 2014, p. 78

1.2 Ecosystem services

The interdisciplinary ES concept is of highly integrative nature, considering ecosystems and human-environmental interactions (MAE 2005; Daily & Madson 2008; De Groot et al. 2010; Haines-Young & Potschin-Young 2010a; Burkhard 2017; De Groot et al. 2017). ES 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 (e.g. MEA 2005; 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 regulation of natural processes are considered as regulating ES (Kandziora et al. 2013; Haines-Young & Potschin 2017). A typical example of regulating ES is pollination by insects, retention of nutrients in soils, ecosystem carbon fixation or water purification in streams. Cultural ES refer to the intangible benefits that people obtain such as non-material inspirational and educational experiences, aesthetics or recreation (De Groot et al. 2010; Kandziora et al. 2013; Haines-Young & Potschin 2017).

On the EU level, the relevance of the ES concept is embedded e.g. in the EU Biodiversity Strategy (Target 2, Action 5). Here, EU Member States are asked to map and assess their ecosystems' states and respective services with the assistance of the European Commission (Maes et al. 2012; Teller 2017). The mapping of ES supports a variety of purposes, amongst which are the generation of knowledge in terms of ecosystem assessments, ecosystem accounting, decision support and awareness-raising (Jacobs et al. 2017). Current applications of ES mapping focus on quantitative ES valuations and accountings (Syrbe et al. 2017). The 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 focal aspects of sustainability of the current land management in the study area with regard to ES utilization. Therefore, a lot of emphasis 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 of provisioning 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 generation of energy.

Besides, ES can be investigated based on *potentials*, *flows* and *demands*. The *potentials* of an ES describe the hypothetical maximum yield of the selected ES (Burkhard et al. 2014). On the other hand, the *flow* refers to the actually utilized ES (Syrbe et al. 2017). An aspect that is 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 of 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 temporally and spatially dependent and directs the ES *flow*. This means, in case there is no demand for a certain service, there will be no ES *flow*. Also, situations of unmet demand can occur, i.e. if the demand for a certain ES is higher than the ES *flow* (Syrbe et al. 2017; Dang et al. 2018).

Figure 1, which is based upon the cascade model after Haines-Young and Potschin (2010b), demonstrates the relations between the items outlined above. Ecosystems and biodiversity are characterized by biophysical structures, processes and functions. The structures and processes can be bundled into certain functions and functional groups. Those functions are the fundamentals of ES *potentials*. They can be turned into ES *flows* if they are 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 ES. 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 the case of unsustainable resource utilization, the chances are high that future *potentials* will be reduced.

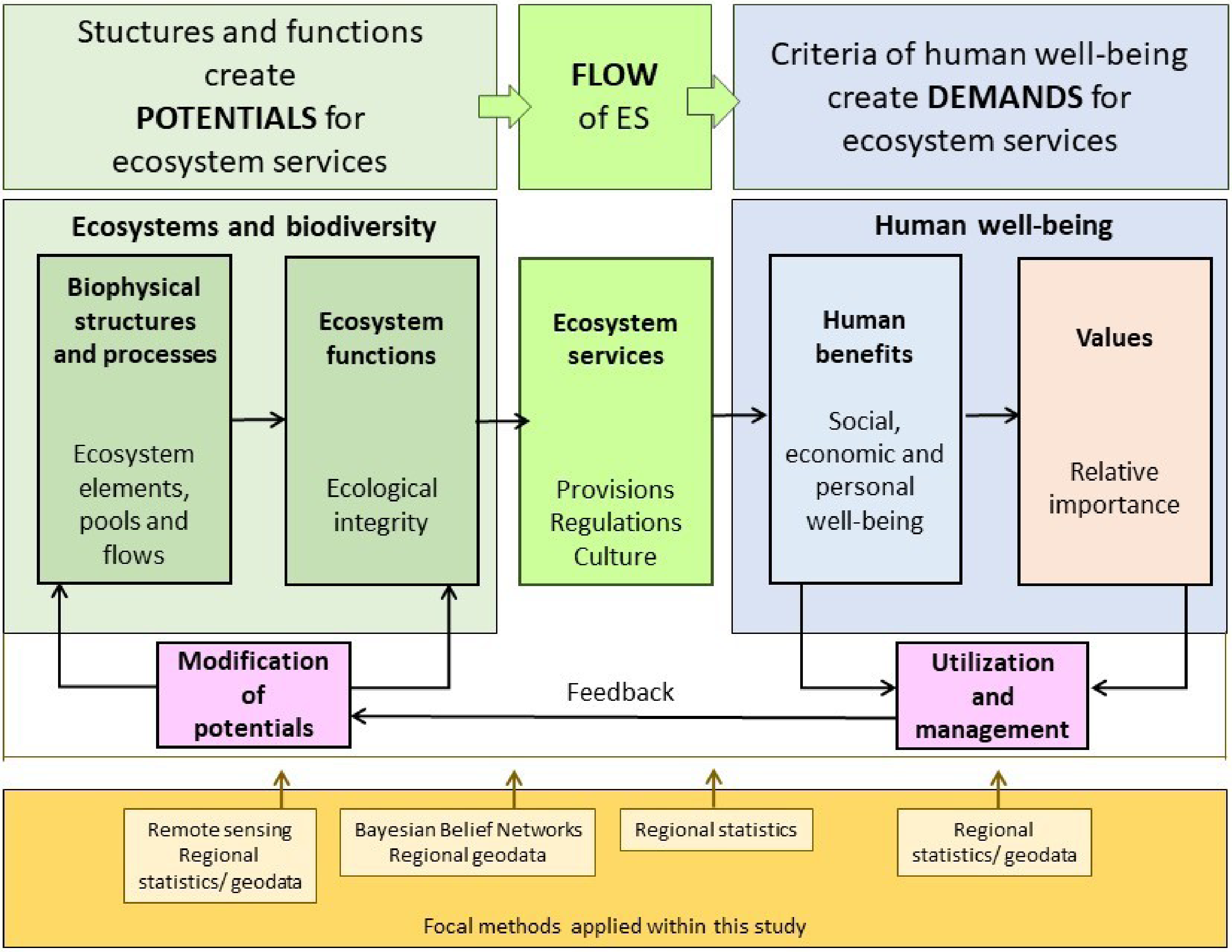

Figure 1: A schematic representation of the different components and feedback loops, which are interacting in the landscape system (based on the cascade model of Haines-Young and Potschin 2010b). Focal methods used for representing each component are listed in the lower part of the figure.

1.3 Aim of the study

We assume that ES 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 EI and ES in a comparable format, in order to provide comprehensive information for current management. Input data sources have to be employed and properly modified realizing the relevant uncertainties (Hou et al. 2013), which can emerge from representing and aggregating landscape features. We aim at providing an extended interpretation of how EI relates to the production of ES in the context of variable human land management and agricultural practices.

Based on literature research and with respect to the omnipresent issue of data availability, six variables representing six holistic indicators of EI have been chosen. These are exergy capture, entropy production, abiotic heterogeneity, biotic water flows, storage capacity and reduction of nutrient loss. The selected indicators used to represent the EI 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).

The objective of the study is to deliver an integrative ecosystem assessment in landscape context. The study focuses on the evaluation of EI as a base for the capacity of the study area to provide the ES crop production. We have selected the German federal state Schleswig-Holstein as a focal case study area,

Table 2: Description of the six selected indicators of EI used within this study.

Indicator	**Description**
Exergy capture	The amount of solar energy absorbed by vegetation during photosynthesis.
Biotic water flows	The volume of water transported within an ecosystem, e.g. during transpiration. Higher flows indicate active hydrological conditions as well as efficient ecosystem metabolism.
Entropy production	The amount of photosynthetic energy, which is consumed and released as heat (entropy) during biotic respiration. High respiration is a sign of high maintenance costs and can indicate either ecosystem maturity or disturbance.
Abiotic heterogeneity	The degree of unevenness of an ecosystem, which is an indication of self-organisation. Anthropogenic land management tends to promote homogenization while during natural succession, a diversity of patterns and niches emerges in cohesion with biodiversity.
Storage capacity	The amount of exergy stored within organic compounds in soils and biomass. In soils, storage capacity affects the general fertility, water and nutrient retention capacity as well as biodiversity.
Reduction of nutrient loss	The capacity of an ecosystem to retain and recycle nutrients. Disrupted ecosystems can be indicated by higher nutrient leakage at the outflow.

because of regional knowledge and as it presents a well delineated gradient of both geomorphological as well as management conditions. Therefore, the study area is suitable to test the EI/ES relation under different conditions. Multiple methodological approaches are applied in order to assess and map the different EI variables and the crop production ES *potential* and *flow*. Subsequently, the spatial distributions of the different variables are compared and interpreted with respect to the characteristics of the main landscape types within the study area.

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

I. Does the spatial distribution of the assessed EI variables reveal a distinct regional pattern?

II. Does the spatial distribution of the ES crop production reveal a distinct regional pattern?

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

IV. How is the EI/ES relation manifested in croplands, grasslands and forests of the three main landscape regions of Schleswig-Holstein?

V. Does the temporal distribution of the assessed EI variables reveal a distinct regional pattern with respect to croplands, grasslands and forests?

Section 2.1 introduces the study area. In section 2.2, the methodological approaches and input data sets are enumerated. In the third section, the results of the assessment of the relationships between EI and ES are presented from three perspectives: the general performance of SH in terms of EI and ES (Section 3.1), a special focus on maize cultivation (Section 3.2) and a comparison between three different land-use types (croplands, grasslands and forests, Section 3.3). Based on these findings, some general conclusions are drawn in Section 4 concerning landscape-related land management aiming to reduce the negative impacts caused by conventional agricultural practices. The research questions outlined above are revised and answered in section 5.

