Analyzing spatial patterns and dynamics of landscapes and ecosystem services – Exploring fine-scale data and indicators

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Abstract

Over the last decades, anthropogenic pressures on ecosystems have been increasing. Trends of land use change including urban expansion and agricultural intensification driven by population increase, and hence food and energy demand, cause environmental challenges including habitat and biodiversity loss. Analyzing major trends of land use change requires additional metrics to capture local processes on a landscape spatial scale. Increasing fine-scale data availability can support analyses of characteristics and processes of landscapes with the help of spatial metrics, e.g. distance or density measures. The aims of this thesis are to incorporate fine-scale data and spatial metrics to develop indicators to measure and assess land-use, ecosystem services (ESS) and their spatial patterns to answer the following questions: How can land use change and ecosystem services of landscapes be described and analyzed? And how can the landscape perspective contribute to our understanding of land systems? The thesis includes three case studies in two different world regions: 1) characteristics of land use within a peri-urban gradient in Dar es Salaam, Tanzania, 2) characteristics of agricultural landscapes in Brandenburg, Germany, and 3) ecosystem service relationships at different spatial units and scales. In both regions, landscapes are investigated with hexagons as spatial units. Hexagons include several advantages in contrast to rectangular grids including a regular surface with equidistant neighborhood relationships between cells. These advantages support the analysis of spatial patterns and relationships among different indicators (i.e., ESS) and conceptualize processes on a landscape level. Although some phenomena manifest at fine spatial scales, it is necessary to 'zoom out' for operationalization and monitoring of these processes. The landscape approach in context with ecosystem services offers important perspectives regarding environmental impacts caused by land use change. Thereby, metrics integrating the ecological, economic, and social dimensions can support obtaining region-specific knowledge on landscape dynamics and transferring this knowledge to decision-makers to design targeted measures towards sustainable land management.

Zusammenfassung

In den vergangenen Jahrzehnten hat der Einfluss des Menschen auf Ökosysteme stark zugenommen. Tendenzen der Landnutzungsänderung, darunter die Ausdehnung von Städten und die Intensivierung der Landwirtschaft als Folge des Bevölkerungsanstiegs und damit des Nahrungsmittel- und Energiebedarfs, führen zu Umweltproblemen wie dem Verlust von Lebensraum und biologischer Vielfalt. Eine Analyse relevanter Entwicklungen im Bereich des Landnutzungswandels erfordert zusätzliche Metriken zur Erfassung lokaler Prozesse auf der räumlichen Ebene von Landschaften. Die zunehmende Verfügbarkeit von Daten mit feiner räumlicher Auflösung kann die Analyse von Merkmalen und Prozessen in Landschaften mit Hilfe von räumlichen Metriken, z. B. Entfernungs- oder Dichtemaßen, unterstützen. Das Ziel dieser Arbeit ist es, feinskalige Daten und räumliche Metriken zu integrieren, um Indikatoren zur Messung und Bewertung von Landnutzung, Ökosystemdienstleistungen und deren räumlichen Mustern zu entwickeln und folgende Fragen zu beantworten: Wie können Landnutzungsänderungen und Ökosystemleistungen einer Landschaft beschrieben und analysiert werden? Und, wie kann die Landschaftsperspektive zu unserem Verständnis von Landsystemen beitragen? Die Arbeit umfasst drei Fallstudien in zwei verschiedenen Weltregionen: 1) Merkmale der Landnutzung innerhalb eines peri-urbanen Gradienten in Dar es Salaam, Tansania, 2) Merkmale von Agrarlandschaften in Brandenburg, Deutschland, und 3) Beziehungen zwischen Ökosystemleistungen in verschiedenen räumlichen Einheiten und Skalen. In beiden Regionen werden Landschaften mit Hexagonen als räumliche Einheiten untersucht. Hexagone bieten im Gegensatz zu rechteckigen Gittern eine Reihe von Vorteilen, darunter äquidistante Nachbarschaftsbeziehungen zwischen den einzelnen Zellen. Diese Vorteile unterstützen die Analyse von räumlichen Mustern und Beziehungen zwischen verschiedenen Indikatoren (z. B. Ökosystemdienstleistungen) und die Konzeptualisierung von Prozessen auf Landschaftsebene. Obwohl sich einige Phänomene auf feinen räumlichen Skalen manifestieren, ist es für die Operationalisierung und Überwachung dieser Prozesse notwendig, ‚herauszuzoomen'. Der Landschaftsansatz im Zusammenhang mit Ökosystemleistungen bietet wichtige Perspektiven im Hinblick auf Umweltauswirkungen, die durch Landnutzungsänderungen verursacht werden. Dabei können Indikatoren, die die ökologische, ökonomische und soziale Dimension verknüpfen, dazu beitragen, regionalspezifisches Wissen über Landschaftsdynamiken zu erlangen und dieses Wissen an Entscheidungsträger weiterzugeben, um gezielte Maßnahmen für ein nachhaltiges Landmanagement zu entwickeln.

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Chapter 1

Introduction

1.1 Scientific background

1.1.1 Land use change – causes and consequences

Globally, land systems have been shaped by human activities throughout the centuries. They provide services to a large and growing population, including the provision of food, fiber, timber, fuel, water, and space itself to live (Ellis et al., 2010). Underlying causes, or drivers, of land use and land cover change (LUCC) operate on different spatial and temporal scales (Lambin and Geist, 2006), ranging from local (e.g., topography, soil quality) to regional (e.g., climate) and global scales (e.g., macro-economy) and from shorter (e.g., market prices) to longer (e.g., policies, demographic change) time horizons. Human societies have transformed much of the earth's surface and are continuing to do so, enforced by rapid population growth. The global human population reached 7.7 billion in 2020[1] and continues to increase, leading to a simultaneous rise in the demand for food, fiber, and energy. Half of the habitable land is used for agriculture, leaving only 45% as (semi-) natural land (Ellis et al., 2010). Land systems are terrestrial social-ecological systems where human and environmental systems interact through land use (Meyfroidt et al., 2022). Land system science is explicitly concerned with understanding the causes and consequences of land changes (Geist et al., 2006), which include both shifts in land use and management (the purposes and activities for and through which humans influence the land), as well as changes in land cover (the physical properties of the vegetation and land surface) (Meyfroidt, 2016).

The European Landscape Convention (2000) defines a landscape as an area whose character is the result of the action and interaction of natural and/or human factors. Turner and Gardner (2015a: 3) define a landscape as 'an area that is spatially heterogeneous in at least one factor of interest.' This definition, originating in landscape ecology, is general and flexible, emphasizing the central focus on the effects of the spatial heterogeneity of pattern and process on ecosystem dynamics. A more holistic definition, similar to the definition of land systems, promotes a landscape as 'the total spatial and visual entity of human living space, integrating the geosphere with the biosphere and the nonspheric man-made artifacts' (Wu, 2019: 176). This definition of landscapes makes it directly relevant to sustainability research by referring to the totality of a regional landscape with all its environmental, economic, and social dimensions included.

[1] https://data.worldbank.org/indicator/SP.POP.TOTL (accessed: 1.3.2022)

Key benefits to human societies provided directly and indirectly by the ecological functioning of nature are defined as ecosystem services (ESSs) by the Millennium Ecosystem Assessment (2005). ESSs are produced by social-ecological systems that are managed and shaped by humans, geographic patterns, ecological structures and functions, biodiversity, management practices, and complex interactions between ecological and social dynamics (Raudsepp-Hearne and Peterson, 2016). Thereby, landscape heterogeneity contributes to the environment and ecosystem functioning with benefits for society (Fahrig et al., 2011).

One major challenge for designing landscapes is finding a balance between diverse ESSs under different and conflicting interests. Prior research has defined types of ESS relationships, including (1) trade-offs, where one ESS is reduced because of the increased use or supply of another; and (2) synergies, where multiple ESSs are enhanced simultaneously (Bennett et al., 2009; Lee and Lautenbach, 2016). These terms consider truly causal interactive mechanisms between ESSs (Vallet et al., 2018). If the changing dynamics between ESSs are not considered, the terms *conflicts and co-benefits* are more suitable for describing ESS relationships. A conflict indicates a static negative association between ESSs (Mouchet et al., 2014), whereas a co-benefit is defined as a similarly high occurrence of multiple ESSs at the same time. For instance, agricultural land use and management to produce food, fuel, and fiber (typically called provisioning ESSs) are largely driven by economic rationales, which often ignore impacts on regulating ESSs, such as the global and regional climate or habitat functions (Turkelboom et al., 2018).

Recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report (IPBES, 2019) added one key element built on the ESS concept, which is the notion of nature's contributions to people (NCPs). The NCP approach recognizes the central and pervasive role that culture plays in defining all the links between people and nature, and it elevates, emphasizes, and operationalizes the role of indigenous and local knowledge in understanding NCPs (Díaz et al., 2018). Another concept that directly considers the landscape level is the denotation of ESSs as landscape services. Thereby, landscape patterns emerge from landscape composition and configuration, which influence ecological processes and ecosystem functions and, consequently, ESSs (Duarte et al., 2018). The landscape services concept contains the idea that a complete landscape can provide services through multifunctionality in both natural and anthropogenically influenced habitats.

Globally, farmland continues to be diverted to urban development, industrial expansion, transportation networks, water management, biodiversity, leisure, tourism, and other demands (Dale et al., 2013). Thereby, newly developed urban areas, in particular, are subject to urban-rural linkages (e.g., flows of people and materials) with high dynamics in space and time. These peri-urban landscapes remain rather undefined, and the terminology remains vague with a variety of definitions (e.g., urban-rural interface, fringe, continuum, periphery, outskirts, hinterland, edgelands) (Laband et al., 2012; McGregor et al., 2006). Some studies describe the peri-urban as a type of land use or a land use dynamic, functioning as a 'divide' between city and countryside (the urban fringe theory; Surya 2016), while others refer to it as the dynamic and fast transformation of rural land into urban land (the sprawl approach; Iaquinta and Drescher 2000). Within research, peri-urban landscapes as a mosaic combining urban and rural land use remain rather underrepresented in land system archetypes (van Vliet et al., 2019).

In order to meet the growing demand for agricultural products, agricultural intensification is one of the major processes shaping land systems in the Global North. Agricultural intensification includes dense monocultures, high inputs of fertilizers and pesticides, the loss of native pastures, and intensive autumn sowings, likely contributing to the continued loss of native grasslands (Killion et al., 2018). Land use changes include the conversion of complex natural ecosystems to simplified managed ecosystems and the intensification of resource use, including the application of more agrochemicals and generally higher inputs and outputs (Tscharntke et al., 2005). Within agricultural landscapes, fields have been amalgamated and enlarged to enhance farming efficiency, resulting in homogeneously farmed landscapes with few non-crop areas. In Europe, the cereal yield almost tripled from 1960 to 2000 through increased fertilizer use and has been linked to 30% of the decline in the variation of European bird populations (Donald et al., 2001). At the same time, the decline in biodiversity may affect ecosystem functioning and yields. Studies suggest that landscape heterogeneity through, for example, crop diversification or the establishment of (semi-) natural elements, can increase crop production (Burchfield et al., 2019; Tscharntke et al., 2021). Another aspect of agricultural land use change is enforced by increasing demand for agricultural biomass for energy. Bioenergy can replace fossil fuels and contribute to greenhouse gas mitigation, the security of energy supply, and rural development (Immerzeel et al., 2014). However, the production of bioenergy crops can result in increased claims on land, competition with food production, and impacts on other ESSs. The growing biogas sector has led to a strong increase in the cultivation of energy crops, especially maize (Lüker-Jans et al., 2017).

