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Comparing participatory mapping and a spatial biophysical assessment of ecosystem service cold spots in agricultural landscapes

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ABSTRACT

In this study, we assess the supply of five ecosystem services (ES, i.e. biodiversity provision, carbon sequestration, erosion control, water availability and yield) in an agricultural landscape in Northeast Germany as perceived by different stakeholders with a web-based questionnaire. We complement this participatory approach with a biophysical assessment of the same ES in the same study area using spatially explicit, indicator-based methods. A research gap exists in the combination of participatory and biophysical ES assessment methods within one study area. We derive spots of low supply of multiple ES (cold spots of ES supply) from the areas identified by the mapping and the biophysical assessment, and in collaboration with stakeholders of the region during an online workshop. Our interest is to (i) identify the advantages of comparing and combining biophysical with participatory methods to assess ES and to (ii) identify interfaces where combining both approaches can help to integrate ES assessment in landscape planning, management and design. Our goal is to establish an assessment basis that allows for a spatially explicit representation of trade-offs and synergies of ES by displaying multiple ES in one case study area, capable of integrating different resolutions. By comparing participatory and biophysical assessments, we identify ecological and social benefits of the landscape, and emphasize the social-ecological interface by limiting the scope of the biophysical assessment to the area of interest by the stakeholders. Besides, areas in which participants over- or underestimate the current ES supply are spotted by quantifying the gap between actual and perceived supply. The results reveal several similarities in the observations derived from both assessments. However, water availability is widely underestimated, whereas biodiversity and carbon sequestration are slightly overestimated. Based on our results, we conclude that in many cases, stakeholders who are familiar with the landscape because they live there or have a professional relation to it have a profound understanding of the ongoing ecosystem processes. The decision whether to use participatory, biophysical or both assessment techniques should be made according to the use case: from a governance perspective, participatory data can be easier to communicate and more easily accessible. We encourage the perspective that there are cases in which the low-threshold participatory data provide sufficiently reliable information to make informed decisions on ES management, particularly when biophysical assessment studies are too resource- and cost-intensive.

1. Introduction

It becomes increasingly important to base land use decisions and landscape management on the current state of scientific knowledge about ecosystem services (Schuwirth et al., 2019). At the same time, management decisions must account for social objectives involving a diverse set of local and regional stakeholders. The understanding of the importance of biophysical modeling and mapping of ES for better informed environmental decision-making has led to the development of various mapping and modeling tools, such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs; Sharp et al., 2020), ARIES (ARtificial Intelligence for Ecosystem Services; Villa et al., 2009) or EVT (Eco-system Valuation Toolkit; Earth Economics, 2022). These modeling tools are used mainly for assessing provisioning and regulating ES and

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have already provided a growing database on the current state of the world's most valuable ecosystems. At the same time, Participatory Geographic Information System (PGIS) approaches have been developed to foster the inclusion of stakeholder perspectives on mostly cultural, and occasionally provisioning and regulating ES (Brown and Fagerholm, 2015; Raymond et al., 2009; Schwartz et al., 2021). These assessments have proven very useful for spatially displaying non-use values, or context- and stakeholder-specific knowledge. However, biophysical and participatory assessments are usually not compared within one study framework. From an ecosystem governance perspective, the interpretation of biophysical modeling data is often difficult for non-scientific personnel. Yet, decision-makers have to include knowledge about complex ecosystem dynamics in their decisions. Participatory data can add critical information such as perceptions and priorities of relevant stakeholders, which might go unseen by the researchers (Klapwijk et al., 2014). This information can be useful to improve existing modeling tools. Therefore, the availability of biophysical in combination with high-quality participatory data is a necessary resource for informed land use decision-making.

1.1. Methods for ES assessment

De Groot et al. (2010) mention three value domains of ES: ecologic, sociocultural and economic values, each of which are measured with different indicators. Ecological values are best measured with biophysical indicators, while sociocultural values require more participatory methods. The measurement unit for economic values is usually money, where a distinction can be made between use values and non-use values (De Groot et al., 2010). Harrison et al. (2018) distinguish between biophysical methods, such as the use of matrices, spreadsheets, modeling or the InVEST tool; sociocultural evaluation techniques, such as deliberative valuation, preference ranking, multi-criteria analysis or participatory methods such as PGIS; and monetary methods, i.e. stated preference, contingent valuation, choice experiments and revealed preference. Further methodological distinction can be made according to the scope of the assessments (e.g. supply, demand), the spatial scale and temporal units of assessment (Harrison et al., 2018).

Changes in landscape management usually affect not only the provision of one but of several interconnected ES. Finding adequate methods for displaying the change in the provision of bundles of connected ES as a reaction to land use change therefore is essential. De Groot et al. (2010) suggest several methods, such as the visualization of ES, ES modeling or integrated cost-benefit analyses, and recommend taking into account all relevant scales and stakeholders involved. Mapping and visual assessments should help decision-makers not only identify the location of the ES but also visualize the spatial heterogeneity in ES provision. According to De Groot et al. (2010), two main types of indicators are needed to assess the quantitative relationship between biodiversity, ecosystem components, and processes and services: state indicators describe the ecosystem component providing the service, and process indicators describe the maximum sustainably available amount of this service.

1.2. Integrating ES assessment results in land use decisions

Involving ES assessment in environmental decision-making requires high-quality knowledge transfer. Posner et al. (2016) evaluated the usage of the Natural Capital Project's InVEST models over a period of 25 months in 104 countries. Their findings show that the probability of model usage increased significantly when a prior training in using InVEST models by official staff had taken place. Capacity building, such as formal training with locally relevant use cases and follow-up training, are essential for the continuous use of ES modeling tools (Posner et al., 2016). Local governments and community administrations do not often have the financial or temporal resources to invest in such training. Unless local authorities are trained, the integration of modeling results in decision-making requires collaboration between environmental decision-makers and ecological modelers (Schuwirth et al., 2019), which is probably as time-intensive as the training. Nevertheless, the information gained by ecological modeling or other biophysical assessments is of high value for them. Lower-threshold alternatives, such as the assessment of biophysical parameters with participatory methods integrating expert knowledge can be useful for enabling more congruency between land use decisions and the status quo of the ecosystems modified by these decisions.