2 Materials and methods

2.1 Study area

The study area, Schleswig-Holstein (SH), 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 (German Federal Statistical Office 2018). Arable land and pastures are predominant land use types (Figure 2b).

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

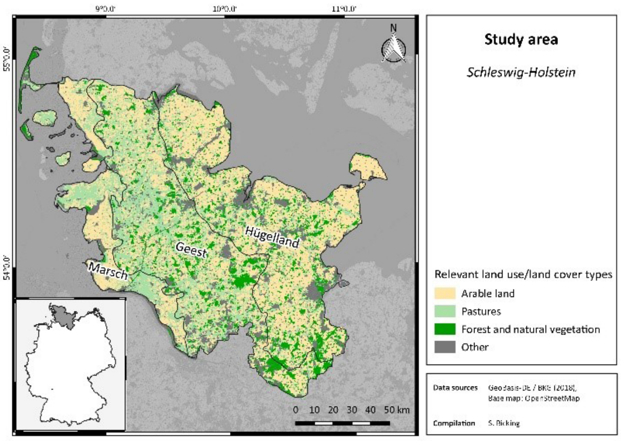

Figure 2: Overview of the study area incl. distribution of dominant land use/ land cover types based upon CORINE 2012 (BKG 2019). The lines indicate the borders of the main landscape regions.

be attributed to the geological development of the area, during the Pleistocene and Holocene periods. 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 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 younger 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 this 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 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).

2.2 Methodological approaches used in the study

Three methods based on remote sensing, regional statistics and geodata and Bayesian Belief Networks have been employed in this section to deliver spatially comparable information on EI, ecosystem service *flows*, *potentials* and management. Firstly, we have used a data set on soil fertility and a probabilistic inference model integrated into a Bayesian Belief Network to estimate the likelihood of high crop production based on information on soil and climatic conditions. The modelled *potential* data sets serve as reference information on the hypothetical crop production, which would be obtained if the system would be mainly dependent on abiotic factors (section 2.2.1). Secondly, the contribution of biotic factors to ecosystem processes in SH were explored as EI 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 (section 2.2.2). Thirdly, actual *flows* of the focal provisioning services were calculated based on the official regional statistics (section 2.2.3).

Since the analysis has mostly been executed focusing on specific land-use management types, it is necessary to delineate the exact meaning of the terms which are used as reference to land-use types defined within the CORINE Land Cover (CORINE LC) nomenclature. We use the terms “arable lands” or “croplands” to represent the CORINE LC class 211: Non-irrigated arable lands (excluding other types of agriculture like agroforestry, orchards, etc.) and the terms “grasslands” or “pastures,” by which we refer to the class 231: Pastures. The CORINE LC class “forests” is referring to a merged group of three classes: 311: Broad-leaved forest, 312: Coniferous forest and 313: Mixed forest.

2.2.1 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). 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 and the crop production ES *potential* (shown in Appendix 1). The network is developed to predict the suitability of agricultural regions based on the Bayesian probability approach under changes in abiotic factors. The crop types integrated into this network include barley, oat, potatoes, rye, maslin, silage maize, sugar, triticale, winter canola and winter wheat. Other crops have been excluded due to data unavailability. The structure of this network has been developed based on the conceptual framework of ES (Burkhard et.al. 2014) and is included in Appendix A1. Accordingly, the three types of ecosystem functions identified in croplands to assess the *potential* of crop production include photosynthesis potential, nutrient availability (in soil) and water availability (soil moisture). The natural sources of these ecosystem functions are estimated from abiotic factors (such as soil radiation, temperature, soil texture, erosion etc.). A description of the respective environmental data sets can be found in Appendix 2.

In the developed BBN, three main components of Bayes' rule were integrated including the prior probability of input and output nodes, and conditional probability tables (CPTs). Lastly, the network was used to run approximately 1100 cases corresponding to the municipalities in Schleswig-Holstein before mapping the crop production *potential*.

2.2.2 Remote sensing procedures

Remote sensing measurements were taken from Landsat 8 TIRS (USGS 2019), Sentinel-2 MSI (ESA 2019) and MODIS (NASA 2019). The instruments, used within this study to derive representative variables and their respective ecological integrity indicators, are summarised in Table 3.

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 reflect 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. Photosynthetic productivity and respiration were obtained from MODIS in the lowest spatial (1 km) and highest temporal (8-day composites) resolution.

2.2.2.1 Indicating biotic water flows

Evapotranspiration, measured as the difference between reference vegetation surface temperature and bare soil temperature, represents the amount of water that is moved in plant stems (thus linked with the indicator "biotic water flows") 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 EI 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). Water evaporation consumes heat energy reducing the surface temperature around the leaves, thus the more water is lost by transpiration

Table 3: Indicators, respective units, resolutions and instruments derived from remote sensing data to deliver representations of selected EI variables.

No.	EI variable	Indicator	Unit	Resolution	Satellite
1	Biotic water flows	Temperature difference (TD)	[°C]	30 m (100 m)	Landsat 8
2	Exergy capture	Normalized Diff. Vegetation Index (NDVI)	[-]	10 m	Sentinel-2
3	Abiotic heterogeneity	Edge density (ED)	[-]	10 m	Sentinel-2
4	Entropy export	Metabolic respiration	$\frac{g\ C}{m2\ y^{-1}}$	1 km	MODIS (MOD17)
5	Net primary production	Net primary production	$\frac{g\ C}{m2\ y^{-1}}$	1 km	MODIS (MOD17)

(higher biotic water flow) from vegetation the cooler it appears using a thermal sensor. The respective band 10, containing thermal information, was recalculated from spectral radiance into At-Satellite Brightness Temperature (see Equation 2) and used for further transformations. The respective equation for the At-satellite brightness temperature calculation is Eq. (2):

$$BT[°C]= \frac{K_2}{\ln \frac{K_1}{(L\lambda+1)}} -273.15, \quad (2)$$

where: BT is the At-satellite brightness temperature (°C), Lλ ($\frac{Watts}{m^2*srad*\mu m}$) is the Top of Atmosphere (TOA) spectral radiance, K1 and K2 are the band-specific thermal conversion constants from the meta-data (Xiao et al. 2007; Jeevalakshmi et al. 2017).

The BT layer contains information on the absolute land surface temperature in a given measurement. Our aim was to separate the temperature reduction capacity of vegetation to represent the integrity indicator biotic water flows, for which a simple mathematical transformation was applied. The transformation converts the absolute surface temperature in °C into a temperature range, where TD = 0 equals the minimum (95% percentile to downweigh outliers) land surface temperature obtained and TD = max represents the highest measured temperature in a single measurement. The procedure is expressed in Eq. (3):

$$TD[°C]= (-BT) + (95\% \text{ percentile } BT), \quad (3)$$

where TD is the parameter temperature difference, representing the temperature gradient created by vegetation in comparison to bare soil, and BT is the measured land surface temperature.

2.2.2.2 Indicating exergy capture

Exergy capture is the capacity of vegetation to capture solar radiation, and it was previously suggested to be readily measured as NDVI (Kandziora et al. 2013). NDVI is a (-1, 1) normalized ratio between the reflected light in the red (RED) and near-infrared (NIR) part of the light spectrum (Eq. 1; Xu et al. 2012). 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 4 describes the calculation of NDVI from Sentinel-2, Eq. (4):

$$NDVI[\ -\ ]= \frac{NIR - RED}{NIR + RED} \text{ or } \frac{Band\ 8 - Band\ 4}{Band\ 8 + Band\ 4}, \quad (4)$$

where NDVI is the Normalized Difference Vegetation Index, NIR is the reflectance in Near-Infrared and RED means reflectance in red part of the visible spectrum.

2.2.2.3 Indicating abiotic heterogeneity

In this study, the ecosystem abiotic heterogeneity index is quantified based upon the unevenness of the distribution of values within a raster data layer. The calculation was designed to represent vegetation surface complexity of natural areas like forests, in contrast to typically homogeneous agricultural areas. The heterogeneity variable quantifies the complexity of vegetation, which is closely related to the capacity to self-organize and provide habitat features for biodiversity. Therefore it is closely related to EI (Parrot 2010).

The abiotic heterogeneity was quantified as edge density and has been produced in the Sentinel Application Platform (SNAP by ESA) using the Diagonal Compass Edge Detector (DCED) filter algorithm. The general approach of calculating the image heterogeneity using edge detection is reviewed in Bakker et al. (2002), who suggest the usage of a multidirectional (diagonal) edge detector to account for the variability of image texture characteristics of landscapes. The filter, which is integrated within the SNAP software, applies a predefined operation on a selected raster, which in this case quantifies the presence of edges (steep gradients). In the case of homogeneous surfaces, the respective cells received the value 0 while heterogeneous surfaces received positive or negative values, based on the orientation of the gradient. Images from the Sentinel-2 bands 4 and 8 were used in the process (reflectance in red part of the visible spectrum and near-infrared, respectively). Non-vegetated[1] surface reflectance measurements were similar in bands 4 and 8, while

1 Meaning mostly urban and harvested lands, since water was not accounted for. Also accounts for natural surfaces such as beaches, bare rocks and mountains.

vegetated surface reflectance differed considerably. As healthy vegetation absorbs radiation in the red part of the spectrum (band 4), while it reflects most of the radiation in NIR (band 8) it is possible to inhibit non-vegetated surfaces by using an appropriate equation (the principle of NDVI calculation). We have decided to transform the images by DCED filtering and to perform the calculation with edge densities to further reduce the effect of the differences concerning the reflectances in both bands (we were working with image complexity rather than reflectance, see Eq. 5). This procedure pronounces the edge density of vegetation only, therefore the resulting parameter can be considered as vegetation surface edge density. 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 product images were further processed by converting all values to absolute (positive) values. They were square-root transformed to obtain a near-normal data distribution (normality not tested). The calculation is represented in Eq. (5):

$$HG[\,-\,] = \left(\sqrt{|DCED\,(NIR) - DCED(RED)|}\right), \qquad (5)$$

where HG is the variable vegetation surface heterogeneity, DCED is the diagonal compass edge detector filter, NIR is the reflectance in the near-infrared and RED is the reflectance in the red part of the visible spectrum.