In a landscape, land uses should be designed and ecosystems protected in such a way that the provision of goods and services is ensured in the long term without endangering biological diversity and ESSs and, at the same time, involves the best possible adaptation to and resilience towards climate change. Maintaining ecologically functional landscapes is critical for sustaining human well-being (Turner and Gardner, 2015a). While land use is essential for human societies, it is also becoming increasingly clear that the current global land use system is unsustainable. Transitioning to sustainable land use systems that will balance growing resource demands with the conservation of ecosystems and biodiversity is therefore a central challenge for science and society (Foley et al., 2011). In 2015, the United Nations established 17 Sustainable Development Goals (SDGs) within the 2030 Agenda for Sustainable Development (UN General Assembly, 2015). In particular, SDG 12 (Responsible production and consumption) and SDG 15 (Life on land) aim for sustainable production and consumption patterns as well as the sustainable use of terrestrial ecosystems. Other SDGs emphasize the need for action to combat climate change and its impacts (SDG 13), access to affordable, reliable, and sustainable energy for everyone (SDG 7), and resilient and sustainable human settlements and cities (SDG 11). The landscape perspective may play an important role when targeting these goals. However, the operationalization of these goals remains uncertain and calls for the regionally adapted development of indicators. An interdisciplinary perspective provided by land system science can support the design of these indicators for the assessment and monitoring of multifunctional land use. Multifunctional landscapes support multiple ESSs (e.g., productivity, habitat, regulatory, social, and economic functions) (Mander et al., 2007). Heterogeneous landscapes imply the capacity to support various, sometimes contradictory, functions simultaneously. The concept of multifunctional land use helps to merge economic, social, and environmental foci by emphasizing the rule that economic action is accompanied by ecological utility *per se*: commodity outputs (e.g., yields) are paid for in the market, but non-commodity outputs (e.g., landscape aesthetics) are public goods with no markets (Wiggering et al., 2006).

Since the 1970s and 1980s, society has paid greater attention to natural capital and the non-productivity issues of landscapes and ecosystems and seeks to decouple economic growth from environmental degradation (Costanza et al., 1997). For example, within the European Union (EU), this has implications for policy design in terms of defending environmental and social assets against the extreme consequences of structural change on farms. The EU's Common

Agricultural Policy (CAP) has the potential to improve measures looking to maintain and restore semi-natural habitats and landscape elements, such as pastures, meadows, trees, hedgerows, forest patches, ponds, and field margins, in agricultural landscapes based on their value for biodiversity, pollination, and the natural biological control of pests (Biodiversa, 2017).

1.1.2 The role of spatial scales in analyzing land systems

Spatial scales in land system science range from the local to regional and global levels. Thereby, land use or ESS patterns are influenced by the characteristic scales of the underlying processes and the scale of observation, which can have major implications for how a system is understood and managed. The scale of observation determines the relative fineness or coarseness of details and patterns that are observed (Raudsepp-Hearne and Peterson, 2016). The spatial analysis scale (or methodological scale) denotes the unit size used for aggregation (Westerholt et al., 2015), which is described based on its extent and resolution. The extent refers to the magnitude of a dimension used in measuring (e.g., the area covered on a map), whereas the resolution refers to the precision used in this measurement (e.g., the grain size) (Verburg et al., 2004). When analyzing land systems, there is no single 'right' scale (Turner and Gardner, 2015a). The appropriate scale depends on the question being asked and the processes being studied. One fundamental dilemma is the modifiable areal unit problem (MAUP), which describes the susceptibility of the results of cartographic or statistical analyses and any form of spatial modeling to the definition of the spatial units under study (Wu, 2004). Therefore, scale effects must be considered carefully since scale mismatches often result in misleading, contradictory, or wrong answers (Turner and Gardner, 2015a). In general, since the hemeroby of landscapes should be considered, spatial scales of less than a certain resolution (e.g., grid sizes) seem less useful because otherwise nearly individual geographical objects are analyzed (Walz and Stein, 2014).

The spatial level of landscapes often retains a general definition that does not require an absolute scale (Turner and Gardner, 2015a). The appropriate scale (extent) depends on the landscape characteristic under evaluation and the specific objective of the analysis (Karau and Keane, 2007). At the landscape level, the individual land use and land management decisions of multiple land users and planners manifest themselves in terms of land use and land cover changes (Plieninger et al., 2016; Selman, 2006). The increasing attention gained by 'landscape approaches' in land system science can be seen as an expression of the relevance landscapes

have gained as an access point for the analysis of sustainability issues and the making of policy, governance, and management more space and scale sensitive (Arts et al., 2017; Bürgi et al., 2022). Landscape approaches embrace an integrated land-sharing philosophy as an alternative to conventional, sectorial land use planning, policy, governance, and management (Arts et al., 2017). Advantages of this integrated approach include the ability to address the interests of multiple (competing) sectors (e.g., nature conservation, agriculture, urban development, or the livelihoods of people). Moreover, landscape approaches attempt to overcome the classical - often objectivist, naturalist, and static - interpretations of landscapes and present relational, embodied, and dynamic alternatives.

Regarding the spatial units of analysis (UoAs; i.e., the level of aggregation), a multitude of reference units exists. First, administrative units are often used since they are the focus of policy, planning, and the target level of policy implementation (e.g. municipalities, counties, and countries). However, administrative units are rarely bound to the natural environment and are defined by irregular boundaries with different area sizes and shapes between single units, which might change over time (e.g., census blocks). Second, regular grids provide a geometric base independent from administrative or natural boundaries and include rectangular, square, triangular, or hexagonal shapes. By nature, remotely sensed data products are stored as pixels, whereby a fishnet grid becomes easily available as the aggregation level. Over the past years, hexagons have gained interest and importance due to their numerous advantages, including their potential for providing appealing visualizations (Birch et al., 2007). Hexagons offer some advantages related to being closer in shape to circles than squares. The centroids of single hexagons are equidistant from each other, and each reference unit has the same number of neighbors (N = 6), independent from the neighborhood contiguity definition (unambiguous uniform adjacency). In contrast, fishnet grid cells have a different number of neighbors if accounting for edge and/or corner neighbors. Furthermore, cells in a hexagonal grid are aligned along three axes rather than just two, so the outlines of groups of cells in a hexagonal grid form more varied, less rectilinear shapes than groups of cells in a rectangular grid (Birch et al., 2007). Third, natural units, such as watersheds, pedons, or plant communities, are the focus of studies analyzing land use change or landscapes (Cullum et al., 2017).

1.1.3 Metrics to describe landscapes and ecosystem services

There is a pronounced demand for indicators to measure progress towards policy aims. Within this thesis, an indicator, different to a single metric, is a measure or component from which conclusions regarding the phenomenon of interest (the *indicandum*) can be inferred (Heink and Kowarik, 2010). Within landscape ecology in particular, indicators have been seen as a potential tool for comparing landscapes across space or in time, such as when monitoring landscape change, and for linking ecological processes to a spatial dimension (Dramstad, 2009). Indicators for landscape analysis, ecology, and related fields are often categorized into thematic groups since aggregating into more general groups can facilitate stakeholders' understanding of landscape management (Duarte et al., 2018). For example, landscape indicators can be grouped into categories of landscape structure (i.e., composition, configuration, or management). Composition refers to the number and proportion of land cover/use types in or of a landscape or farm, while configuration describes the spatial arrangement of land cover/use types (Fahrig et al., 2011). Management (outcomes) covers practices or the outcomes of practices that clearly refer to individual behavior.

The combination of a landscape's configuration and composition allows for the quantification and assessment of landscape heterogeneity. Landscape metrics were developed in the late 1980s as incorporated measures from both information theory and fractal geometry (Herold et al., 2005). Based on the number, size, shape, and arrangement of patches of different land use/land cover types, they can be successfully used as indicators of landscape heterogeneity (Lausch and Herzog, 2002; Uuemaa et al., 2013). The quantification of spatial heterogeneity is a key topic in landscape ecology due to its influence on many ecological processes (Walz, 2011). Heterogenous landscapes can provide multiple ESSs through multifunctionality. However, analyzing landscapes through indicators of landscape patterns and ESSs requires an awareness of the metrics' interrelationships (Duarte et al., 2018). After the introduction of landscape metrics, many metrics are available for quantifying landscape patterns, many of which are correlated with one another (Uuemaa et al., 2009). While one metric is insufficient in characterizing a landscape, determining how many and which ones to use must be based on the questions or objectives of a study and well justified by the analyst (Turner and Gardner, 2015b). Furthermore, many metrics are sensitive to changes in the spatial resolution of the data or the area (extent) of the landscape (Uuemaa et al., 2009), and the downscaling and upscaling of

landscape metrics as functional and structural landscape indicators on different scales create a challenge (Mander et al., 2005).

The application of spatially explicit methods that incorporate the locations of the supply and demand of ESSs represents a key challenge for research, and there is the necessity to develop and test different approaches to quantify and (jointly) map different services across the landscape, highlighting 'hotspots' with synergies and conflicts (Ungaro et al., 2014). Under the name of landscape metrics, spatial metrics are already commonly used to quantify spatial heterogeneity and ESSs in landscapes. Within this thesis, spatial metrics specifically refer to spatially explicit metrics, which depend on the location and/or spatial relation of geographical objects (e.g., distance or density metrics). In addition, the measurement, analysis, and interpretation of spatial patterns receive much attention in landscape ecology (Uuemaa et al., 2009). For instance, spatial autocorrelation measures, such as Moran's I or join count statistics, were quickly assimilated in the ecological sciences for quantifying and assessing spatial patterns of ecological data (Fortin et al., 2001). A characterization of the shape, size, and spatial arrangement of different habitat patches within a landscape can be used to connect the detected spatial patterns to the driving forces generating them, such as natural ecological processes or human management practices (Plexida et al., 2014).

1.2 Motivation and study regions

1.2.1 Integrative measures for landscape analysis

Land use and land cover change can be conceptualized as a macro-level manifestation of micro-level behavior (Verburg et al., 2004; Wu et al., 2004). However, not least due to data limitations, much of the existing empirical research on LUCC determinants focuses on macro-scale dynamics. In the past, classifications and typologies were often conducted on large spatial scales (Levers et al., 2018; Oberlack et al., 2019), often linked with administrative boundaries. Despite this, there is a lack of unified (landscape) definitions (e.g., peri-urban, agricultural). In addition, (agri-) environmental policies seldom adopt or target the landscape perspective. At the same time, determinants of spatial dynamics in landscape structure, but also relationships with and between ESSs, such as habitat provision or the production of fuel, fiber, and food, remain poorly understood (Crossman et al., 2013; Vallet et al., 2018).