Cebrián-Piqueras et al. (2017) found that perceptions of ES and land use are strongly influenced by stakeholders' perspectives. When farmers and conservationists were asked to state their preference for ES and evaluate the value in regional landscape areas to provide these services, farmers tended to express a preference for provisioning services related to production, while conservationists preferred conservation values. Interestingly, their views also differed when it came to associating biophysical ecosystem properties to the services. Different observations have also been found Schwartz et al. (2021) only observed weak correlations between the type of stakeholder and the demand stated, respectively, perceived supply, in a PGIS survey on five ES. The only exception was erosion. However, integrating stakeholders' perspectives in land use decisions allows the raising of awareness of both ecological and social demands related to the respective landscapes. Furthermore, it can visualize conflicts and trade-offs arising across different value dimensions and help prioritize land uses (Langemeyer et al., 2016).

1.3. Comparing biophysical and participatory assessment techniques

The combination of biophysical and participatory assessment techniques within the same study can have the advantage of displaying a broader set of interconnected ES. As of today almost all of the world's ecosystems are at least to some degree planned and managed by humans, and cultural intentions and cultural values are an integral part of all of them (Comberti et al., 2015). Furthermore, including sociocultural values by applying participatory techniques in biophysical ES assessments enables potential managers and planners to understand the perspectives of those living in these landscapes and the ecosystem conditions with which they work.

To our knowledge, no studies exist that compare a biophysical to a participatory assessment for the same ES in one study region. Bagstad et al. (2017) combined biophysical and participatory data for mapping different ES in six national U.S. forests and identifying hot and cold spots of ES. Hot spots were calculated with six different methods, such as quantile methods (top and bottom 10 % and 33 % of values), or area based methods (top and bottom 10 % or 33 % of each forests' total area). They used the ARIES tool in the biophysical assessment for modeling carbon sequestration and storage, water yield, sediment regulation and aesthetic viewsheds from recreation sites. For cultural ES, such as aesthetic, cultural, future, historic, intrinsic, learning, recreation, spiritual, therapeutic and subsistence values, they used the SolVES tool (Sherrouse and Semmens, 2020). They used quantile, area-based and statistical methods for identifying hot and cold spots of the ES supply. The amount, extent and clustering of hot and cold spots differ according to the methods used to identify them. They concluded that the choice of method should depend on the size of the area analyzed, and the management possibilities of several distributed spots in comparison to fewer large spots. They recommend the use of statistical methods for landscape scale planning, based on their results. They further suggest clarifying the management implications of hot and cold spots, such as high management support and mediation between conflicts arising due to management objectives and traditional resource use in hot spot areas, and resource extraction from cold spots in which other important natural or cultural resources are absent.

The integration of ES assessments into land use decision-making should not only distinguish between a set of available methods for assessment, but also account for the perspective of the stakeholder group

(s) by which the assessment is made. A combination of different assessment techniques can help to identify different stakeholder perspectives and align them with the ecosystem state and resulting management requirements. This is based on an understanding that humans are an essential part of their landscapes and not separated from them.

The aim of our study is to compare a participatory assessment of five ES in agricultural landscapes with a spatially explicit biophysical assessment of the same ES in the same area. With this procedure we seek to (i) identify advantages of comparing and combining biophysical with participatory assessment techniques to assess ES, and to (ii) identify interfaces where combining both approaches can help to integrate ES assessment in landscape planning, management and design. Therefore, we conducted a web-based questionnaire with a mapping component and assessed ES in the same area with spatially explicit methods. We derived potential cold spots of ES supply based on both assessments, and discussed results and management implications in a workshop with regional stakeholders.

2. Material and methods

2.1. Study area

The study area is a subregion in the district of Maerkisch-Oderland in the Federal State of Brandenburg in Northeast Germany (Fig. 1), which encompasses the Maerkische Schweiz Nature Park (205 km^2) and several smaller nature reserves, as well as the towns of Buckow, Muencheberg and Strausberg. The whole district area of Maerkisch-Oderland amounts to 2159 km^2; our study area covers 481 km^2 (22 %) of the district area. The landscape is characterized by intensive agriculture, forest and nature protection areas. We selected this subregion because of its comparably high population density (91 inhabitants per km^2 in 2020) combined with the high number of nature reserves, a high density of forest and agricultural area and several lakes.

2.2. Assessment methods

We used data on the perceived supply of ES from a PGIS study by Schwartz et al. (2021) and biophysical ES assessment data for the same region by Ungaro et al. (2021a). We combined both assessments by normalizing the respective indicators and generating overlay maps of both datasets. Our focus was on the direct comparison of participatory and model based spatially explicit assessment values. Our analysis emphasized the question whether the supply of different ES perceived by participants is higher than, lower than or equal to the supply of ES determined with biophysical assessment methods and remote sensing. In the second analytical step, we created a map displaying cold spots of supply of multiple ES from the data by Ungaro et al. (2021b). Cold spot analyses provide the advantage of differentiating between ES specific scale and spatial location. Hence, they consider location specific changes in ES provision for several ES within the same landscape. We consequently used the term cold spots to define areas in which multiple ES scored jointly below the 25th percentile of the observed distribution, and compared these areas to the areas mapped with the participatory assessment. Generating a broader picture by not only assessing one but five ES allows us to make more generalized statements about the usefulness of combined or single assessments, according to the use case. It can help identify trade-offs or synergies between ES, or show other types of relations between ES and stakeholders, depending on the objective of the study, the ES assessed, the methods the ES are assessed with, the stakeholders involved and the landscape. We also generated maps showing cold spots of multiple ES supply derived from the biophysical assessment.