2.2.2.4 Indicating primary production and entropy export

Gross and net primary production (GPP, NPP respectively) are important parameters estimating the amount of solar energy, which is captured during photosynthesis 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, following Eq. (6):

$$Respiration\left[\frac{g\ C}{m2\ y^{-1}}\right] = (NPP\text{-}GPP), \qquad (6)$$

where NPP is net primary production and GPP is gross primary production.

2.2.2.5 Aggregation and image processing

Individual images of SH, obtained from remote sensing data sets, available on the different respective geoportals, were selected for the year 2016. Only relevant land-use types were considered during the analysis. These coincide with the dominant land-use types in the study area: croplands, grasslands and forests. The spatial distribution and extent of the land-use types were derived from the European 2012 CORINE land cover data set. All respective raster layers were clipped and the sea and water surfaces were removed prior to the analysis since the approach is based on terrestrial vegetation only.

The resulting data sets were sampled on the municipality level (1176 units) to meet the criteria for comparability with other data sets, mainly for data from the regional statistics. An exception are the results of the analysis presented in section 3.3, which were sampled using the three CORINE 2012 classes, croplands (non-irrigated arable land), grasslands (pastures) and forests. The sampling was done using a zonal statistics tool for QGIS (QGIS Zonal statistics plugin 2019), which enables the calculation of several statistical parameters, in our case the median value from the extent of the individual municipality polygon for each raster. Thus, median values were obtained for each variable and each measurement, aggregated on the municipality level and were further processed as Excel spreadsheets.

The 8-day calculations of net primary production (NPP) and respiration from MOD17 were first summed into monthly composites and further summed up for the whole year. The remaining 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 volume of space under a given time curve (summation of squares between each measurement point in the respective time period); the calculation is expressed in Eq. (7):

$$AUC_t = \left(\frac{y_{t+1}+y_t}{2}\right)*(x_{t+1} - x_t), \qquad (7)$$

where AUCt is the area under curve in time t, calculated as the average of two subsequent measured values y in time t and t + 1, multiplied by the number of days between the two respective measurements x. Equation (8) further describes the total AUC calculation for the whole vegetation period, which is calculated as summation of the individual AUCs.

$$AUC = \sum_{t=0}^{n} AUC_t + AUC_{t+1} + ... + AUC_{t+n}, \quad (8)$$

2.2.3 Official regional data utilization

Data provided by official institutions such as the Statistical Agency North (2010) and the LLUR (2011) were also consulted for this study. Table 4 gives an overview of 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 (Statistical Agency North 2010) served as the base of information on the spatial extent (in ha) of arable land and pastures as well as the cultivated crop types at the scale of municipalities. Average values on the harvests (in dt/(ha*a)) of the different crop types were available at the scale of counties or the federal state of Schleswig-Holstein (Statistical Agency North 2010). This information has been processed in order to deliver the indicator for the crop production ES *flow*. In addition, the harvest of silage maize has been quantified and mapped. The plant residuals (in dt/(ha*a)) left to decompose on the field after harvest have been estimated as an indicator for the EI variable storage capacity. We assume that when more plant residues are left to be decomposed, there will be more organic matter and energy available for soil life to incorporate and create 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 from the agricultural census 2010 (Statistical Agency North 2010), average values on the products, secondary products and root biomass (Louis Bolk Instituut 2009) and average residual management values for the different assessed crop types including grasslands.

As some data entries at the scale of the municipalities are missing in the regional statistics due to the data privacy law, the information at 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 the 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 and soil fertility in the federal state. The LLUR (2011) calculated the nitrate leaching potential and soil fertility mainly based upon soil properties and climatic conditions. These data sets were defined as the indicators for the EI reduction of nutrient loss and ES crop production *potentials*,

Table 4: Indicators, respective units and data sources of selected EI and ES variables.

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

respectively. As outlined in the introduction, the EI reduction of nutrient loss describes the ecosystems' capacities to recycle and especially retain nutrients.

2.2.4 Data aggregation and statistical analysis

All data sources were selected based on the criteria of good comparability. Therefore, the data were preferably chosen from the same period (2016 for remote sensing and 2010 in case of official statistics) and comparable resolutions. The common scale of aggregation for all data was the level of municipalities (1106 municipalities). Some of them have been excluded from the analysis, as a consequence of data consistency and data availability. Besides, the urban areas of Flensburg, Kiel, Lübeck and Neumünster have been neglected from the assessment due to their disparities compared to the rural areas.

The variables were statistically assessed, focussing on correlation analysis, using the software R. The target was identifying correlations that indicate co-dependencies between the investigated variables. The correlation method used was Spearman´s rank correlation. The correlation analysis covered all relevant variables and data sets in a particular case. These include the already described variables representing EI, ES *potentials* and *flows*, while four types of analysis were performed: one for croplands, grasslands and forests as a whole, and three more for the individual land-use classes.

The results in Section 3.3 have been produced with the CORINE 2012 land cover data, which was used to sample values for three land-use types: croplands (non-irrigated arable lands), grasslands (pastures) and forests. The sampled median values for each polygon served to construct graphical representations of temporal developments of the three EI indicators exergy capture, biotic water flows and entropy export (Fig. 10). The measured points in time have been interpolated using third-order polynomial functions in Excel to enable the identification of seasonal trends (Eq. 9):

$$y = ax^3 + bx^2 + cx + d \qquad (9)$$

3 Results

The results section is divided into four sub-sections, where the first one (section 3.1) gives an overall perspective of SH via the selected variables in all three relevant land-use types. The remaining specific storylines, which are related to the research sub-questions introduced above: In section 3.2, the focus lies on the relation between EI and ES *flows* and *potentials* in arable lands including the specific role of silage maize cultivation in SH. Another storyline (section 3.3) compares the seasonal development of three selected EI variables in croplands and grasslands within the three landscape regions of SH.

3.1 General EI and ES assessment

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

3.1.1 Ecological integrity variables

In Figures 3, 4 and 5 the spatial distributions of the assessed EI variable are presented. Their spatial patterns approximately coincide with the borders 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 EI compared to the other two regions (Figure 3 and Figure 4). One exception is exergy capture, which received highest values in the area of the Geest. Besides, in terms of NPP, the three regions deliver rather similar results. Thus, despite a relatively high level of photosynthetic potential in the area of the Geest, the resulting NPP is equivalent to areas with average 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 greater part of the potential photosynthesis, which takes place in the Geest, is being inefficiently conserved within the system and is released as entropy.

Further assessed variables, such as biotic water flows, reduction of nutrient loss and storage capacity, show similar trends according to the spatial distribution of the main landscape region. Whereby, the area of the Geest performs the worst (Figure 4).

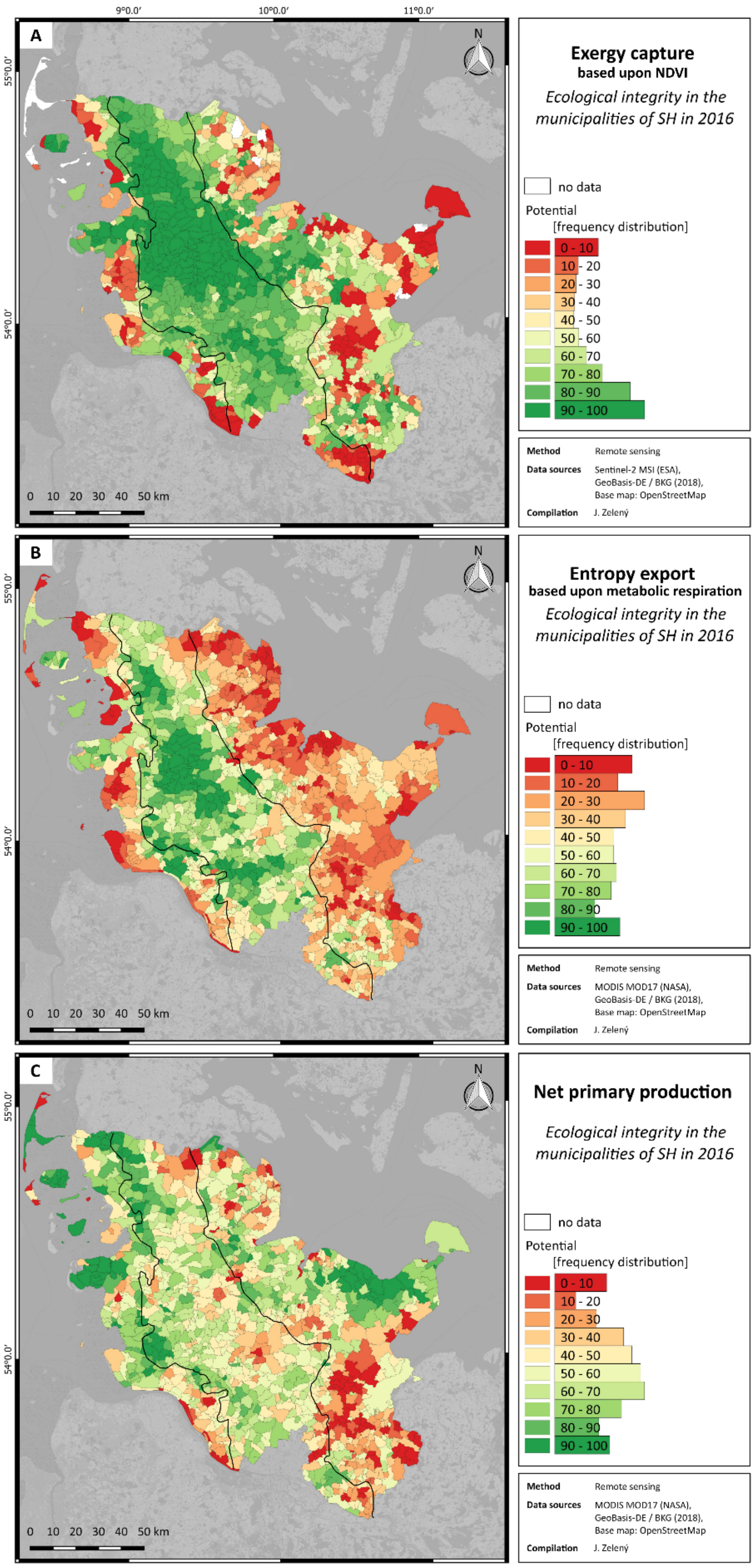

Figure 3: EI variables in the municipalities of SH in 2016: A) exergy capture (based upon calculated NDVI), B) entropy export (based upon calculated respiration) and C) net primary production. The lines indicate the borders of the main landscape regions.