Incorporating fine-scale spatial data can provide additional information, which can contribute to a better understanding and conceptualization of landscapes with regard to explicit spatial features. Therefore, the generation and assessment of integrative metrics that combine ecological, economic, and social dimensions to monitor and support governance are needed. Spatial analyses through spatial metrics or statistics have advanced tremendously during the 2000s, and integrating different approaches to quantify spatial patterns - especially the degree to which they provide complementary and/or unique insights into landscape patterns - remains a priority (Turner and Gardner, 2015a). To analyze landscapes and ESSs in a spatially applied and explicit manner, two study regions were chosen to represent two different landscapes, which are described in the following.

1.2.2 Dar es Salaam as an example for studying peri-urban landscapes

Dar es Salaam provides an interesting case to study highly dynamic peri-urban landscapes. This city located on the eastern coast of Tanzania is one of the fastest growing cities in the world, with a projected population increase of 100% from 2020 (estimated population of 6,702,000) to 2035 (13,383,362)[2]. Rapid population growth has led to substantial changes in the city's spatial pattern and land development (Kombe, 2005). At the same time, urban expansion is driven by a number of other factors, including internal migration, transport and communication, or agglomeration policies (Lupala, 2021). The process of urban expansion is partly affected by informal and unplanned growth, which especially challenges the access to basic services. In fact, unplanned settlement agglomerations may not provide enough space to establish sufficient infrastructure services or community facilities. The peri-urban areas in Dar es Salaam are characterized by large sections with this informal and/or unplanned growth. Emerging spatial patterns are driven by individual efforts to secure land to construct buildings (Lupala, 2021). This unplanned spatial expansion has led to a mismatch between the established (or rather unbalanced) infrastructure and services and planning guidelines.

The spatial growth of Dar es Salaam has mainly followed a star-shaped pattern. Following the ribbon and village magnet theories (Doan and Oduro, 2012), expansion typically starts around smaller villages or scattered settlements, most often under customary tenure, and along major roads. While the spatial extent of Dar es Salaam was only 17 km in radius from the city center in 2002, this had extended to 30 km by 2012 (Lupala, 2021). Urban expansion transformed

[2] https://worldpopulationreview.com/world-cities/dar-es-salaam-population (accessed: 28.01.2022)

sparsely populated rural or peri-urban areas, dominated by bush and agricultural land use, into more densely developed residential areas (Andreasen, 2016). Therefore, the peri-urban areas have extended beyond the administrative boundaries of Dar es Salaam, generating additional administrative challenges with regard to planning. In addition, the rapid increase in unplanned settlement development has put Dar es Salaam's mobility system under pressure, characterized by inadequate road networks, insufficient public transport, and severe congestion problems (Melbye et al., 2015). Increasing car ownership rates, along with the transformation and densification of central areas with high-rise commercial buildings, have further increased this pressure.

Other challenges that emerge from (unplanned) spatial expansion are natural habitat fragmentation and deforestation (John and Kagembe, 2022). Alongside decreasing biodiversity, peri-urban landscapes are vulnerable to the occurrence of disasters in the context of climate change (e.g., the increasing risk of floods and wildfires or soil degradation) (Lupala, 2021).

1.2.3 Brandenburg as an example for studying agricultural landscapes

Brandenburg provides a suitable study area for analyzing agricultural landscapes due to its high share of agricultural land use, relatively low overall soil quality, intensive management, and high share of maize cultivation. With regard to the federal state of Brandenburg, Germany, 45% of its area is covered by agricultural land and characterized by large farm sizes, high technological levels, yield limitations based on water supply and low soil fertility, and subsidies for agricultural energy production. Brandenburg's agricultural landscapes are typical of large-scale post-socialist agriculture, with an average physical farm size of 240 ha (Uthes et al., 2020). Compared to the German average cereal yield per area (68.2 dt/ha), cereal yields are very low (46.9 dt/ha) in Brandenburg (Amt für Statistik Berlin-Brandenburg, 2019). Agricultural production is limited by the annual precipitation (450 to 600 mm per year with frequent periods of drought) and by the predominance of loamy sand or sandy loam soils (Glemnitz et al., 2015). The demand for irrigation water increased by 180% in the period from 1998 to 2004 (Drastig et al., 2011), and this tendency is expected to continue due to the high risk of drought and the potential improvement in profit margins for energy crops (Glemnitz et al., 2015). The dominant crop species are maize, rye, winter wheat, and winter rape (Troegel and Schulz, 2018).

The financial promotion of renewable energy, which was introduced in 2004, has resulted in the intense growth of technical capacities for producing energy from biomass in agriculture and in maize becoming the predominant crop species (Glemnitz et al., 2015; Troegel and Schulz, 2018). Although one third of the agricultural area is already contained within conservation areas, the biodiversity of Brandenburg is under severe threat due to intensive land use and the increasing use of pesticides and fertilizers and the rise in water pollution and eutrophication and drainage (Drastig et al., 2011; Venghaus and Acosta, 2018). Compared to the German average, Brandenburg's agriculture consists of relatively high shares of organic agriculture (12.3% in 2018)[3]. In addition, Brandenburg drafted an agri-structural mission statement ('Agrarstrukturelles Leitbild'; Schillemeit 2021), which emphasizes the importance of ecological and cultural soil functionalities. While aiming for sustainable agriculture, it suggests strengthening regional supply chains and social aspects (creating and securing jobs) and promoting special forms of cultivation and production (meeting the requirements of environmental, soil, water, and climate protection and biodiversity). The mission statement highlights these aims while considering changing land markets in the region. From 2007 to 2019, purchase prices for agricultural land in Brandenburg increased almost fourfold, while lease prices increased about twofold over the same period (Schillemeit, 2021). Approximately 25% of agricultural land transferred to new owners in recent years was acquired by non-farmers, demonstrating the competitive situation between agriculture and other land uses, particularly settlement development.

In the European context, a number of (agri-)environmental policy measures are in place to align the production of food, fuel, and fiber with the provision of regulating ESSs (Gocht et al., 2017). However, other sectoral policies, such as Germany's Renewable Energy Sources Act (*Erneuerbare Energien Gesetz*, EEG), have also been shown to affect LUCC patterns (Britz and Delzeit, 2013; Csikós and Szilassi, 2020) with adverse effects on the provision of ESSs by landscapes (Gutzler et al., 2015; Jerrentrup et al., 2017; Sauerbrei et al., 2014). At the national and subnational levels, regionally differentiated policy impacts can, for example, result from land zoning policies and the siting of nature conservation areas (Hoffmann et al., 2018; Meyer et al., 2021).

[3] https://lelf.brandenburg.de/lelf/de/landwirtschaft/acker-und-pflanzenbau/oekologischer-landbau/ (accessed: 13.3.2022)

1.3 Conceptual framework

1.3.1 Research questions

The overarching aim of this thesis is to better understand landscapes and their spatial patterns that arise from underlying environmental and LUCC processes. Designing and monitoring sustainable land use pathways require a better understanding of land systems and spatial dynamics of landscapes, which contribute to ecological transformation and multifunctionality. Therefore, this thesis targets the following two overarching research questions.

Research Question I*: How can land use change and ecosystem services of landscapes be described and analyzed?*

A better understanding of land systems requires the integration of the landscape level while determining spatially explicit characteristics of the landscape structure and ESSs it provides. Accounting for heterogeneous geographies of different study regions can improve the understanding of landscapes and their spatial reference scale(s) while allowing the incorporation of the specific character of regional land use change processes. Within landscapes, multiple actors and decision makers, pursuing different and sometimes conflicting interests, interact. ESS supply and relationships at the landscape level are influenced by the actors' decisions. Knowing how and where ESSs conflict or co-benefit each other can inform decision makers on how to design targeted measures towards sustainable land management. In order to design sustainable and multifunctional landscapes, integrative measures are needed to maintain, at the same time, ecosystem functionality and the provision of ESSs for human needs, leading to research question II.

Research Question II*: How can the landscape perspective contribute to our understanding of land systems?*

Landscapes represent an essential spatial scale for studying and practicing sustainability because they integrate human-environment interactions and link local processes below and global patterns above. The landscape perspective provides a common platform for scientists, land designers/planners, policymakers, and stakeholders to collaborate on sustainability issues that resonate with all. Knowing how landscapes are structured and where differences and similarities occur can inform decision makers in terms of designing regionally adapted measures towards more sustainable land management. This particular landscape perspective is

relevant due to the interaction and management decisions of the multiple actors included. Thereby, decision-making processes at the landscape level remain manageable, but the spatial reference is large enough to accommodate the different interests of actors and stakeholders. The conceptualization of landscapes with dynamic spatial patterns allows for reducing complexity while integrating spatially explicit information. Answering the research questions can be useful for deepening knowledge about land systems and thus provide decision makers with tools and perspectives regarding context-specific land management policies.

1.3.2 Objectives and workflow

This thesis explores the landscape perspective using two study regions. Addressing the goals of the research questions is challenging due to different regional heterogeneities and (fine-scale) spatial data availability. To explore spatially explicit and exemplary landscapes, the case samples focus on the characterization of peri-urban (in Dar es Salaam, Tanzania) and agricultural (in Brandenburg, Germany) landscapes. Each of the four objectives relates to one research question (Figure 1.1). The two objectives used to answer research question I were as follows:

Objective 1) *Identify integrative metrics/indicators for the spatially explicit description of landscapes and ESSs*

Objective 2) *Identify and map spatial patterns of landscape structure, ESSs, and their relationships*

Objective 1 targets obtaining region-specific knowledge to find integrative measures for describing landscape structure, ESSs, and their relationships. In addition to scientific literature, qualitative research methods, such as expert interviews, can improve knowledge on local decision making and land management. Incorporating this knowledge and to subsequently analyze landscape structure and ESSs, (spatial) metrics were created, and indicators were identified. Objective 2 focuses on the spatial dynamics of the metrics, indicators, ESSs, and their relationships. In addition, the spatial scale sensitivity of ESSs and their relationships was analyzed for different spatial units of analysis of agricultural landscapes. Within this scale sensitivity analysis, differences between administrative reference units and regular grids (hexagons) can be identified.

The main objectives used to answer research question II were the following:

Objective 3) *Map metrics/indicators at the landscape level from fine-scale data*

Objective 4) *Identify and conceptualize landscapes/landscape characteristics and ESS relationships*

Based on the outcomes of objective 1, objective 3 targets calculating and mapping metrics and indicators using (open-source) fine-scale spatial data to describe landscape structures and ESSs. In order to fulfill objective 4, the metrics were conceptualized by applying different methods. To describe peri-urban landscapes and their dynamics, a gradient approach was used and applied to the study region. Agricultural landscapes were characterized using a cluster analysis to obtain agricultural landscape types. Additionally, ESS relationships within agricultural landscapes were analyzed using bivariate choropleth maps.