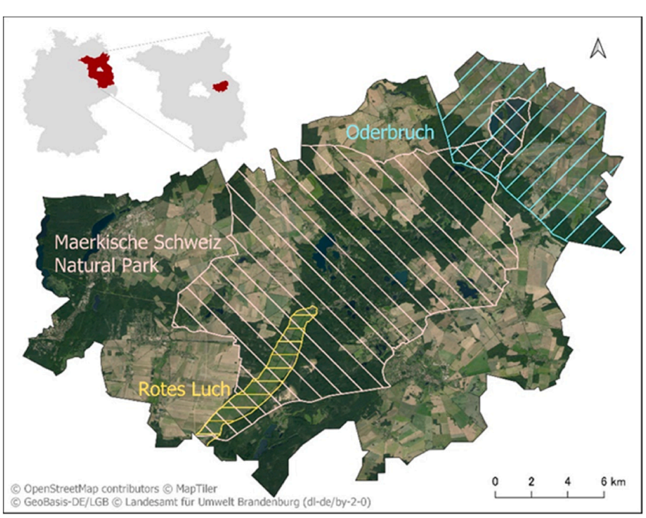

Fig. 1. Case Study Area encompassing the drained area Rotes Luch, the Natural Park Maerkische Schweiz and the plane Oderbruch, in which the river Odria is embedded.

2.2.1. Biophysical ES assessment

Different data sources, including remote sensing data, and proxy indicators were used in the biophysical assessment to evaluate and spatially display the provision of the five ES for the agricultural lands (140 ha) of the Maerkisch-Oderland District in East Brandenburg, Germany. The five ES were chosen with reference to the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin, 2012) and are: i) biodiversity, ii) carbon sequestration, iii) erosion control, iv) water availability and v) yield / biomass production. The ES were assessed and mapped on a regular grid at 1 ha resolution over the study area; the assessment method for each ES is described in detail in Ungaro et al. (2021a, b). Each indicator value was normalized as a number in the range of 0 to 1. The maximum values observed in the study area were then set equal to 1, and the value 0 indicated the relative minima in the area considered.

2.2.2. Participatory ES assessment

Participants were informed about the different ES during the web-based questionnaire of the PGIS-study – biodiversity, carbon sequestration, erosion control, water availability and yield. The definition of the respective ES given was based on the CICES (Haines-Young and Potschin, 2012). After an introduction to the goal of the survey and the topic of ES, participants were able to self-assign to different stakeholder categories. The procedure was similar for all ES: participants were given an explanation of the ES, and agricultural management practices that influence the supply of the respective ES were described. Participants were then asked to self-assess their knowledge of these ES based on the previous explanation. In a second step, they were asked to map up to three areas they consider relevant for the supply of the respective ES and to estimate the current ES supply levels perceived ("*In percentage of the optimum state (100 %), how do you estimate current supply levels?*") in these areas. The survey was conducted between March and November 2020. The reason for this long period was the sudden outbreak of the COVID-19 pandemic and its impact on the availability of stakeholders and the impossibility of face-to-face interviews. After a pretest with selected participants, a thorough search for stakeholders in the region was conducted based on a spatial raster with previously defined categories related to our chosen ES, i.e. agriculture, forestry, nature conservation, tourism, inhabitants and others. The target audience were potential multipliers in our case study area, i.e. people with a sufficiently large network and the possibility of distributing the questionnaire further. 30 complete questionnaires were collected in the study area, of which 30 % self-categorized as scientists, 24 % as farmers, and below 10 % self-categorized as foresters, civil society or entrepreneurship.

2.2.3. Combination of both assessment types

We compared the current relative supply perceived by the survey participants with the supply identified in the biophysical assessment for the same area (Table 1).The indicator species habitat, consisting of the sum of the area share under specific designations, such as nature protection areas as a proxy, was compared with the perceived supply of biodiversity, defined as all living organisms in their respective habitats. In the biophysical assessment, the indicator total carbon stock (mg ha^{-1}) was derived via geostatistical downscaling from the Food and Agricultural Organization of the United Nations (FAO) soil carbon stock map (FAO, 2022) and the potential carbon stock (mg ha^{-1}) was estimated by calculating possible soil carbon changes within the range of each combination of current land use and soil class (Stolbovoy et al., 2005; Stolbovoy et al., 2006). We used the total carbon stock and compared it with carbon sequestration supply perceived by participants of the PGIS study for the combination of assessment types. Soil erosion is often estimated by the Revised Universal Soil Loss Equation (RUSLE), as a function of the rainfall and runoff factor, the soil erodibility factor, the slope length-gradient factor, and the crop/vegetation and management factor (Benavidez et al., 2018). We used the ARIES tool for obtaining RUSLE-based results for potential soil erosion (Mg/ha yr^{-1}) and soil mass retained by vegetation (Mg/ha yr^{-1}). As soil erosion is a disservice, we calculated the indicator as 1-erosion based on the log transforms, so that the lowest values have the higher indicator scores, using the 5th and 95th percentiles as limit for the interval normalization.

$$\text{Indicator erosion control}_{(0-1)} = 1- [(\text{Log} \times - \text{p5}^{\text{th}}(\text{Log x})) / (\text{p95}^{\text{th}}(\text{Log x}) - \text{p5}^{\text{th}}(\text{Log x}))], \quad (1)$$

where x is the Log transform of the potential soil erosion (Mg/ha yr^{-1}). Participants in the assessment were asked for perceived levels of erosion control on the areas mapped. The indicator water storage, inferred resorting to the System for Automated Geoscientific Analyses (SAGA) Wetness Index (Brenning, 2018), was compared with the perceived supply of water availability, which is described as the amount of groundwater and surface water available to plants. We compared the biomass production, inferred resorting to the Normalized Difference Vegetation Index (NDVI) for the months of June over the time period 2000–2019, to the perceived supply of biomass yield, defined as the biomass of crops and fodder plants harvested and marketed per year and per hectare in a defined area.