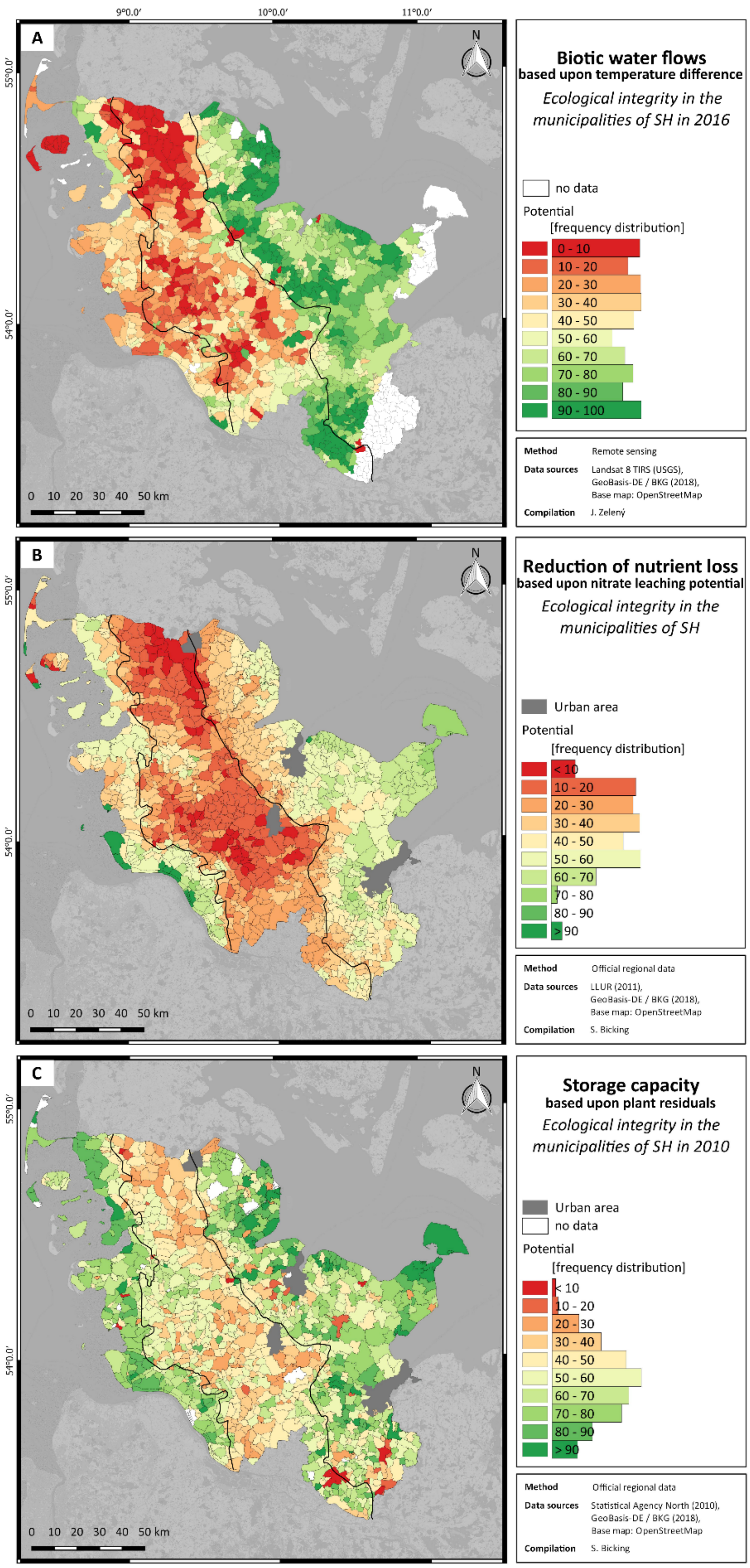

Figure 4: EI variables in the municipalities of SH: A) biotic water flows (based upon calculated temperature difference) in 2016, B) reduction of nutrient loss (based upon nitrate leaching potential) and C) storage capacity (based upon estimated plant residuals) in 2010. The lines indicate the borders of the main landscape regions.

The EI 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 center of SH, 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 in comparison to the coastal areas, which scored highest values (Figure 4). Besides storage capacity, the Geest comprises remarkably poor conditions to retain nutrients (reduction of nutrient loss, Figure 4). Whereas the area of the Hügelland features on average highest potentials concerning the reduction of nutrient loss.

Another variable, which received high values in the area of the Geest alongside exergy capture, is abiotic heterogeneity (Figure 5). This spatial feature originates from the historical land management and distinct land ownerships 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.

To sum up, the Geest area is featured by the highest photosynthetic potentials and respiration rates and high abiotic heterogeneity, while all remaining EI 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 compared to the Geest, the resulting net primary production is nevertheless, virtually equal in all three regions.

3.1.2 Provisioning ecosystem service variables

The spatial distribution of the crop production ES *potential* in Schleswig-Holstein (see Figure 6A) was mapped based on a Bayesian Belief Network (BBN) shown in Appendix 1 and based upon the soil fertility of the study area (see Figure 6B). Even though specific differences arise comparing the two crop production ES *potential* maps, the spatial distribution of the ES *potentials* does, in both maps, roughly follow the geomorphological characteristics of the areas. The Marsch region is characterized by the highest ES *potentials*, followed by the Hügelland. The lowest crop production *potential* can be found in the Geest area. This spatial pattern is strongly influenced by soil properties and other abiotic landscape parameters. The sandy and rather infertile soils of the Geest are featured by lower capacities to retain water and nutrients, which makes the area less favorable for agricultural purposes. 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. The spatial pattern of the crop production ES *potential* based upon the soil fertility follows the distribution of the three main landscape regions more extremely. Contrary to the ES

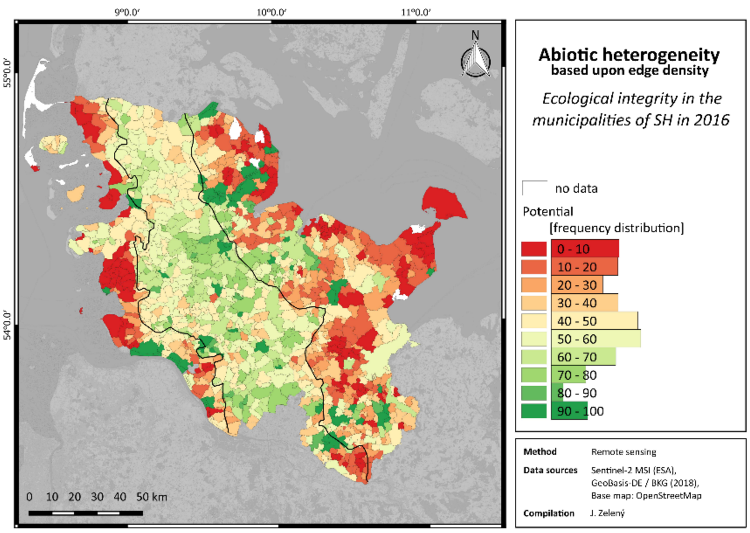

Figure 5: EI variable abiotic heterogeneity (based upon calculated edge density) in the municipalities of SH in 2016. The lines indicate the borders of the main landscape regions.