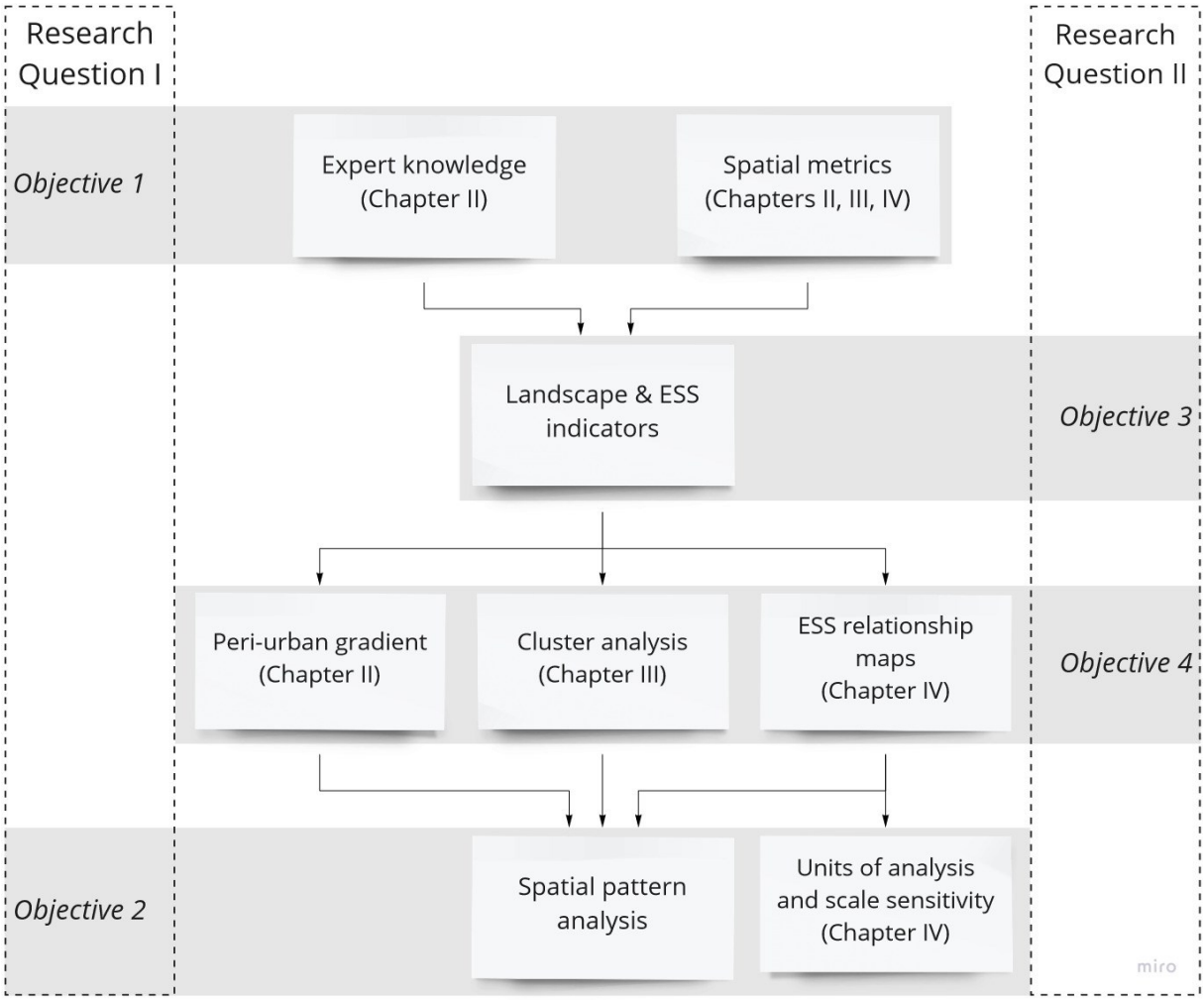

Figure 1.1: Thesis workflow illustrating the relations between the research questions (dashed boxes), objectives (gray boxes), and methods (white boxes)

1.3.3 Thesis structure

This thesis consists of five chapters. Chapter I, the introduction, serves the wider framing in the scientific literature and motivates the research questions and objectives, which relate to the following three core research chapters (Chapters II-IV). Each of the three chapters was written as a stand-alone manuscript, which has either been published in or submitted to an international, peer-reviewed journal. The thesis concludes with a synthesis section (Chapter V), which summarizes the answers to the research questions and presents more general conclusions and implications and provides an outlook for future research.

Chapter II Wolff, Saskia; Mdemu, Makarius V.; Lakes, Tobia (2021): Defining the Peri-Urban: A Multidimensional Characterization of Spatio-Temporal Land Use along an Urban–Rural Gradient in Dar es Salaam, Tanzania. In: *Land* 10 (2), S. 177. DOI: 10.3390/land10020177.

Chapter III Wolff, Saskia; Hüttel, Silke; Nendel, Claas; Lakes, Tobia (2021): Agricultural Landscapes in Brandenburg, Germany: An Analysis of Characteristics and Spatial Patterns. In: *Int J Environ Res* (15), S. 487–507. DOI: 10.1007/s41742-021-00328-y.

Chapter IV Wolff, Saskia; Hüttel, Silke; Verstegen, Judith; Lakes, Tobia (under review): Ecosystem Service Relationships and Scale Sensitivity of Agricultural Landscapes in Brandenburg, Germany. *Agriculture, Ecosystems and Environment.*

Chapter 2

Defining the Peri-Urban: A Multidimensional Characterization of Spatio-Temporal Land Use along an Urban–Rural Gradient in Dar es Salaam, Tanzania

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Abstract

Highly dynamic peri-urban areas, particularly in the Global South, face many challenges including a lack of infrastructure, ownership conflicts, land degradation, and sustainable food production. This study aims to assess spatial land use characteristics and processes in peri-urban areas using the case of Dar es Salaam, Tanzania. A mixed-method approach was applied, consisting of expert interviews and spatial data analysis, on a local scale along an urban–rural gradient. Expert interviews were conducted during a field study and analyzed regarding the characteristics and processes of peri-urban land development. A GIS-based analysis of land use patterns was applied using satellite imagery and Open Street Map data to identify a number of variables, such as building density and proximity to environmental features. Results show specific patterns of land use indicators, which can be decreasing (e.g., house density), increasing (e.g., tree coverage), static (e.g., house size), or randomly distributed (e.g., distance to river), along a peri-urban gradient. Key findings identify lack of service structures and access to public transport as major challenges for the population of peri-urban areas. The combination of qualitative expert interviews and metrics-based quantitative spatial pattern analysis contributes to improved understanding of the patterns and processes in peri-urban land use changes.

2.1 Introduction

With increasing urbanization and over half of the world's population living in cities, urban areas and their inhabitants face many challenges, including socio-economic and ecological changes (United Nations Human Settlements Programme, 2014). Urban growth spreading into peri-urban areas is a key driver of unsustainable development (Nilsson et al., 2013), and in Sub-Saharan Africa, local and regional governments face difficulties in monitoring and addressing urban expansion. Significant demographic pressure is expected in Dar es Salaam, for example, where approximately 226,000 new urban dwellers are expected annually (United Nations Human Settlements Programme, 2014). Dar es Salaam has exceeded Nairobi as Eastern Africa's largest city. Urban food security is critical and contributes to the increasing pressure on peri-urban areas that are important for urban food provision and undergo the transition from agricultural lands into residential areas (Karg et al., 2019; Nuhu, 2019). In the less-developed world, urbanization surpasses all other uses for land adjacent to the city, including prime croplands (Lambin et al., 2001).

The ways in which nations define what is urban and what is rural can vary significantly; the boundaries of urban settlements are not as clearly defined as the administrative delimitations (Schlesinger and Drescher, 2018). Doan and Oduro (2012) introduced the village magnet hypothesis, whereby peri-urban development appears to be attracted to pre-existing villages that already have basic levels of critical services. Hence, they often become the nuclei of fast-growing, densely populated pockets. However, Dar es Salaam has also developed along highways and major roads, as per the ribbon hypothesis (Doan and Oduro, 2012). Peri-urban areas are lacking a precise definition and a comprehensive approach or framework: the terminology remains vague with a variety of definitions (e.g., urban–rural interface, fringe, continuum, periphery, outskirts, hinterland, edgelands) (Banu and Fazal, 2016; Laband et al., 2012; McGregor et al., 2006; Meeus and Gulinck, 2015; Zasada, 2011; Zasada et al., 2013). Some studies describe the peri-urban as a type of land use or a land use dynamic, functioning as a 'divide' between city and countryside (the urban fringe theory) (Banu and Fazal, 2016; Surya, 2016). Others refer to it as the dynamic and fast transformation of rural land into urban land (the sprawl approach) (Dekolo et al., 2015; Iaquinta and Drescher, 2000). According to Ravetz et al. (2013), peri-urban areas are often understood to be mixed areas under an urban influence but with a rural morphology from a European perspective, whereby in the Global South, the 'peri-urban interface' relates to newly urbanized zones at the fringes of cities. In light of enhancing sustainable development of (urban) areas, peri-urban zones play a critical role at

a global level (Wandl and Magoni, 2017). Due to the complex characteristics of peri-urban areas, studies have addressed multiple dimensions of spatial change, mobility, identity, and economic activities (Gonçalves et al., 2017; Shaw et al., 2020). Approaches describing and defining the urban–rural interface range from focusing on morphology and land use characteristics to socio-economic or cultural transitions (Laband et al., 2012; Shaw et al., 2020; Tacoli, 1998; Zivanovic-Miljkovic et al., 2012). Although the dynamics and characteristics of peri-urban areas and processes might be regionally specific (Mbiba and Huchzermeyer, 2002; Nagendra et al., 2018), conceptual models of patterns and dynamic trends can be applied independently from regional specifics. Globally, a substantial amount of studies particularly trends to incorporating spatial metrics and analysis to develop such concepts (Appiah et al., 2015; Banzhaf et al., 2009; Mpofu et al., 2018; Shaw and Das, 2017). However, the understanding and conceptualization of processes in studies with, e.g., European focus have usually limited transferability to regions of the GS (Nagendra et al., 2018).

The inherent complexity of the peri-urban areas puts the traditional duality of rural vs. urban areas in question (van Vliet et al., 2019). Laband et al. (2012) emphasize that the urban–rural dichotomy is still deeply embedded in the field and suggests a more open discussion and the eventual adoption of a continuum or gradient approach. Pryor (1968) previously described the peri-urban as a landscape phenomenon, in which the fringe varies between cities and over time. The peri-urban is mainly characterized as a hybrid transitional zone, combining urban and rural conditions (Andreasen et al., 2016), forming a new type of multi-functional territory (Nilsson et al., 2013).