The analysis was conducted by using the geographic information system software QGIS Version 3.24.0 (QGIS Development Team, 2021). The spatial data was transferred into the Lambert conformal conic (*N*-E) projection based on the European Terrestrial Reference System 1989 (EPSG 4839). Both datasets were transformed into raster files with a resolution of 100 m.

Regarding each raster cell of the areas mapped by the participants, perceived supply values were absolutely normalized on a scale from 0 to 1, meaning that 1 represents the highest possible value (i.e. 100 %). Overlapping raster cells were revalued to a single cell value that represents the arithmetic mean of the respective cell values. The supply values of the biophysical assessment were normalized in a coherent way for the same areas. We then calculated the difference between the actual and the perceived supply (), resulting in values gradually ranging from −1 to 1, where −1, highlighted in blue, indicates an overestimation of actual ES, and 1, highlighted in red, an underestimation. Values that approach zero () represent an equilibrium of perceived and actual ES supply and are displayed by greyish colors.

2.3. Identification of cold spots of multiple ES

Different approaches can be used to delineate hot and cold spots on maps (Bagstad et al., 2017; Baral et al., 2013; Gimona and van der Horst, 2007; Ungaro et al., 2014; Wu et al., 2013). We adopted thresholds based upon order statistics for the biophysical assessment. As the indicators range along a scale from 0 to 1, we considered as thresholds the values of the upper and lower quartiles of the observed indicator distribution, as physical thresholds would not be meaningful. Our focus in this study was on cold spots of ES, indicating areas with particularly low ES supply and, thus, a high need for action. Cold spots of ES supply were then identified and mapped for each single indicator as areas where their normalized values are below the 25th percentile of the observed indicator distribution (Anderson et al., 2009), i.e. the grid cell with values that are below the value of the lower quartile for any given indicator. Only the areas with existing data values for all ES were considered for the cold spots mapping. The sum of cold spots of all ES for each grid cell then provided a joint index, potentially ranging from 0 (no ES value below the 25th percentile) to 5 (all ES have values below the 25th percentile), that can be displayed on a map.

Regarding the participatory assessment, due to low data density in the spatially explicit assignment of multiple ESS and the risk of incorrect interpretation we refrained from performing a similar cold spot analysis. Instead, we displayed all mappings for all ES on one map and looked for visual overlays in areas that were perceived as high supply areas. Both maps were then compared in a visual assessment.

2.4. Stakeholder workshop

We discussed how far the combination of biophysical and participatory data could be useful in regional and landscape management during a three-hour online workshop with ten local representatives of the stakeholder groups addressed in the participatory assessment. The workshop was conducted in March 2021 with the goal of identifying remarkable areas of neighboring distinctiveness based on the results of the biophysical and the participatory assessment. We explained the methodological approach in detail in an open discussion and group work with the use of a MURAL board (Tactivos, 2022) and looked at the cold spots identified before subsequently focusing on possible management strategies to enhance the ES provision in these regions.

3. Results

We present three results for each ES assessed in the following order: the result of the PGIS exercise, the result of the biophysical assessment of the corresponding ES, and the overlay analysis of combining and comparing these two assessment methods. We can derive areas of relatively high and relatively low ES supply, both perceived by stakeholders and estimated with the biophysical assessment methods, from the first and the second map. From the third map, we can derive areas of interest

Table 1
Indicators for ES as used in the biophysical and in the participatory assessment.

ES	Biophysical Assessment	PGIS Study
biodiversity	habitat for species	Perceived sum of living organisms in their respective habitats
carbon sequestration	carbon stock total; derived from the FAO soil carbon stock map	perceived capacity of soils to sequester and store carbon in form of soil organic matter
erosion control	RUSLE based potential soil loss and soil mass retained by vegetation (Mg/ha yr^{-1}; Eq.1)	perceived levels of erosion control
water availability	water storage by SAGA wetness index	perceived amount of groundwater and surface water available to plants
yield	biomass production by NDVI	Perceived crop biomass (t/ha yr^{-1})

in which both data types are available, and can distinguish between areas where participants over- or underestimated the current supply, and areas in which the participatory estimation and the biophysically measured supply showed coherence. In the participatory assessment, no correlations were identified between stakeholder categories and supply perceived, which is why we display the mapped areas by all stakeholder without differentiation. We then created a map of cold spots of ES, based on the biophysical assessment, and compared these spots to the respective supply levels estimated by the participants.

3.1. ES assessment

3.1.1. Biodiversity

Participants mapped several areas as valuable in terms of biodiversity supply. No biophysical supply data is available for the areas mapped in the center and estimated most valuable. This is because a major part of these areas mapped by the participants is part of the Maerkische Schweiz nature reserve and is not coded as an agricultural area. Participants estimated the current supply rather low for agricultural areas (Fig. 2a, values between 10 and 55 %), whereas the biophysically measured values in these areas are even slightly lower (Fig. 2b, values between 0 and 40 %). An exceptional area in the third map displaying the difference between the biophysical and the participatory assessment (Fig. 2c) is visible around Rotes Luch, an agriculturally used wetland area, where participants underestimated current biodiversity levels.

3.1.2. Carbon sequestration

Estimated carbon levels range from 1 to 82 % in the areas mapped by the participants (Fig. 3a). Rather low values of carbon sequestration were mapped. Only two areas appear as those perceived with a high supply. The biophysical assessment generally confirms this assumption. Most of the area is characterized by low to very low carbon stock levels. However, there appear to be three high supply areas: a small one in the east, an elongated one in the mid-southern part and a relatively large area in the north (Fig. 3b). Participants were able to identify the high supply area in the east, and underestimated current carbon levels in the mid-southern part (Fig. 3c). No areas in the northern area were mapped by the participants.