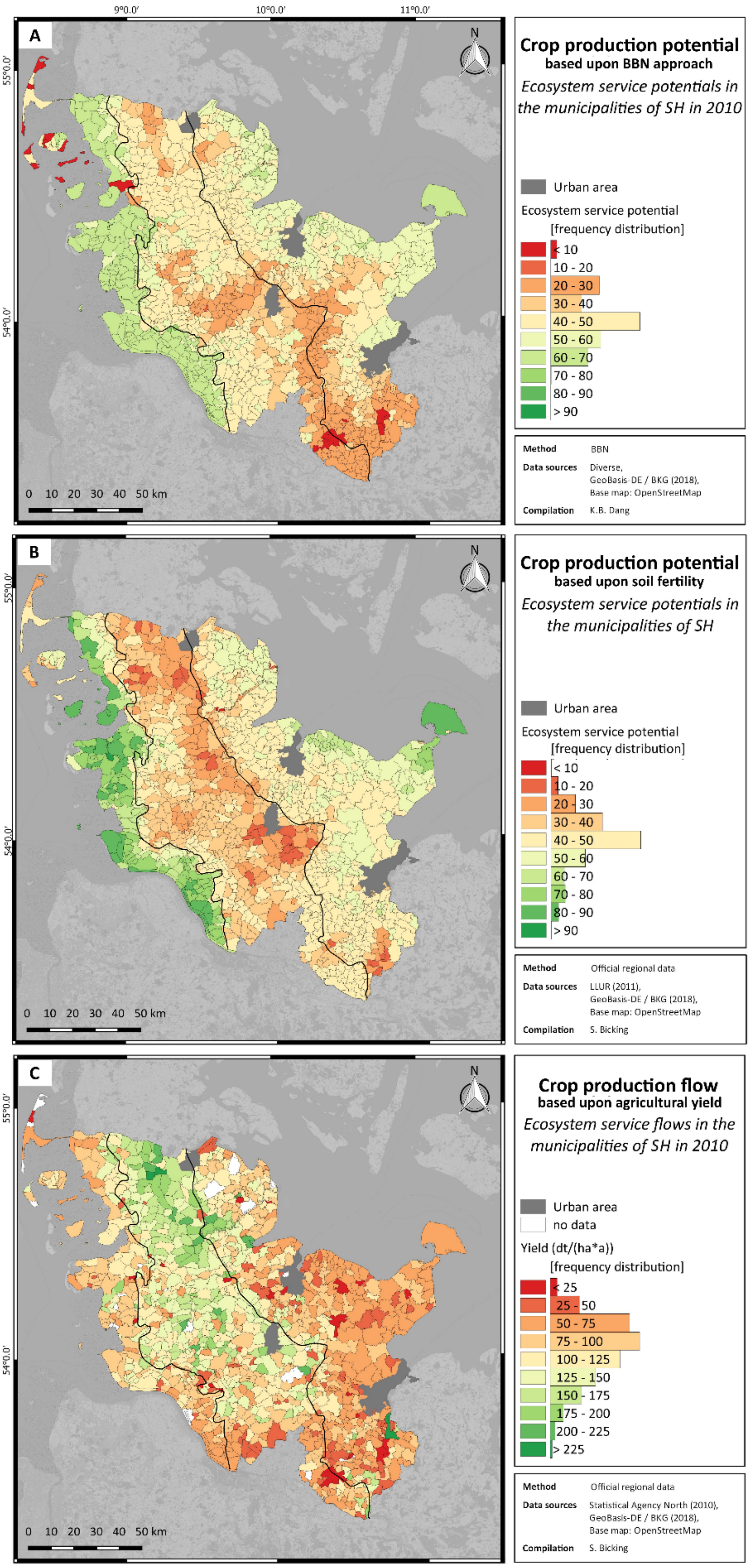

Figure 6: Crop production ecosystem service: A) *Potential* derived by BBN assessment (see Appendix A1), B) *potential* based upon soil fertility and C) *flow* based upon agricultural census. The lines indicate the borders of the main landscape regions.

potentials, 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 Marsch is characterized by medium ES *flow* values and the Hügelland area exhibits the lowest ES *flows*.

3.1.3 Statistical interrelations between variables

The correlation analysis between the assessed EI variables and crop production ES *potential* and *flow* support the findings outlined in Fig. 7. There is a significant positive relation between the EI 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 EI variables exergy capture and entropy production. On the other hand, the crop production ES *flow* and the EI parameter exergy capture are negatively related to the other integrity parameters like biotic water flows and reduction of nutrient loss and the ES *potential* parameter soil fertility. This means, that in fact the highest actual crop production and photosynthesis are taking place in conditions, which are unfavorable with respect to the soil nutrient and water retention potentials as well as fertility. A second point worthy of notice is a positive relationship 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 *flow* of the ES crop production is higher in the area of the Geest, also the associated respiration of the system is much higher. Thus, biomass is produced with lower efficiency compared to the Marsch and Hügelland.

3.2 It's all about the maize…

The assessment reveals a distinct spatial pattern of the crop production ES *flow* (Figure 6B). As described above, the highest harvest values 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 production of si-

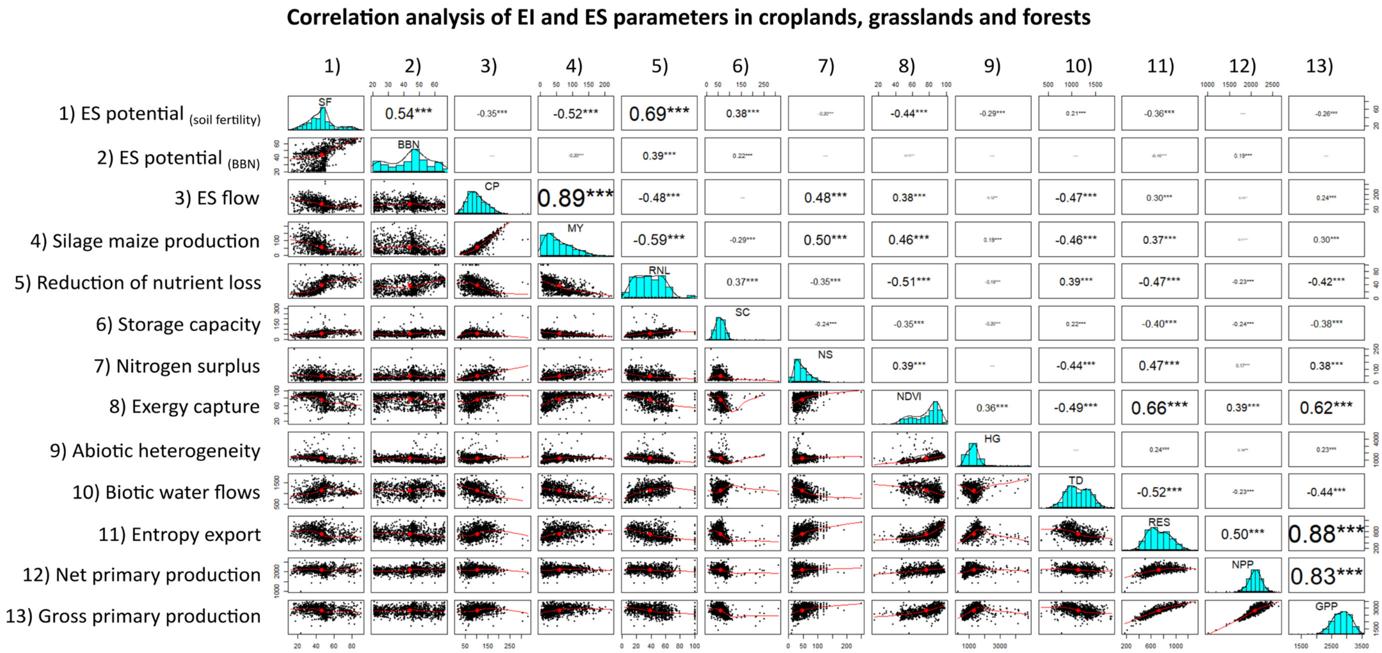

Figure 7: Correlation table presenting the statistical correlations between the selected EI and ES variables. The remote sensing data sets were sampled for the three major land-use types: **croplands (non-irrigated arable lands), grasslands (pastures) and forests**. A Pearson's correlation was performed for: 1) Crop production ES *potential* (BBN approach), 2) Soil fertility ES *potential* 3) crop production ES *flow* (as actual yield) 4) Silage maize production (part of ES *flow*) 5) EI variable reduction of nutrient loss (as nitrate leaching potential), 6) EI variable storage capacity (as residual biomass), 7) Nitrogen surplus, 8) EI variable exergy capture (as NDVI), 9) EI variable abiotic heterogeneity (as edge density),10) EI variable biotic water flows (as temperature difference), 11) EI variable entropy export (as respiration), 12) Net primary production and 13) Gross primary production.

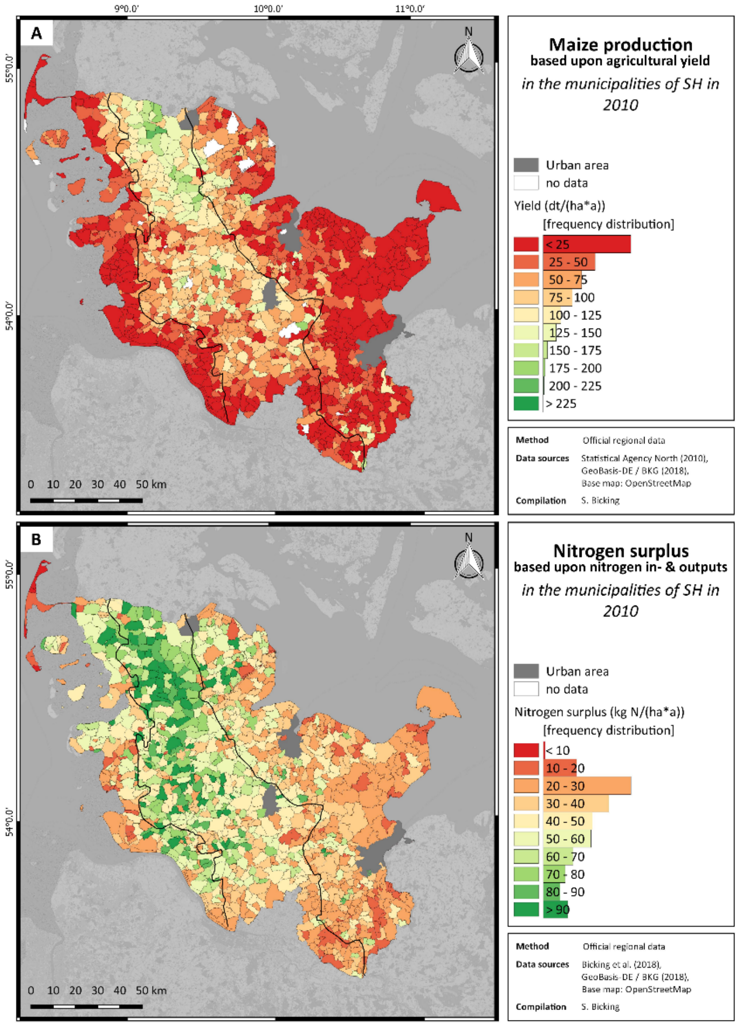

Figure 8: Silage maize harvest (a) and estimated nitrogen surplus (b) in the municipalities of SH in 2010. The lines indicate borders of the main landscape regions.

lage maize 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.