According to Nilsson et al. (2013), there are common features wherever peri-urban areas are found, such as a relatively low population density (by urban standards), scattered settlements, high dependence on transport for commuting, fragmented communities, and lack of spatial governance. Particularly in the context of Africa, studies often refer to the importance of urban fringe agriculture and rural linkages (Andreasen et al., 2016; Laband et al., 2012). According to Chirisa et al. (2016), the problem of conceptualizing the peri-urban interface has been implicit in development policy studies in developing countries for several decades. More recently, attention has been focused on the emergence of formal and informal land markets and the related land use changes in peri-urban areas (van Vliet et al., 2019). Studies with spatial reference to Dar es Salaam mainly focus on urban expansion along the urban–rural gradient, in relation to agriculture, transport, and policies (Bhanjee and Zhang, 2018; Briggs and

Mwamfupe, 1999; Eckert, 2011; Kombe, 2005; Lupala, 2002; Mkalawa and Haixiao, 2014; Msangi, 2011).

Although the majority of peri-urban research has focused on the global North (Europe and North America), Nilsson et al. (2013) have emphasized the arising global challenges of peri-urbanization, particularly in the Global South (GS). A number of studies have investigated the land use dynamics of African cities and peri-urban regions (Karg et al., 2019; Kombe, 2005; Mbiba and Huchzermeyer, 2002; Nuhu, 2019; Willkomm et al., 2019), as well as the challenges posed by rapid urbanization, particularly food insecurity or land degradation (Wenban-Smith, 2014) and the spatial patterns of informal growth and interdependencies of city centers and peri-urban settlements (Kombe, 2005). However, there is a lack of information on the characteristics of the spatio-temporal processes of the peri-urban: these data are urgently needed for an improved understanding, particularly for cities in the GS (Lerner and Eakin, 2011).

Previous studies have included spatial indicators, such as land cover, access to public transport, road density, distance to roads, building density, or travel time (Bhanjee and Zhang, 2018; Karg et al., 2019; Kleemann et al., 2017b; Schlesinger and Drescher, 2018). Developing strategies to understand and monitor these changes are also in line with the Sustainable Development Goals (United Nations Sustainable Development, 2015). The city of Dar es Salaam in Tanzania is committed to the development of sustainable cities and communities under the Sustainable Development Goals. The need for ongoing research for understanding characteristics and processes, in combination with analyzing land use change, is crucial in peri-urban areas, particularly in the GS, where population numbers and urbanization is rapidly increasing. This rapid population growth drives urban expansion, with unregulated development leading to challenges in regulation, control, and monitoring.

The aim of this study is to characterize the patterns and underlying processes of the spatio-temporal dynamics of the peri-urban area in the GS. We identify and analyses indicators using a gradient approach in order to answer the following questions: (1) What are spatio-temporal characteristics and patterns of peri-urban areas? (2) How can dynamics along a peri-urban gradient be generalized and conceptualized? While we show the processes along a case-study specific peri-urban gradient, the methodology and conceptual conclusions may be transferred to other regions. The case of Dar es Salaam is investigated, with the focus on a peri-urban gradient in the Msongola ward. An urban–rural gradient was chosen that includes the former peri-urban and more urbanized areas, as well as sparsely populated areas within the Dar es

Salaam region representing different stages of peri-urbanization with heterogeneous spatial and temporal dynamics.

We followed a workflow of combining qualitative and quantitative approaches. In particular, we conducted expert interviews to explore characteristics and processes within the peri-urban followed by spatial pattern analysis of a selected set of characteristics quantified through indicators including socio-economic and environmental indicators. Finally, we propose trends of dynamics to generalize peri-urban characteristics and processes.

2.2 Methodology

2.2.1 Study Area

Dar es Salaam was selected for this study because it is one of the most rapidly growing East African cities, with a population of 4,364,541 in 2012 (last census) to projected 5,017,294 in 2017 (National Bureau of Statistics, 2017; National Bureau of Statistics and Ministry of Finance, 2013). The city is located on the eastern side of Africa, bordered by the Indian Ocean (Figure 2.1). Since its independence (1961), Dar es Salaam has been the dominant business and industrial center of Tanzania (Mkalawa and Haixiao, 2014). It has a radial structure and grows outwards following the main infrastructure lines of the water supply, electricity and major roads (Msangi, 2011). Since the 1970s, the city has been growing rapidly without adequate planning and enforcement regulations (Hill et al., 2014). The majority of unplanned settlements in the urban periphery lack service infrastructures. Msongola ward, within the Ilala district of the Dar es Salaam region, was chosen as the case study area (Figure 2.1). The ward represents a peri-urban gradient, with a rapidly growing population (2002: 7268; 2012: 24.461), a relatively low population density (2012: 3762/km^2) (National Bureau of Statistics and Ministry of Finance, 2013), and a change in characteristics from urbanized residential zones to rural areas in the periphery. The administrative area of 65 km^2 was overlaid by a hexagonal grid (cell size 1 km^2), resulting in an extended study area of 98 km^2.

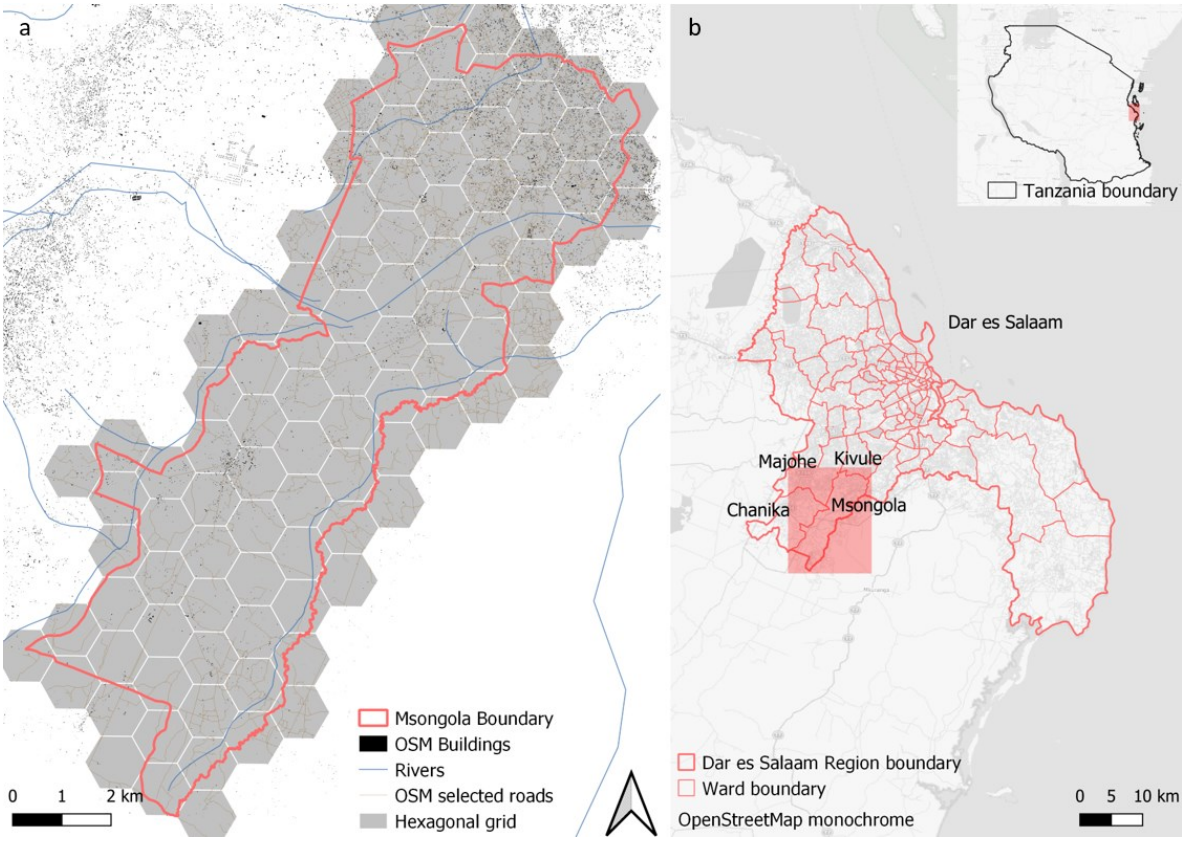

*Figure 2.1: Study region of Dar es Salaam with (**a**) Msongola ward details with data including rivers, roads, and buildings and hexagonal grid overlay (1 km²) and (**b**) Location of Msongola ward in the city of Dar es Salaam.*

2.2.2 Data

The following open-source data was used: OpenStreetMap (OSM) and remote sensing images from Sentinel 2 (ESA CCI LAND COVER, 2016; OpenStreetMap contributors, 2018). OSM can be accessed and used for free by anyone and for any purpose, which makes it a viable data source when availability and access to geoinformation is limited (Grippa et al., 2018). Considering the lack of digitalization within the study area, the (2018) building footprints were completed manually using JOSM software, based on remote sensing image tiles with a high resolution (2018 MapBox). Incomplete buildings, i.e., (brick) wall structures were included in the digitalization, as far as possible with the level of detail used (zoom factor 18). The digitized data was uploaded and made publicly available via OSM. Other datasets from OSM included roads and waterways (accessed 2018, Figure 2.1). Roads were selected, while pathways or tracks were excluded due to their unsuitability for vehicles, except motorcycles. Waterways were supplemented by river data from ICPAC Geoportal (2017). Land cover data derived from Sentinel 2, supplied as a prototype land cover map (2016) by the European Space Agency (ESA) (ESA CCI LAND COVER, 2016), was analyzed for tree coverage by extracting the tree cover

area. To generate up-to-date information on land cover, remote sensing is one of the most effective techniques available. Data was then used for calculating metrics on a local scale to investigate small-scale land use patterns in peri-urban areas.

2.2.3 Expert Interviews

In-depth expert interviews provide qualitative data where quantitative information is not available (Kleemann et al., 2017b); however, studies focusing solely on interviews often lack an understanding of the interdependencies between human behavior and spatial configuration, such as the effect of the distance to roads, markets, or the suitability of a location for house construction. Consequently, linking analytical approaches, e.g., remote sensing-based land use observations with human behavior, is necessary to understand the complexity of human–environment interactions (Kleemann et al., 2017b). In-depth expert interviews, field visits, and photo documentaries were used to identify peri-urban land use characteristics, processes, and challenges. Expert interviews with officials from Ilala municipality were conducted from August 2017 to October 2017. *Experts* are defined as people with extensive knowledge and experience regarding land use planning in the study region. Six in-depth interviews were conducted, at ministerial, municipal, and ward administrative levels. The interviewees included persons involved in planning, research, and community development and an executive ward officer. Following an open interview guideline (Appendix B), interviewees were asked about characteristics and changes in the study area, planning strategies and regulation, the role of different institutions and actors, and the challenges and perception of peri-urban development. Employing open questions, additional topics were discussed depending on the interviewees field of expertise. Each interview took between 30 and 120 min depending on the expertise of the interviewee and the level of detail of the answers (a list of interview dates and expert functions are shown in Table A 2.1). Interviews were transcribed and analyzed in a qualitative content analysis according to Mayring (2000), followed by inductive category development by adjusting categories including subsuming and formulating new categories. Results were qualitatively interpreted and complemented by a coarse quantitative analysis, e.g., word frequency to approximate importance of categories. Information derived from expert-interviews was supplemented by the analysis of secondary documents, such as the Dar es Salaam Master Plan (in development, 2018 draft version), the Land Act and Village Land Act (1999), and the National Human Settlements Development Policy (2000).