3.1.3. Erosion control

The perceived supply of erosion control ranges from 1 to 89 % within the areas mapped by the participants. Most erosion control values are estimated below 50 %, however, supply levels in the area known as Rotes Luch and in the western part were estimated between 70 and 80 % (Fig. 4a). The RUSLE calculation with ARIES showed high supply levels in the northeast, and in the south around the region of Rotes Luch (Fig. 4b). The comparison of the maps shows that participants were able to identify this area as particularly valuable in terms of erosion control (Fig. 4c). The other areas depict a slight underestimation of erosion control supply levels. However, participants identified the northeastern region as somewhat relevant for erosion control.

3.1.4. Water availability

Stakeholders mapped the whole case study area as deficient in water availability, which leads to a general underestimation of water availability in large areas. Almost all participants mapped the water availability below 50 %; only one area in the west and two areas in the northeast were mapped with a current moderate supply of up to 60 % (Fig. 5a). The SAGA wetness index is shown in the biophysical map. Water availability is generally very heterogeneous, but high supply areas occur in the north east and mid-south (Fig. 5b). The comparison of both maps shows a general fragmentation of water availability in the whole study area (Fig. 5c).

3.1.5. Yield

Estimations of current yield supply varied from 8 to 90 %. Yields estimated above 50 % of the optimum were found in the central west region (Fig. 6a). The biophysical assessment shows the area around Rotes Luch as an especially high yielding area in biomass, whereas yields in the rest of the case study area appear to be rather low, with the only exception being in the northeast (Fig. 6b). Participants overestimated yield supply in the region close to the Maerkische Schweiz nature park, while their estimations for the other regions were close to the biophysical biomass assessment data (Fig. 6c).

3.2. Identification of cold spots of multiple ES

A map with cold spots of multiple ES supply was created based on the results of the biophysical assessment (Fig. 7a). A cold spot of any given service occurs where its value is below that of the 25th percentile of the observed distribution of the corresponding indicator. We then assigned a value of 1 to each cell with a value < 25th percentile of the indicator, and then summed the values for the 5 ES we considered. We applied the same approach to the data collected in the participatory assessment. Fig. 7b shows all areas with 0 to 5 ES scoring below 25 % of the optimum, as perceived by the participants. Red and orange areas on the map show where 0–1 cold spots appear, yellow areas show 2 cold spots, while blue areas indicate the presence of 3 (light blue) to 5 cold spots (dark blue). Red and yellow areas are not to be considered hot spot areas, but show the absence of multiple cold spots, i.e. areas where all or almost all ES score higher than 25 % of all values observed.

The maps exhibit several particularly interesting areas where the number of cold spots is very low. One of these is an area with a lengthy extension in the south west of the case study area where the number of cold spots is < 2, directly next to an area in which several cold spots are found. This area appeared several times in the participatory assessment as well and is known as Rotes Luch an agriculturally used wetland area. The wetlands were regularly drained and used for peat extraction

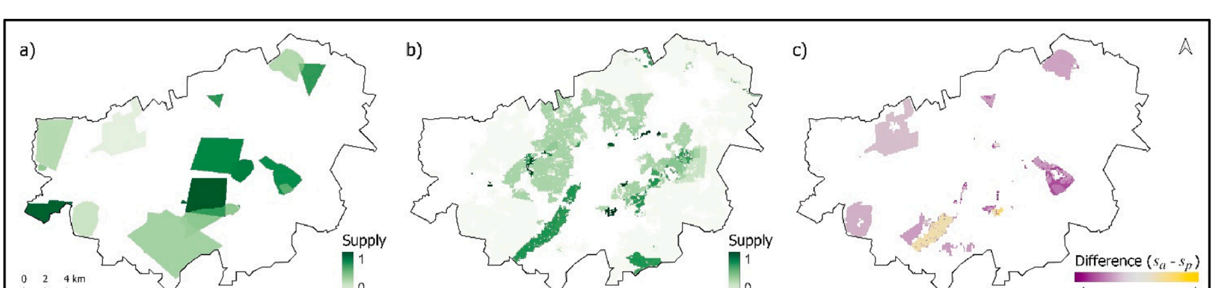

Fig. 2. Biodiversity Supply derived from a) participatory supply assessment and b) biophysical supply assessment. Map c) shows the difference between the biophysical and the participatory supply assessment (), in which negative values of (purple) represent an overestimation of ES by the participants, whereas positive values (yellow) indicate an underestimation. Values around zero (i.e.) are shaded grey and imply an equilibrium of perceived and actual ES supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

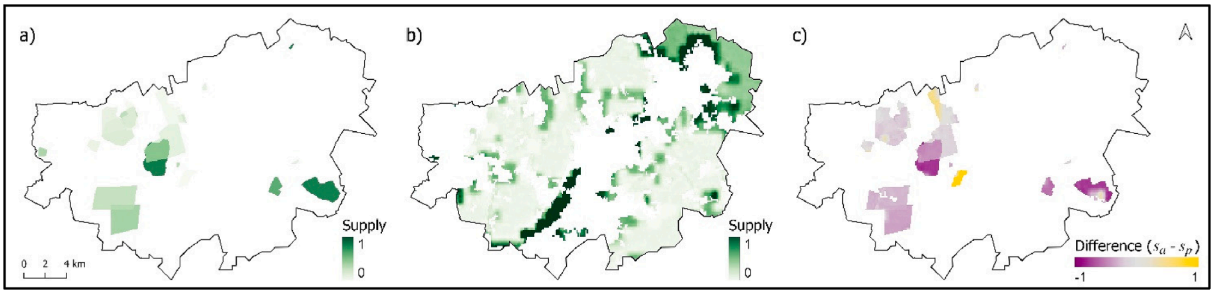

Fig. 3. Carbon Sequestration Supply derived from a) participatory supply assessment and b) biophysical supply assessment. Map c) shows the difference between the biophysical and the participatory supply assessment (), in which negative values of (purple) represent an overestimation of ES by the participants, whereas positive values (yellow) indicate an underestimation. Values around zero (i.e.) are shaded grey and imply an equilibrium of perceived and actual ES supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