The development of the silage maize cultivation in SH 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 by pastures. The cultivation of pastures as fodder for the livestock has been supplemented with silage maize cultivation since the 1960s. 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. In 2004, the Renewable Energy Act 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 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 areas is in line with the spatial distribution of the harvest pattern of the silage maize (Figure 8A).

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 production are featured with high nitrogen surpluses. In combination with the assessed EI variable reduction of nutrient loss (Figure 4B) a serious picture arises, as 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 (non-irrigated arable land) prior to the assessment. Generally, there is a strong positive correlation between the silage maize harvest and the total 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*a) (Statistical Agency North 2010), made up a large share of the total harvest in 2010 in SH. Further positive correlations have been found between the silage maize harvest and the EI variables exergy capture, entropy export and the nutrient surplus. Negative correlations arise between the maize harvest on the one side and the EI variables biotic water flows, reduction of nutrient loss and storage capacity on the other (Figure 9). The silage maize production does not correlate with the crop production ES *potential*, obtained from the BBN, but it shows a strong negative correlation with the ES *potential* parameter soil fertility. Thus, silage maize is often cultivated on infertile soils, which explains the negative correlation between the ES *flow* and soil fertility to some extent.

3.3 Grass or Grain?

Differences in the three main landscape regions can be assessed in more detail by looking at the temporal developments throughout the vegetation period. The climax of the silage maize cultivation in the area of the Geest takes part in later periods of summer 2016 compared to the other crop types. This instance produces the most significant difference in Figure 10 - in March and June, the croplands in the Geest area 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. The respective cereal plantations are already harvested in June or July. By that time, maize is peaking in the Geest region. When NDVI values are summed up across the different seasons, the Geest region surpasses Hügelland and Marsch, possibly due to the vegetation period of maize cultivation extending into the late summer (Figure 10).

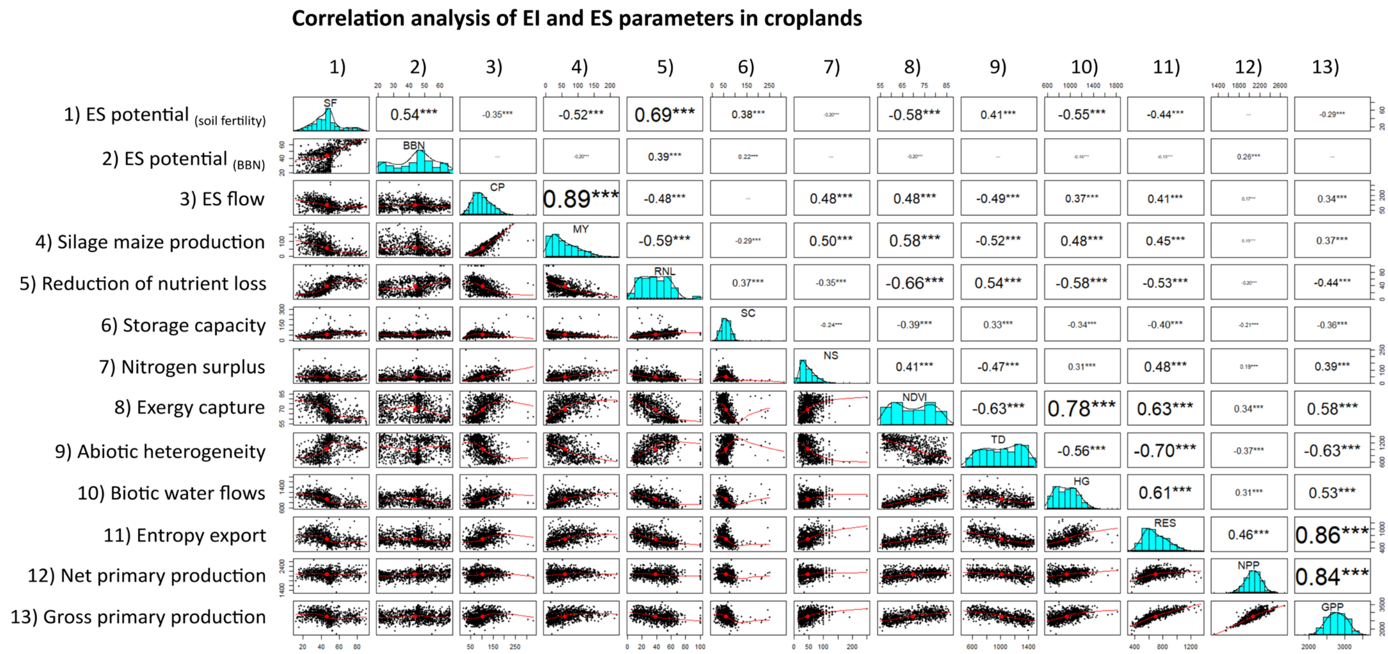

Figure 9: Correlation table presenting the statistical correlations between selected EI and ES variables. The remote sensing data sets were sampled in **croplands** only. A Pearson's correlation was performed for: 1) Crop production ES *potential* (BBN approach), 2) Soil fertility ES *potential* 3) crop production ES *flow* (as actual yield) 4) Silage maize production (part of ES *flow*) 5) EI variable reduction of nutrient loss (as nitrate leaching potential), 6) EI variable storage capacity (as residual biomass), 7) Nitrogen surplus, 8) EI variable exergy capture (as NDVI), 9) EI variable abiotic heterogeneity (as edge density),10) EI variable biotic water flows (as temperature difference), 11) EI variable entropy export (as respiration), 12) Net primary production and 13) Gross primary production.

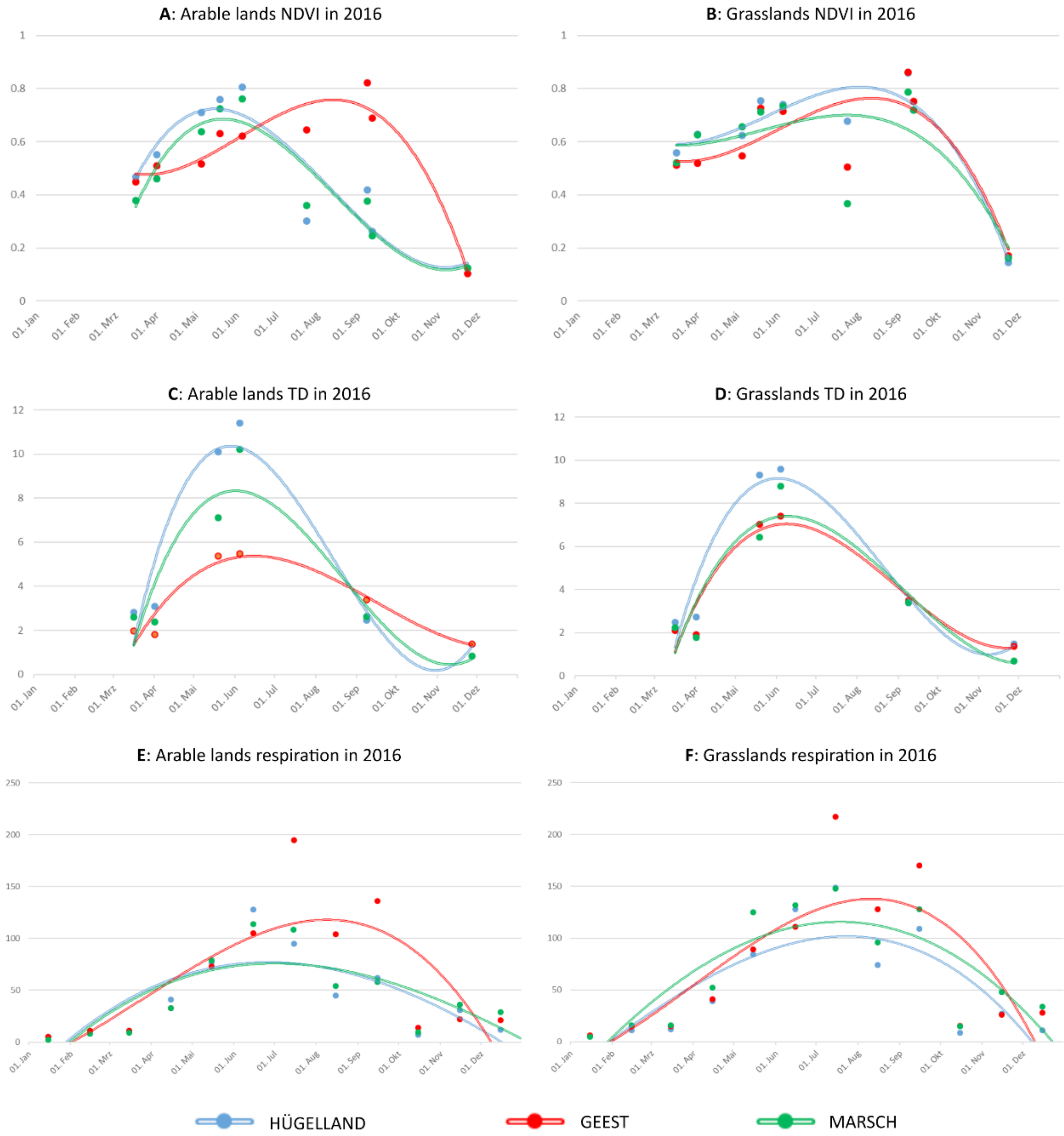

Figure 10: Performances of selected EI variables in **arable lands** (non-irrigated arable land) and **grasslands** (pasture) in the three main landscape regions Hügelland, Geest and Marsch throughout the year in 2016: A) Exergy capture (NDVI) in arable lands, B) exergy capture (NDVI) in grasslands, C) biotic water flows (TD - temperature differences) in arable lands, D) biotic water flows (TD - 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). Analogical analysis were performed in forests, but since the curves were virtually identical to grasslands curve, they were not included in the figure.