2.2.4 Spatial Pattern Analysis along a Peri-Urban Gradient

The selection of characteristics derived from literature and expert interviews was subsequently analyzed using a gradient approach with increasing distance to the city center. We identified spatial indicators for those characteristics and applied a spatial pattern analysis, using the datasets explained above. The following indicators were selected based on previous studies (Appiah et al., 2014; Laband et al., 2012) and the results of the qualitative expert interviews and field visits: number, size, and density of building structures, road length, and Euclidean distance to roads, river (valleys), and the city center. Following Birch et al. (2007), a hexagonal grid-based approach was chosen to cover the entire study area in a more systematic way than administrative boundaries. All variables were subsequently averaged for each hexagonal cell (1 km^2 area) as mean values (Table 2.1).

Table 2.1: Indicators calculated for spatial pattern analysis

Variable	Indicator for	Data Source	Processing (1 km^2 Grid Cells)
		Land Cover/Use	
House Density	Urban density and proxy for population density	Open Street Map	Houses per km^2
House Size	Building size	Open Street Map	Mean house size per km^2
Tree Coverage	Land degradation	CCI Landcover	Share of tree cover per km^2
		Proximity	
Road density	Access to transport and infrastructure density	Open Street Map	Road length km per km^2
Distance to city center	Proximity to city center (central business district)	Centroid central business district	Hub Distance from cell centroid
Distance to main roads	Access to transport and infrastructure density	Open Street Map	Mean distance from house centroids
Distance to river	Access to water resources	ICPAC Geoportal	Mean distance from house centroids

The information derived from expert interviews and the literature review were combined with the results from the spatial data analysis to suggest a generalized scheme characterizing peri-urban development, including environmental (including land cover and proximity to features), social, and economic variables.

2.3 Results

2.3.1 Peri-Urban Characteristics and Processes

The majority of interviewees stated that their primary definition of peri-urban is based on the distance to the city center (central business district). This is in line with the Tanzanian Land

Act of 1999 that defines peri-urban areas as 'those located within a radius of 10 km outside the boundaries of an urban or semi built-up area, which may be prescribed by the Minister for Lands, Housing, and Human Settlements Development' (Parliament of the United Republic of Tanzania, 1999). The definition based on distance seems straight forward; it does not account for the boundary of an urban area or a semi-built-up area, which, unlike administrative entities (regional, districts, wards, mtaa[4] areas, etc.), is evolving and shifting as towns and cities expand. In the Dar es Salaam Master Plan (guideline for urban land use development and zoning) (Ministry of Lands, Housing and Human Settlement Development, 2016), the peri-urban is the target location for settlements, infrastructures, and areas of preservation of croplands in the urban fringe.

Furthermore, infrastructure conditions characterize the peri-urban, especially the limited access to roads and public transport. Access to roads is limited, not only by availability, but also by road quality. Most of the roads are gravel; tarmac roads are rare, except major routes connecting municipalities. Transport infrastructure depends on decision makers (ward administration) and the priorities set by the Tanzania Rural and Urban Roads Authorities. Roads are built on demand and small access roads are built after the construction of houses (Interviewee #4).

In Dar es Salaam, development of houses primarily takes place along major roads, with land prices increasing with proximity to major roads, but also with the possibility to include shops that provide income (Interviewees #1 and #3). Transport mostly requires private cars, since public transport is not well developed. Citizens of Dar es Salaam mostly rely on Daladala (small buses), Bajaj (three-wheeled motorized vehicles), and Bodaboda (motorcycle taxis); however, bus stops are only established if an (undefined) threshold of population is reached. Thus, motorcycle taxis are the most common mean of transport in the peri-urban, also because they can commute on smaller access streets or pathways.

According to all interviewees, and in accordance with the literature, the peri-urban is additionally characterized by a lack of service structures for water (Figure 2.2) and electricity, as well as schools, hospitals, and dispensaries. The exemplary water storage tank, shown in Figure 2.2, was a community project in Msongola ward: land is often 'donated' from one or more owners for the construction of roads or service buildings (Interviewee #6).

[4] Wards can be sub-divided into urban wards, "mtaa" (Kiswahili for streets) Commonwealth Local Government Forum (2017).

'Most of the peri urban area [have] poor infrastructure, especially roads. And in urban area[s] there [area the requirements of] poor people. Basic needs, especially hospital[s], clean water, even electricity. Even schools. Especially government and private schools are [lacking] in peripheral areas.' (Interviewee #2)

Figure 2.2: Example of an elevated water storage tank as a water supply system (photo: Saskia Wolff 2017)

The main reason for ongoing land use changes, mainly from agricultural to residential use, is that urban dwellers move to more remote peri-urban areas because of cheaper land prices and the desire to own property instead of renting (Interviewees #2, #4, and #5). Other pull factors include the possibility for agriculture and the lower crime rates than in urban centers (Interviewee #6). If a farmer sells their property, the land is first divided and sold in small sections. Therefore, trees are cleared from the land, except some isolated trees (e.g., cashew or coconut nut) (Figure 2.3) that do not require maintenance and are often used as property boundary marking.

'…These were the areas which were formerly very green, and used as the lands of the city. Food production was [done] in these areas. Now people moving in are clearing the green area, they clear the trees, [so there is] no more land for farming. It is only residential. So, it is […] transforming them into urban [areas]. Even [if] there had been natural resources found in those areas, they are no longer there. It is only houses, houses, houses.' (Interviewee #6)

Figure 2.3: Single trees between residential plots that remained after clearance of the area for house development (photo: Saskia Wolff 2017)

Agricultural activity changes from large to small-scale: it is concentrated within the river valleys and limited to vegetable production. These small plots are mainly managed by women whose families either own or rent the plots. Potential land buyers are middle to high income and can afford to commute between the peri-urban and their place of work, usually in the city center. Land ownership often remains unclear, and land can be sold more than once to multiple owners, resulting in shifting property boundaries and conflicts of ownership. Characteristic structures of these conflicts are unfinished brick houses, marking the owners right to a piece of land (Figure 2.4). This is also due to nonexistent or unfeasible planning hierarchy and strategies; however, local planning authorities interviewed in this study state the necessity for those strategies to come from a regional governmental level. These strategies include customized and context-specific planning 'to make sure [peri-urban areas] are not going back to where they come from and being a replica of urban areas, which are informalizing' (Interviewee #6). In Dar es Salaam, local authorities of the wards organize themselves with the help of citizens, in a demand-based system; for example, when certain population thresholds are reached. This includes the development of new Daladala stops, schools, and health facilities, which are then implemented with the help of the superordinate authorities, i.e., the ward and city administration.

> *'Yes, there is a challenge […] and issues [with] urban planning. Some [urban settlements] are planned and others are built without any plan so as time goes on, the issues of urban planning become[s] difficult.'* (Interviewee #5)

Figure 2.4: Unfinished cement block wall house structure, which often remain unfinished due to conflicts about land ownership (photo: Saskia Wolff 2017)

Peri-urban areas function as a dynamic continuum for people, goods, and services, linking these areas to the city center. The characteristics of the peri-urban areas need to be determined by incorporating an environmental, socio-economic, and political framework. To assess and describe the peri-urban, the following set of indicators can be used (Figure 2.5):

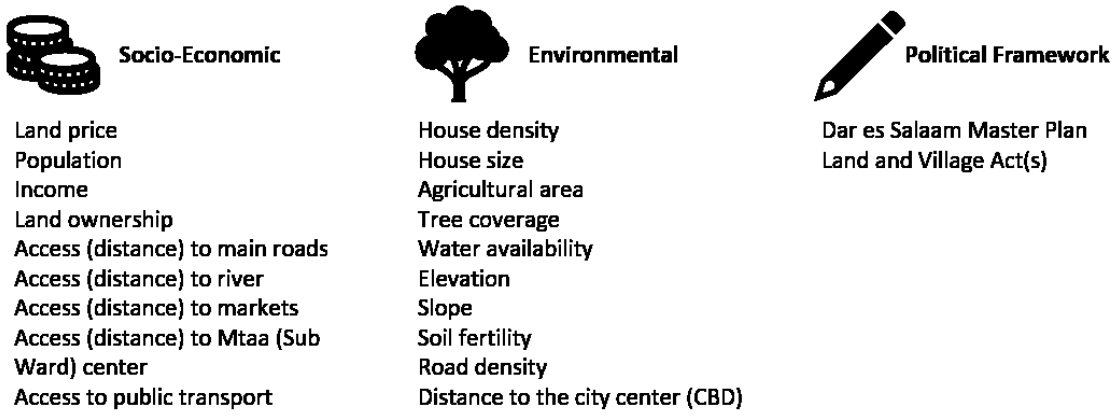

Figure 2.5: Set of indicators to characterize the peri-urban, with regard to sustainability pillars. Socio-economic indicators include social and economic indicators, as well as accessibility; environmental includes ecological factors and conditions including land cover; the political framework refers to planning guidelines of land development

2.3.2 Spatial Patterns along a Peri-Urban Gradient

For the selected set of the identified indicators (Figure 2.5,Table 2.1), spatial patterns on the peri-urban gradient were analyzed on a 1 km^2 hexagonal grid of the Msongola ward. These included housing density, mean house size, tree coverage, road density, distance to central business district (CBD), mean distance to main road from buildings, and mean distance to river from buildings. One characteristic per category is illustrated in the maps in Figure 2.6 and a scatter diagram of dependence to distance from the city center in Figure 2.7.