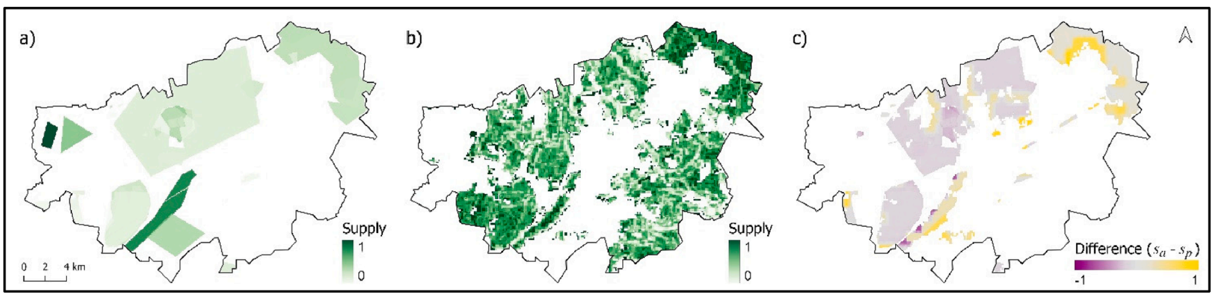

Fig. 4. Erosion Control Supply derived from a) participatory supply assessment and b) biophysical supply assessment. Map c) shows the difference between the biophysical and the participatory supply assessment (), in which negative values of (purple) represent an overestimation of ES by the participants, whereas positive values (yellow) indicate an underestimation. Values around zero (i.e.) are shaded grey and imply an equilibrium of perceived and actual ES supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

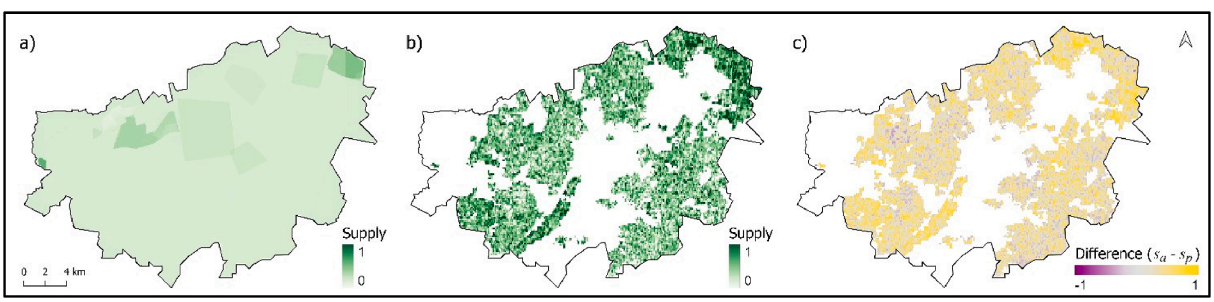

Fig. 5. Water Availability Supply derived from a) participatory supply assessment and b) biophysical supply assessment. Map c) shows the difference between the biophysical and the participatory supply assessment (), in which negative values of (purple) represent an overestimation of ES by the participants, whereas positive values (yellow) indicate an underestimation. Values around zero (i.e.) are shaded grey and imply an equilibrium of perceived and actual ES supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

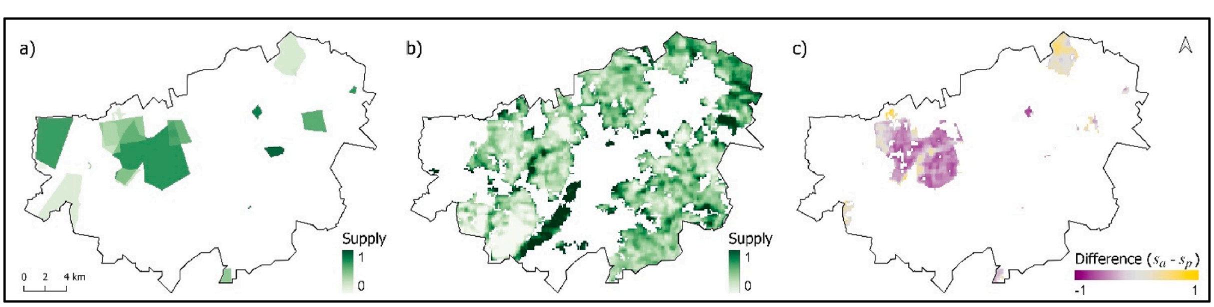

Fig. 6. Yield Supply derived from a) participatory supply assessment and b) biophysical supply assessment. Map c) shows the difference between the biophysical and the participatory supply assessment (), in which negative values of (purple) represent an overestimation of ES by the participants, whereas positive values (yellow) indicate an underestimation. Values around zero (i.e.) are shaded grey and imply an equilibrium of perceived and actual ES supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

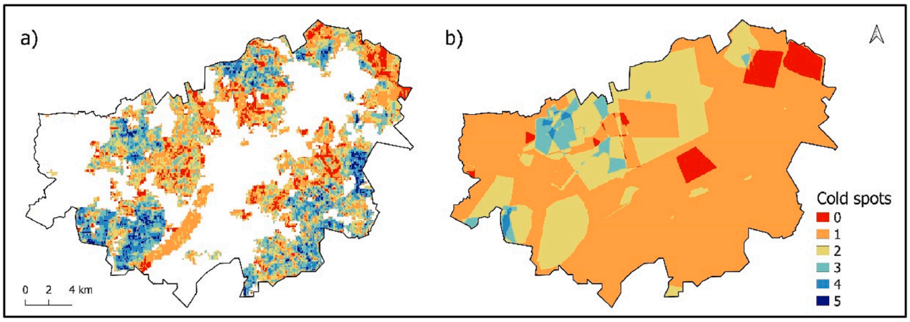

Fig. 7. Cold spots of ES in the biophysical assessment (a) and in the participatory assessment (b). The classes represent the numbers of ES cold spots for each raster cell.