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 in biomass, does not differ significantly for any of the natural regions. Thus, higher exergy capture does not automatically mean more production, when this trend is bound to significantly increased levels of respiration (Figure 10E & F).

We assume that arable lands utilize solar energy more efficiently in Hügelland and Marsch as the EI indicator values such as biotic water flows are much higher in these regions (Figure 3 and 4). These results are linked to lower intensities of evapotranspiration by vegetation and thus, lower volumes of water transported. These distributions relate to lower metabolic rates and ecosystem efficiencies in the Geest. The results are consistent with the regional diverging soil properties for each of the three major land-use types in SH (Taube et al. 2015, Stewig 1982; Bähr and Kortum 1987). This can partly 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 compared to the other regions but also compared to other land use types such as pastures and forests within the area of the Geest (Figure 10C & D).

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 croplands, grasslands and forests including an overall comparison of the three landscape regions with a wide selection of variables. An outstanding perspective for the assessment of EI alongside ES 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 EI on the other. The goal is to give as rich explanation of this obvious paradox as our data and methods allow.

4.1 The paradox of crop production

One part of the statistical processing was the comparison between the three major land use types, relevant for the study area: arable lands (non-irrigated arable land), pastures and forests. All tested variables were correlated much stronger in arable lands compared to grasslands (see Figure 7 and 9) and forests (Appendix 3 and 4). These include the 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. It is noticeable, that a strong positive correlation between production and exergy capture is present, but seems to be decreasing in grasslands, and is virtually gone in forests (see Appendix 3 and 4). We thus support the assumption, that as anthropogenic influences decrease in ecosystems, which are used less intensively like pastures and forests, also the decoupling between production and EI is reduced (Rousseau et al. 2013; Tully and Ryals 2017). Thus, the three land-use types are representatives of a single gradient: On one side, production in arable lands is done at the expense of EI, while on the other, forests provide wood but also harbor the highest EI. This is a challenge with respect to the hypothesis, that EI and ES are positively related as we have found the opposite trend in arable lands.

Here, we would like to stress the importance of human inputs, which are not comprehensively integrated into the EI/ES causal chain. Conventional agriculture has brought remarkable increases in yields at severe environmental costs, which can make the achievements unsustainable in the long run (Tully and Ryals 2017; Isbell et al. 2015). Luckily, there is a rich body of evidence that alternative agricultural practice exist which are both productive and environmentally beneficial. Such practices comprise intercropping, cover cropping, integrating livestock, organic matter amendments, conservation tillage and most notably, agroforestry (FAO 2005; Pelosi et al. 2014; for a review, see Tully and Ryals 2017). Torralba et al. (2016) conclude, that structurally and functionally more complex systems then crop- or tree-based systems exhibit tighter coupling of nutrient cycles, organic matter, water retention and biodiversity, while not necessarily compromising commercially perspective productivity.

4.2 Is the recent agriculture in Geest suitable?

The relatively high respiration rates in the area of the Geest indicates a lower potential to convert solar energy into enduring biomass compared to Hügelland and Marsch. Thus, in order to maintain equivalent NPP across SH, the area produces approximately ⅓ more entropy along the way, compared to the rest of the study area. This result indicates that considerably higher energetic costs are associated with plant production in Geest, which potentially reduces the overall agricultural efficiency. The NPP/respiration ratio, therefore, serves as a measure of production efficiency, indicating lower performance in Geest, despite higher production. Besides high respiration rates, the Geest area also exhibits the highest potential to lose nutrients due to unfavorable soil conditions. Sandy soils contribute heavily to the overall low capacity to maintain nutrients (Taube et al. 2015); combined with low amounts of residual biomass (storage capacity), the soil is not suited for holding soluble nutrients and they are leached into the groundwater (Tully and Ryals 2017; Taube et al. 2015). Based on the results, we conclude that the production in Geest is accompanied by heavy overall waste production, mainly in the form of metabolic heat and nutrient surpluses. This discussion can provide arguments for the evaluation of the benefits and costs of conventional agricultural production in unproductive areas, but also production in environmentally unfavorable conditions in general.

4.3 Uncertainties and limitations

The main feature of this paper is the attempt to illustrate socio-ecological interrelations on the base of the spatial patterns of respective environmental indicators. Besides some interesting outcomes, this concept is also linked with several sources of uncertainties, which create insecurities 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 could 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 main landscape regions of SH, the assessment of their EI is only relative, given the conditions of the study area. The contemporary agricultural practices are almost exclusively based upon spending resources to diminish EI. 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 regions' specific potentials and thus sustainable agricultural production systems, in which provision of crops is fully in line with EI.

Besides the above-mentioned issues, Schulp et al. (2014) are discussing some further sources for insecure analyses. For instance:

- the uncertain definition of the EI and ES indicators might not be consistent,
- the potentially biased selection of the most relevant indicators influences parameter comparability,
- the failures and inaccuracies of the data sources themselves can be enormous.

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

- uncertainties due to ecosystem and landscape dynamics (e.g. uncertain dynamics of land-use or climate, temporal shifts incomparable data sets),
- 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 technical problems (e.g. methodological weaknesses, de-compatibilities of methods, data scarcity),

- uncertainties due to insufficient parameter inclusion (e.g. concentrating on land cover without considering soils, elevations, land use intensities, etc.),

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. Related to the described approaches, focal future improvements to reduce the insecurities could be:

- completion of the spatial integrity indicator set by including e.g. biotic heterogeneity, vegetation transpiration and/or standing biomass.
- employment of more advanced remote sensing instruments with higher spatial and temporal resolution and the employment of more sophisticated spatial algorithms to assess the EI of a landscape.
- addition of economic features to calculate the costs and benefits associated with the ES flows in SH.
- consideration of a wider range and higher resolution of spatial data comprising abiotic factors such as elevation, local climate, precipitation or soil type.
- inclusion of finer data quantifying the balance of anthropogenic inputs and outputs such as nutrients, organic matter and pesticides.
- development of the method of data aggregation for an improved statistical explanation of the interactions between the respective indicators.
- setting a reference point to demonstrate the difference in the current EI of SH and the „optimal“ and/or „natural“ potential.
- verification of the indicators by application of ground-truth testing using analogical instruments.

5 Conclusions

This study contributes to the theoretical assessment of the relation between EI and the provision of ES. Additionally, 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. Summing up the knowledge obtained from the study, the research questions are revised and answered accordingly:

I. Does the spatial distribution of the assessed EI variables reveal a distinct regional pattern?

   Yes, generally the assessed EI variables can be divided into two different groups with reference to their spatial pattern.

   a. The EI variables which have a strong relation to the production of biomass show the highest values in the area of the Geest. This is the case for the EI variables entropy export and exergy capture. The landscape regions Hügelland and Marsch are characterized by lower values for both of these EI variables.

   b. The spatial assessment of the EI variables which indicate the functionality of the ecosystem apart from biomass production indicated a reversed regional pattern. The area of the Geest is featured by the lowest values for the EI variables reduction of nutrient loss, biotic water flows and storage capacity. The assessment reveals that both, the Hügelland and Marsch, deliver higher EI with respect to these variables.

II. Does the spatial distribution of the ES crop production reveal a distinct regional pattern?

   Yes, the assessment of the crop production identifies the Hügelland and Marsch as the regions with the highest ES *potentials*. In contrast to that, these areas are characterized by rather low ES *flow* values. Highest values for actual crop production (ES *flow*) can be found in the Geest area, which manifested the lowest ES *potentials*.

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

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

IV. How does the EI/ES relation manifest in croplands, grasslands and forests in the three landscape regions of SH?

The correlation analysis revealed that the ES *flow* is negatively related to the ES *potential* and the underlying EI. In simple terms, intensive conventional agricultural production in SH is clearly traded-off against the underlying EI. Contrary to all expectations, crop production and exergy capture, representing the potential photosynthesis, are highest in areas with the lowest ES *potentials*, namely in the area of the Geest. The revealed negative relation between the ES *flow*, EI and ES *potential* in croplands is diminishing in grasslands and non-existent in forests.

V. Does the temporal distribution of the assessed EI variables show a distinct regional pattern in croplands, grasslands and forests?

In terms of exergy capture, the Geest region is reflecting the fact, that the silage maize cultivation peaks in a much later period in the year than the dominant crop types produced in Marsch and Hügelland. The photosynthetic potential of maize production in SH is, however, not accompanied by a significant increase in EI. A comparison, based upon the temporal development in grasslands (and forests), demonstrates that these land-use types can to a large degree cope with rather low ES *potentials*, maintaining integrity and productivity similar to regions with higher ES *potentials*, in our case the Marsch and the Hügelland. This leads us to the conclusion, that management types like grasslands and forests are far better suited in areas that are featured by low ES *potentials* then short-spanned intensive cultivation of annual crops.