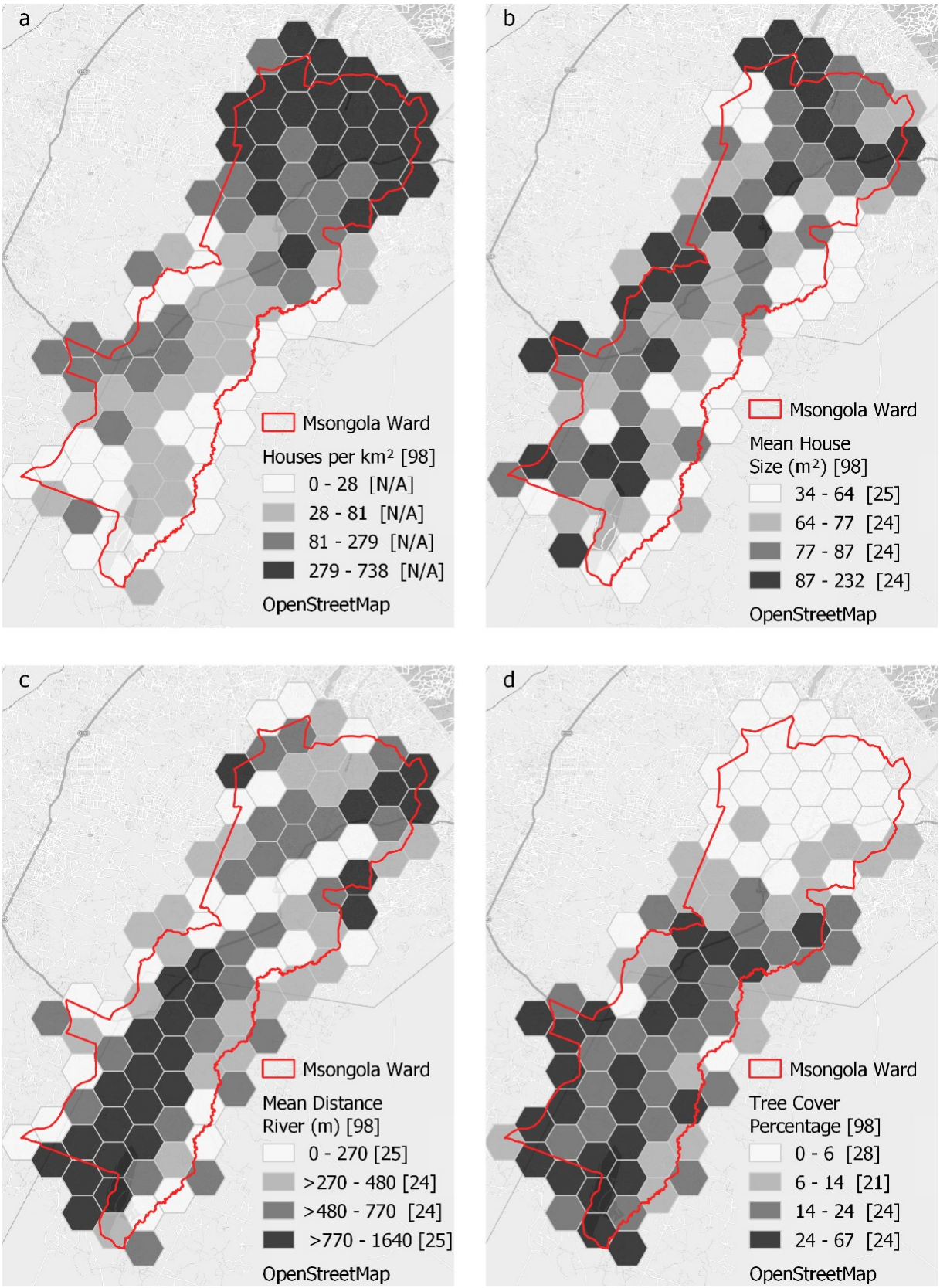

*Figure 2.6: Maps of peri-urban spatial characteristics in four categories: (**a**) decreasing with distance to city center, (**b**) constant, (**c**) random, and (**d**) increasing with distance to city center (central business district)*

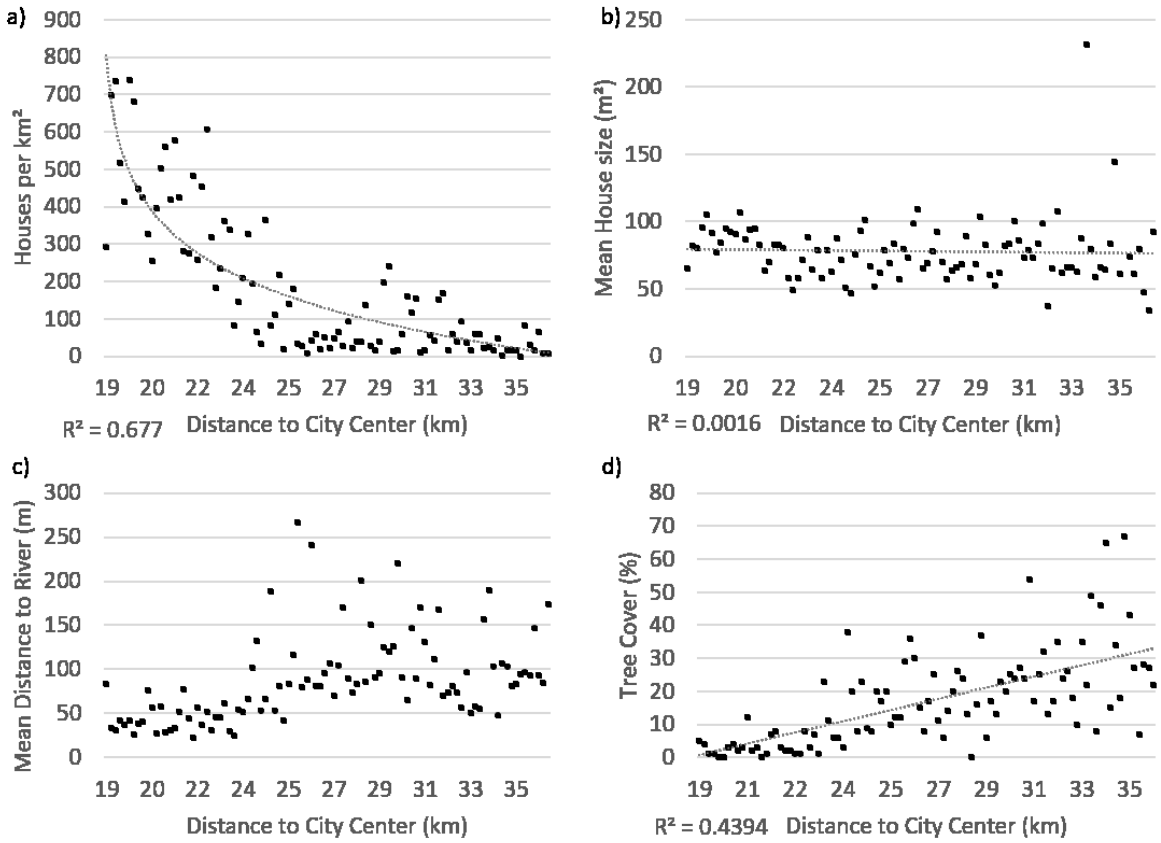

*Figure 2.7: Distribution of values along a peri-urban gradient with trend lines for the following categories (**a**) decreasing houses per km² with distance to city center, (**b**) constant house size, (**c**) random mean distance to river (m), and (**d**) increasing tree cover (%) with distance to city center*

Houses per km² (i.e., one grid cell) showed a strongly decreasing trend with increasing distance from the city center, with a maximum value of 738/km² at 20 km distance and a minimum of 0/km² at 35 km distance (Figure 2.7a). On the contrary, tree coverage increases, with highest value of 67% of the cell area at 35 km distance and a minimum of 0% at 20 km distance. Areas with lower housing density show higher tree coverage. The random distribution of values, e.g., mean distance to river (Figure 2.7c), is due to natural landforms resulting in an unpredictable distribution of values. The mean distance to a river (from buildings) ranges from 22 to 267 m (Figure 2.7c). Mean house size remain constant with increasing distance to city center ranging from 34 to 232 m², with a mean house size of 78 m² (Figure 2.7b). The spatial patterns are in line with the statements from the expert interviews. The decreasing house density with increasing distance to the city center illustrates the availability of space for house development for cheap prices. Increasing tree coverage along the gradient area is connected to the clearance of plots, and former farm area, in order to build houses. This clearance of former large-scale agricultural areas leads to limited availability of agricultural land, which is concentrated in river valleys. As a consequence, some dwellers have to rent agricultural plots from other landowners

in the river area. Hence, the spatial distribution of mean distance to rivers results in a rather random pattern but with a majority of grid cells showing values below 100 m. Preferably, houses are built in close distance to river valleys. The changes in spatial patterns on the peri-urban gradient can be differentiated into four categories: *increasing* or *decreasing* (with distance to city center), *constant/no change*, and *random* (unpredictable) (Figure 2.8).

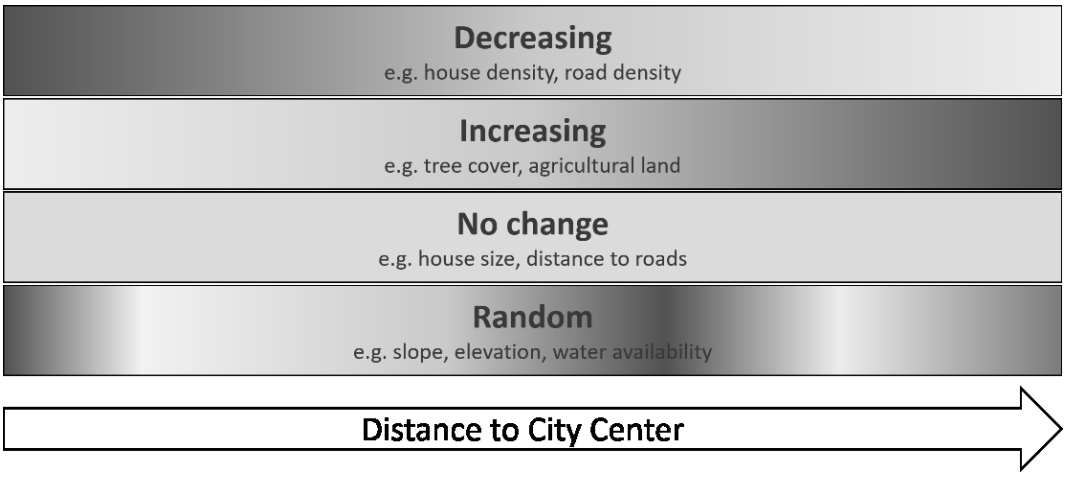

Figure 2.8: Spatial dynamics of characteristics on a peri-urban gradient

2.4 Discussion

The findings from this case study of Dar es Salaam suggest that the peri-urban is a highly dynamic space with specific characteristics and processes. In particular, it is characterized by poor accessibility and a lack of service infrastructures, as determined by Kombe (2005). The urban–rural fringe, located between an urban area and the rural regions, shows a particular landscape structure that differs in land use patterns from both the urban and rural regions and is characterized by rapid development and changes over time. The quantitative findings on land use patterns, e.g., housing or road density, support earlier studies (Karg et al., 2019; Peng et al., 2016; Schlesinger and Drescher, 2018), showing a decreasing trend with increasing distance to the city center. Experts and legal documents primarily define the peri-urban with a focus on distance to the city center, which is even considered in the definition given in the Tanzania Land Act (1999) (Parliament of the United Republic of Tanzania, 1999). The consideration of peri-urban space on its own, opposed to urban or rural areas, is highlighted by many studies (Adam, 2014; Bhanjee, 2019; Msangi, 2011), which emphasizes that the simple dichotomy between the urban and rural must be overcome for planning and policy strategies (Bhanjee and Zhang, 2018; Karg et al., 2019; Lerner and Eakin, 2011). On the other hand, Karg et al. (2019) argue that planning policies are often reflected in the administrative, dichotomous entities of

'urban' and 'rural' that do not adequately reflect the real-world situation in many cities. However, the peri-urban is not necessarily tied to administrative boundaries or entities of an urban area (Allen, 2003) but is strongly linked to the urban (and the rural) by forward and backward flows of people (migration), goods (trade), and money (investment) (Karg et al., 2019; Tacoli, 2003). Two very important factors for peri-urban development are the land price and the land tenure system. In terms of tenure, Msangi (2011) noted that peri-urban areas exhibit both customary (commons may be owned by indigenous peoples or other communities with customary tenure systems, and this may be legally recognized; FAO, 2016) and quasi-customary arrangements. Quasi-customary refers to land tenure arrangements where occupiers have acquired land from customary holders largely through non-customary modes such as purchasing (Kombe, 2005). Land acquisition is strongly linked to different actors, i.e., institutions, land owners, or local authorities (Msangi, 2011; Namangaya and Kiunsi, 2018); however, this is beyond the scope of this research. Land price and actual construction of houses is influenced by different variables, including accessibility and service provision (Msangi, 2011; Namangaya and Kiunsi, 2018): if a road is connected to the parcel, it becomes more expensive. This is also reflected by the decreasing road density along the peri-urban gradient: hypothetically, land price shows a similar gradual pattern. To determine accessibility, features from OSM were chosen that are suitable for vehicles; however, particularly paths and footways can be frequented by motorcycle taxis as well.