between 1784 and the 1960s (Driescher, 1996). However, the surrounding deciduous forests with orchid occurrences in the fringe area of the wetlands have been declared protected areas since 1990. Crossed by the river Stobber and with natural forests surrounding the area, it is a habitat with a variety of animals from beavers and otters to birds and insects (Landesamt fuer Umwelt, 2022). This area scored above average values in biodiversity, carbon stock, water availability, erosion control and biomass yield in the biophysical assessment. In the participatory assessment, respondents identified Rotes Luch as being especially valuable in terms of erosion control. In the biodiversity mapping, only areas within the center of the Maerkische Schweiz nature park, with a high share of forests, were estimated to have a high supply, which is probably the reason the area of Rotes Luch is not particularly mentioned by stakeholders. A further observation is the absence of cold spots in the surrounding area close to the Maerkische Schweiz nature park. Even though these are also intensively used agricultural areas, ES generally score higher than 25 %. This is not particularly reflected in the stakeholder mapping, where most perceived high supply areas lie within the borders of the nature park.

Apart from the area surrounding the nature park, the North Eastern part of the study area exhibits relatively few cold spots. This area belongs to a larger area called Oderbruch and is characterized by fertile alluvial soils. Oderbruch was a wetland region prior to the 18th century, flooded by the Odra River approximately twice per year. The area was drained and repopulated during the time of the Prussian kingdom (Arbeitskreis brandenburgische Landesgeschichte, 2022). Participants identified this area as interesting but did not evaluate it as a particularly high supply area.

3.3. Stakeholder viewpoint

Stakeholders mentioned structural changes in the landscape through the intensification of agriculture as one major problem causing a decrease in ES supply and promoting the development of cold spots. A lot of smaller parts of the land were joined together in the era of land consolidation and reallocation of land, with the consequent reduction of crop diversity, uniform crop rotations, and the disappearing of niches for animals and plants. Key factors for the implementation of ES-based management measures mentioned by the stakeholders are trade-offs and systemic knowledge about the complexity of relationships between ES.

A lot of diversification measures were mentioned throughout the workshop that would lead to various benefits for multiple ES and facilitate the conversion of ES supply from cold to hot spots: the creation of synergies by defining holistic management goals focusing on multiple instead of single ES, guaranteeing economic support for regional, ES-based production value chains, limiting the number of livestock animals and, therewith, manure per hectare by implementing land-based animal husbandry, or the implementation of measures on a landscape instead of a field scale. Necessary changes in ES landscape management were generally identified in three different dimensions:

i) the technical dimension, with practical guidance for farmers on, for example, how to increase biomass and soil organic carbon production, insect-friendly mowing techniques or the creation of mosaic landscape structures with diversified crop rotations;

ii) the legal-political dimension, with the need for modified European Union common agricultural policy regulations that incentivize carbon sequestration measures, agroforestry and funding for regional circular flows of resources; and

iii) the social dimension, focusing on education and participation for stakeholders not involved in farming activities, in order to increase social acceptance and create a connection between inhabitants and land use decisions.

The potential use of combining biophysical assessments with PGIS was pointed out for participatory processes in workshops with technical guidance in regional development, for example, for the co-development of strategies or integrating the views of different actors' groups into landscape planning and decision-making in municipalities. However, it was also emphasized that technical guidance, for example, in the form of technical support with tools and direct advice in workshops, was critical.

4. Discussion

We aimed in this study to provide an assessment basis with two methodological benefits:

a) Integrating participatory data, assessed with participatory and biophysical methods. This was achieved with the normalized representation of ES indicators derived from a PGIS study respectively from secondary data at a resolution of 1 ha.

b) using bundles of ES in the assessment for the designation of cold spots that shows a scale-differentiated and spatially located representation of multiple ES in the same area. It became evident here for a) that ES-specific, differentially classified subareas could be delineated in a uniform manner. For planning exercises, this can facilitate the identification of potential intervention spaces at the cross-farm level, or the identification of trade-offs and synergies by displaying several ES within one case study area. However, even experts are easily overwhelmed by the challenge of understanding trade-offs of multiple ES in their spatial dimension, since the spatial extension of the processes behind the various ES differ. In order to discuss agricultural measures against this background together with stakeholders, it seemed essential to reduce the complexity. Accordingly, it became evident for b) that reducing the complexity via the cold spot analysis facilitated the analysis of causes for low ES supply, as we could show in an online stakeholder workshop. Further it led to the identification of useful management measures to convert cold spots into hot spots of ES supply.

4.1. Challenges in ES assessment

Uncertainties in ES assessments arise from different aspects. The focal source of uncertainty is the high complexity of social ecological systems (Hou et al., 2013). Neither the application of participatory nor spatially explicit methods can overcome this source of uncertainty since it addresses the fundamental challenge of human environmental systems. In order to frame research within this field of extreme insecurity and uncertainty, Hou et al. (2013) suggest accompanying ecosystem service assessments by uncertainty assessments, structured decision-making methods and an adaptive management framework: "As this framework builds on learning processes, it is not necessary to wait for new comprehensions and knowledge, but to learn by doing". This openness towards unexpected results is necessary to enable the paradigm shift towards an understanding of interwoven and nested socio-ecological systems, in which humans are not considered separate from their landscapes. When it comes to deciding what methods to apply, Harrison et al. (2018) found that a key consideration for choosing a method was the orientation of the research, i.e. decision-oriented research or stakeholder-oriented research.

Another aspect of our approach is dealing with the heterogeneity of ES in space. In the introduction, we referred to De Groot et al. (2020), who brings up the aspect of the spatial heterogeneity of ES provision in order to claim the consideration of different scales and the involvement of different stakeholders. The implementation of this requirement poses a methodological dilemma, which is the reason why trade-offs and synergies between different ES have so far been presented in many studies in aggregated form, i.e. not differentiated by ES-specific scale and spatial location. This is because the spatial extent of a functional area compartment is different according to the nature of the ES of interest: groundwater recharge for instance requires observations in large and areal compartments, while biodiversity can be estimated by punctual or linear interconnections between habitats. In order to avoid the dilemma, intervention-based scales are mostly chosen to represent trade-offs between ES, i.e. those areal units that are related to the management decision: plot, farm, administrative unit or landscape (Ungaro et al., 2014).