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 EI as a consequence of agriculture de-coupling from natural site conditions.

The inverse relation between integrity and service provision and the accompanying costs give us evidence of unsustainability of a production regime, in which costs are likely to exceed the benefits. 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. Overall, the lower natural productivity in the Geest should result in larger areas covered by pastures or forests, which perform far better concerning most EI indicators. We would also like to argue for a paradigm shift towards novel management of production systems based on high EI and self-organization (e.g. agroforestry), generating multiple co-benefits (ES), and which are the opposite of conventional agricultural methods. Such an improved environmental system will also be correlated with a strong overall rise of comprehensive ecosystem service bundles.

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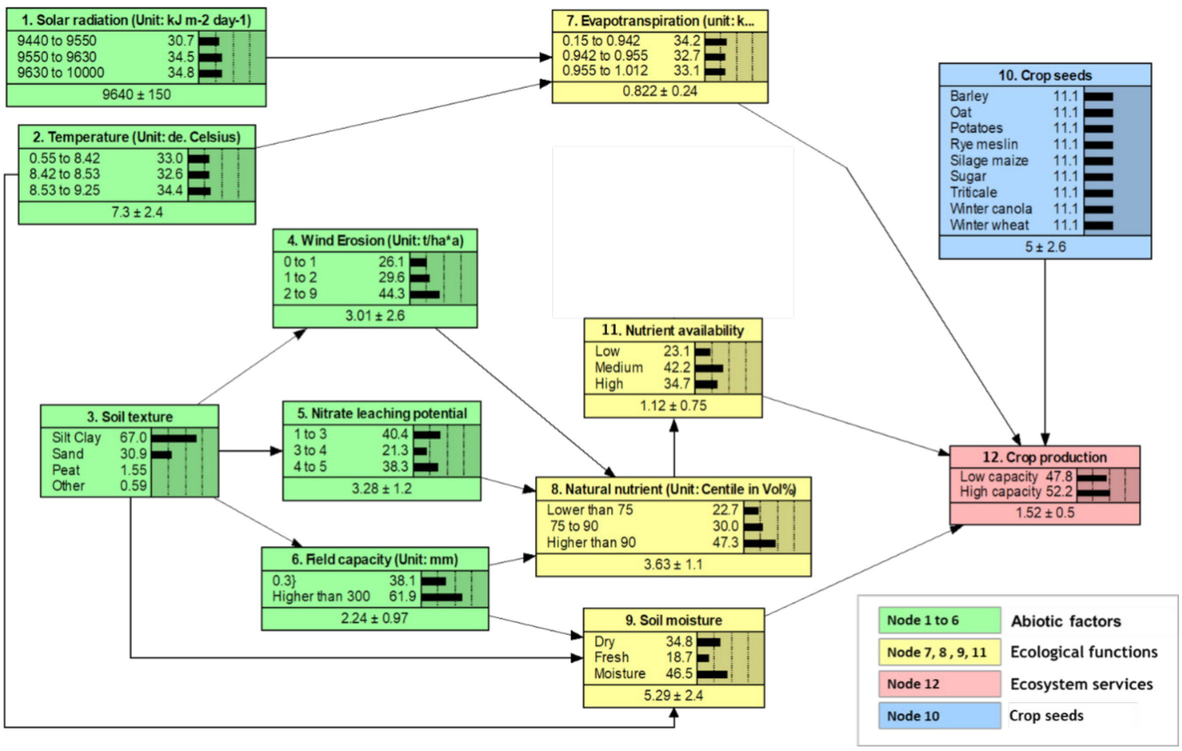
Appendix

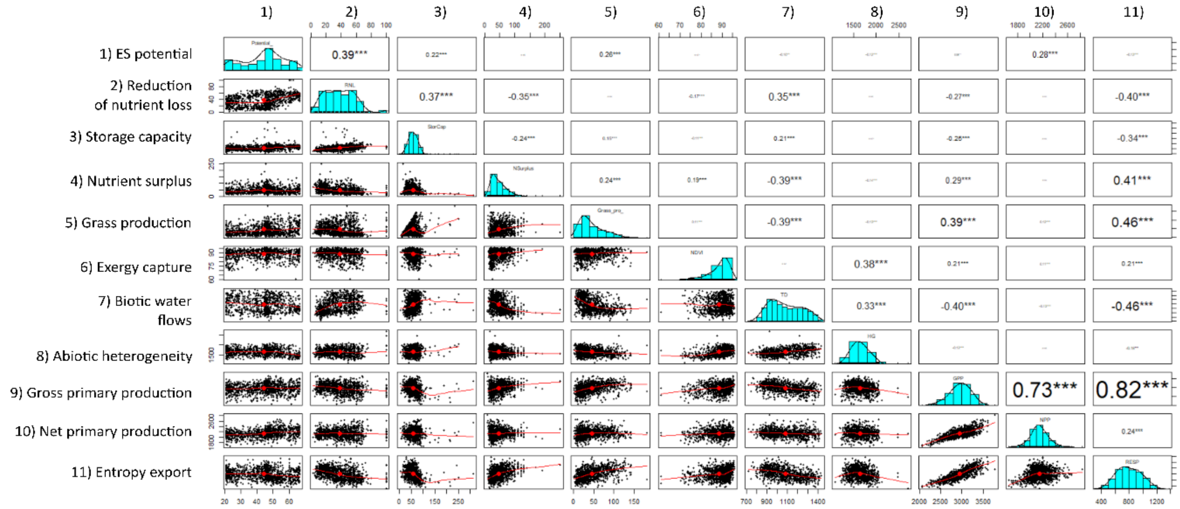


Appendix 1: Bayesian Belief Network assessing crop production potential in Schleswig-Holstein state.

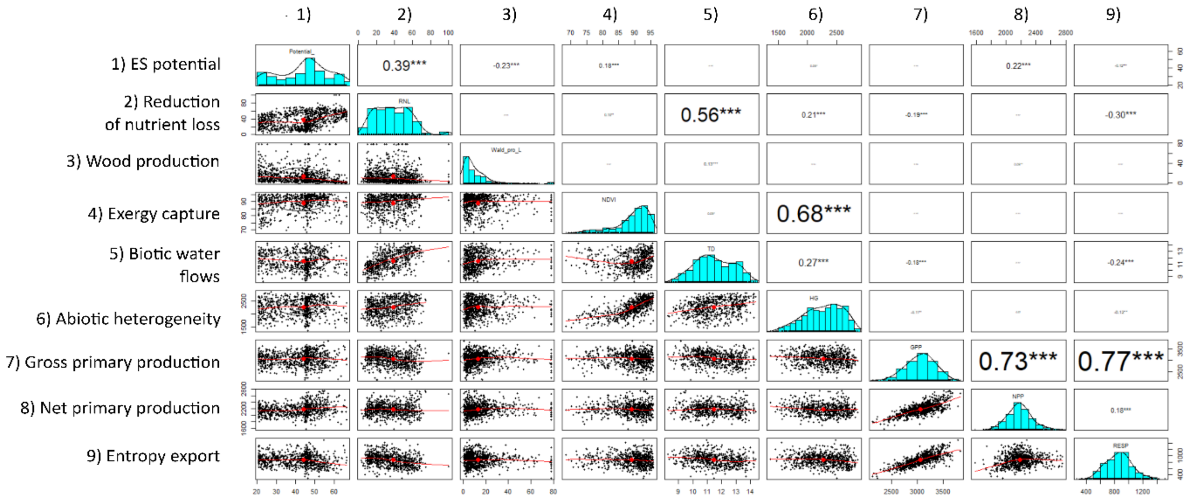
Appendix 2. The description of environmental, fertilizer and crop data as input data for the developed Bayesian Belief Network.

No.	Variable	Source	Available values
1	Land use and cover (LULC)	The CORINE Land Cover (CLC) inventory provided by Copernicus Land Monitoring Service [2] with resolution of 100m	33 types from CORINE LULC
2	Soil	Landesamt für Landwirtschaft, Umwelt und ländliche Räume (LLUR, eng.: State Agency for Agriculture, the Environment and Rural Areas) [3] at scale of 1 : 250 000	Include soil properties about field capacity, nutrient availability and soil moisture in detail for whole region
3	Geology	LLUR [3] at scale of 1 : 250 000	Include stratigraphy in detail (more than 30 types)
4	Erosion by wind	LLUR [2] at scale of 1 : 250 000	For whole region, including 9 classes (0-5 representing from “no” to “very high” risk; 6 = dike; 7= tidal flat, 8= urban area, 9=waterbodies)
5	Erosion by water	LLUR [3] at scale of 1 : 250 000	For whole region, including 9 classes (0-5 representing from “no” to “very high” risk; 6 = dike; 7= tidal flat, 8= urban area, 9=waterbodies)
6	Nitrate leaching potential	LLUR [3] at scale of 1 : 250 000	5 classes from “very low“ to “very high“
7	Temperature	Downloaded from WorldClim [4] website - Free global climate data (period of 1960-1990) with resolution of 1 km2	Monthly, In average (Unit: degree Celsius)
8	Wind speed		Monthly, In average (Unit: m/s)
9	Water vapor pressure		Monthly, In average (Unit: kPa)
10	Precipitation		Monthly, In average (Unit: mm)
11	Solar radiation		Monthly, In average (Unit: kJ m-2 day-1)
12	Crop types	Statistical reports, on the scale of municipalities	9 crop types (including barley, oat, potatoes, rye meslin, silage maize, sugar, triticale, winter canola and winter wheat)

2 https://land.copernicus.eu/
3 http://www.umweltdaten.landsh.de/
4 http://www.worldclim.org/



Appendix 3: 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 4: 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).