4.2. Advantages of combining biophysical and participatory assessment techniques

The low density of data from the empirical study on perceived ES supply must be recognized as a limiting factor for the robustness of these initial data. Nevertheless, it is interesting to note that stakeholder assessments indicated some understanding of ES-specific spatial-functional relationships or conditions. In particular, the normalized distribution was shown to facilitate the identification of spatial units with ES states that are equally ranked. Stakeholders proved interested and able to use the results for exactly the purpose intended by using indicators, and identify a relationship between causes and effects of management decisions at different scales. They particularly mapped many areas as being relevant for ES supply within the boundaries of the nature reserve. A special feature of our case study area is the spatial proximity of agricultural areas, nature reserves and residential areas. While the areas in the nature reserve were not part of the biophysical ES assessment, it is interesting that the agricultural areas surrounding the nature reserve show higher supply levels than those further outside. The positive effect of high value landscapes on surrounding areas has been well documented in ES research (Baker et al., 2013; Brudvig et al., 2009; Tscharntke et al., 2005). The PGIS results however underestimate the multiple ES provision at medium level (no cold spots) to some degree. This underestimation may be explained through the visual appearance of this particular landscape compartment, rapidly changing from high diversity in relief and land use in the nature reserve to rather uniformity at large scale in a cereals dominated cropping pattern in the adjacent plateau. It can be an indication that if land use is perceived to be very uniform, also the associated ES supply will be assessed rather low, even if actually provided higher. Accordingly, the biophysical assessment can with higher precision identify areas where several ES score higher or lower. However, comparing and combining these results with the awareness of stakeholders, e.g. for biodiversity within the nature reserve, can facilitate management planning for surrounding areas by integrating the knowledge of the stakeholders on the respective areas and the current management practices. Another example is that water availability is very uniformly assessed on a large scale (albeit uniformly underestimated), while smaller-scale and more nuanced assessments were mapped for biodiversity. Here, we see a methodological added value in the discussion initiated by De Groot et al. (2010), which, as was shown in the stakeholder workshop, can also be differentiated by various actors with the help of such maps. These can contribute to the development of requirement profiles for different decision-makers. Assessing not only one, but several ES in the same landscape with participatory methods could accordingly be shown to provide relevant qualitative and semi-quantitative information going beyond only academic interests. Stakeholders are able to bring this information into a problem–solution context, but this requires a concrete spatial representation of the data without a too high degree of detail.

4.3. Integrating ES assessment results in land use decisions

Especially the planning of management interventions e.g. collaborative measures, for the provision of ES at landscape scale (Kleijn et al., 2006), requires participatory approaches and the consideration of differentiated views and motivations of potentially involved actors (Barghusen et al., 2021). Different approaches on how to integrate participatory mapping in land use planning appear to be feasible: an unguided PGIS for all ES in a given landscape setting, but on a smaller scale than we did or with a markedly higher density of responses to all ES. An alternative would be a clear delineation of ES-specifically characterized sub-landscapes or a limited set of ES to be assessed through PGIS. The clear bottleneck we experienced in our research is the lack of systematically ordered allocation rules for the spatial patterns that favour the provision of the specific ES under different land management realities. And connecting the related scaling problems of ES-specific provision knowledge and management practices allocation (e.g. across plot and farm borders).

The participatory and biophysical cold spots analysis is a first appropriation to complexity in space that enables access to the knowledge context of stakeholders. We suggest hot and cold spot comparisons of ES clusters in different sub-landscapes as a valuable research issue, in particular in case of multi-stakeholder involvement. In any case a higher data density of the PGIS than we could achieve in our study would be essential. Finally, they may support visioning and discussing what landscapes management patterns of the future might look like when oriented along ES-specific bundles of interventions, such as those conceptually designed by Shaaban et al. (2021).

5. Conclusion

We addressed a twofold research gap, and were able to deliver the following new findings through this study: (i) We provide first insights into possibilities and limitations of comparing biophysical with participatory assessment techniques to assess ES and with indicator-based, spatially explicit methods for the same region. (ii) We exemplified how an integrated ES assessment with cold spot analysis can support agricultural landscape planning and management strategies. We suggest an approach that allows to compare science-based ES indicators, i.e. developed from geophysical data, to individual statements of the perceived status of ES. Hence, we deliver with this paper a methodological contribution to make the bias in assessment results geographically identifiable in terms of type and magnitude and, thus, discussable.

The spatial patterns mapped in the normalized representation of PGIS data of our study display some understanding of ES-specific spatial-functional relationships by the participants. In combination with our online workshop, we could show that stakeholders are able to bring this pattern identification into connection with cause-effect relations that led to the development of ES cold spots, and to conceptualize measures for increasing ES supply in these areas.

The possibilities to derive management recommendations based on the combination of biophysical and participatory methods depends on the data available, management objectives and resources available for the analysis. The methods chosen must, first and foremost, fit the research objective. The combination of methods can serve as a cross-validation of the results obtained in each assessment, if matches between biophysical and participatory data occur. The other way round, making use of local knowledge in landscape planning can help identify mismatches or conflicts that could arise when solely relying on biophysical assessments are made. We recommend considering a combination of biophysical and participatory assessments for landscape scale evaluations of ES.

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CRediT authorship contribution statement

Carmen Schwartz: Conceptualization, Data curation, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fabian Klebl:** Data curation, Visualization, Writing – review & editing. **Fabrizio Ungaro:** Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing. **Sonoko-Dorothea Bellingrath-Kimura:** Funding acquisition, Supervision, Writing – review & editing. **Annette Piorr:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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