The development of peri-urban space can follow different spatial patterns. According to the village magnet and ribbon theory (Doan and Oduro, 2012) and the interviewees in this study and confirmed by the spatial data analysis, high shares of development take place around (former) village centers and major roads. This is mainly revealed through house densities per square kilometer along the grid overlaying Msongola ward, where small agglomerations of higher building densities along major roads were identified. According to the interviewees, one major difference compared to peri-urban areas of the Global North is that the main function of buildings is residential, with rarely a mixture of purposes (Nilsson et al., 2013), except small commercial shops at bus stops or on the front of buildings, for example (Nuhu, 2019). Independent from the area, studies worldwide emphasize the integration of peri-urban areas into sustainable development monitoring and planning. According to Wandl and Magoni (2017), peri-urban areas have enormous potential to play a positive role in enhancing urban sustainability, which is in line with our interview results. Sustainable development of peri-urban areas include better-tailored planning and development of built-up areas in order to limit the

transformation of open spaces (Hedblom et al., 2017; Wandl and Magoni, 2017). At the same time, peri-urban areas are under increasing pressure regarding the provision of ecosystem services like recreation or food production (Hedblom et al., 2017). However, a better balanced and more sustainable development requires more policy attention at the regional level and the urban–rural interface (Piorr, 2011). Peri-urban areas present opportunities to shape ecological networks and to foster productive economic activity (Wandl and Magoni, 2017). For example, Magoni and Colucci (2017) describe how innovative integrated planning has addressed multifunctionality in peri-urban areas by bringing together food production with environmental and landscape planning.

With the set of indicators and the spatial trend of the peri-urban gradient, we propose a systematic assessment and characterization of patterns and processes. These indicators are similar to those suggested by Karg et al. (2019) to identify access, services, and built-up areas for peri-urban classification; these are structured according to three dimensions of sustainability: environmental, socio-economic, and policy framework. This is in-line with ongoing discussions and policy aims for achieving sustainability goals of food security (SDG 2) and inclusive, safe, resilient, and sustainable settlements (SDG 11) (United Nations Sustainable Development, 2015). All dimensions and characteristics cannot be fully captured, but the results from the literature review and expert analysis reveal the most important ones on which to focus. To the best of our knowledge, this is the first time the trends in these indicators have been categorized over the peri-urban gradient. These indicators can be modified and utilized for other study areas. As studies of other regions/cities have shown, a comparative approach might reveal additional insights (Dekolo et al., 2015; Follmann et al., 2018; Liu et al., 2016; Salem, 2015).

There are a number of uncertainties and limitations of this study. First, the focus of this research is on a specific study area and peri-urban subset in Dar es Salaam. The direct transferability of these results (i.e., spatial patterns and dynamics of specific indicators) to other areas is, therefore, limited and is also not the aim of this study. Instead, the detailed insights from this study can be used to develop a set of indicators to characterize the peri-urban. Second, due to a lack of official spatial and temporal data on land use, infrastructure, or population on a suitable spatial resolution, not all variables could be analyzed quantitatively. Alternatively, crowd-sourced OSM data was used, with additional digitalization to meet the requirements of this study. Using this kind of open-source spatial data, the quality of data cannot be guaranteed due to the type of data assessment (Grippa et al., 2018). To identify the high spatio-temporal

dynamics of the peri-urban, new remote sensing datasets with high temporal resolution, such as Sentinel, offer additional possibilities for future studies to explore the dynamics in more detail. Thirdly, we relied on few expert interviews in this study and did not do a representative quantitative survey covering different administrative levels beyond the one ward. However, the aim of this paper was to explore and identify the characteristics in an initial step and, therefore, the qualitative in-depth interviews produced good results for this aim.

The results from the applied mixed-method approach for analyzing peri-urban characteristics has the advantage that information derived from the qualitative research can be incorporated into the quantitative method and that their outcomes can be compared (Kleemann et al., 2017a). In the analysis of indicators to assess peri-urban characteristics, methods from social science perspectives provide more information; therefore, a combination of qualitative and quantitative data analyses from natural and social sciences are applied. The methodology draws from local community knowledge to provide background information and develops a backdrop of social relations that produce the spatial patterns of peri-urban land use (Koti and Weiner, 2006).

2.5 Conclusions

In our study, we propose a conceptual identification of indicators characterizing the urban–rural interface in terms of spatio-temporal dynamics. While results and trends might differ for other study areas, the methodological set and categorization of dynamics (random, no change, increasing, decreasing) can be transferred and utilized for the characterization of peri-urban areas using a gradient approach. In Dar es Salaam, the peri-urban is characterized by socio-economic challenges including the lack of infrastructure and services, i.e., schools, hospitals, or land ownership. Environmental challenges include the clearance of vegetation, particularly trees and availability of land for large-scale agricultural cultivation. These patterns could also be identified in spatial dynamics along a peri-urban gradient, including a decreasing house density, which relates to available land and the flow of people through migration. At the same time, large scale agriculture mostly vanished and small-scale cultivation is mainly linked to river valleys. As a consequence, access to agricultural land is limited, also related to conflicts in land ownership. Many households have no property at the river but need to rent agricultural plots. The limited availability of agricultural space in peri-urban areas is critical, particularly considering its function as food production areas. In terms of sustainable transformations, the city planning of Dar es Salaam focuses on the implementation of sustainable city development

goals, which is also reflected by the wish of local administrations for formalization and support by planning authorities.

In general, sub-Saharan African cities, including Dar es Salaam, are growing unmonitored and without adequate urban planning (Kombe, 2005; Lupala, 2002; Mkalawa and Haixiao, 2014). Planning and policies have to address the specific dynamics and the spatio-temporal gradient in the peri-urban. The city center is closely linked to the peri-urban and needs to be considered as a continuum (of people, including transport and housing, and products, e.g., agricultural products). Particularly the provision of service infrastructures plays a decisive role and needs to be tackled in planning and political strategies. To face the continuous population increase in Dar es Salaam and other cities in the GS, providing living space and food production in a sustainable manner remains one of the major challenges. The peri-urban area, where urban and agriculture intermingle, should be the focus of future research, policies, and planning.

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Appendix

Table A 2.1: List of interview dates and expert function

#	Date	Function
1	September 12, 2017	Town Planner
2	September 18, 2017	Community Development Officer
3	September 20, 2017	Executive Officer
4	September 20, 2017	School Principal
5	September 21, 2017	Community Development Officer
6	September 29, 2017	Researcher

Appendix B: Interview Guidelines

Date:

Institution: Interviewee:

Introduction

Introduction of project…

Anonymity agreement, recording

Function of the expert

Current position and area of responsibility

Background

How would you describe peri-urban areas?

What are the characteristics and functions?

What are challenges?

Structure and Characteristics

What is the major structural change occurring?

Peri-urban farms: What are specific characteristics/how are they organized?

What is the difference to rural farms?

What are biophysical characteristics/limitations? (natural elements)

What are limiting/relevant socio-economic characteristics?

How is the peri-urban connected to…

… rural areas?

... urban areas?

Interests and Strategies

What are people's (farmer, residents) motivation to settle in peri-urban areas?

Where do they come from?

What are people's long-term plans?

What are strategies to achieve long term plans?

Regulations and Decision Making

Who are the relevant actors, decision makers, and authorities?

What is the role of different institutions?

What responsibilities do they have?

How do actors interact?

What are current policy and planning strategies?

How are strategies implemented in practice?

What are the formal/informal aspects, regulations?

How does the city react towards the increasing population pressure and rising demand for settlements?

Perception and Opinion

How does lifestyle, e.g., household type, affect land use decisions?

What are future expectations, trends?

Additional comments?

Chapter 3

Agricultural Landscapes in Brandenburg, Germany: An Analysis of Characteristics and Spatial Patterns

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Abstract

The increasing demand for agricultural commodities for food and energy purposes has led to intensified agricultural land management, along with the homogenization of landscapes, adverse biodiversity effects and robustness of landscapes regarding the provision of ecosystem services. At the same time, subsidized organic agriculture and extensive grassland use supports the provision of ecosystem services. Yet little is understood about how to evaluate a landscape's potential to contribute to protecting and enhancing biodiversity and ecosystem services. To address this gap, we use plot-level data from the Integrated Administration and Control System (IACS) for Germany's federal state of Brandenburg, and based on a two-step cluster analysis, we identify six types of agricultural landscapes. These clusters differ in landscape structure, diversity and measures for agricultural land management intensity. Agricultural land in Brandenburg is dominated by high shares of cropland but fragmented differently. Lands under organic management and those with a high share of maize show strong spatial autocorrelation, pointing to local clusters. Identification of different types of landscapes permits locally- and region-adapted designs of environmental and agricultural policy measures improves outcome-oriented environmental policy impact evaluation and landscape planning. Our approach allows transferability to other EU regions.

3.1 Introduction

A sustainable pathway is needed to increase agricultural production and achieve food security in the future, while simultaneously reducing the adverse environmental effects of agricultural production. The provision of ecosystem services from agricultural land, in particular, needs to be improved, and this has been increasingly highlighted by science and enacted in policy changes (Schaller et al., 2018). European agricultural landscapes have experienced diverging shifts towards intensification and specialization on the one hand, and marginalization and abandonment on the other hand, and these dual trends are expected to continue into the future (Lambin et al., 2000; Monteleone et al., 2018; Stoate et al., 2009). Marginal agricultural landscapes, characterized by unfavorable biophysical conditions such as steep slopes, shallow and/or poor soils and inferior accessibility (Harvolk et al., 2014; Lüker-Jans et al., 2016), can increase biodiversity and habitat richness. This, however, requires low-input production, wide crop rotations, permanent grassland and small-parceled mosaics. High Nature Value (HNV) farming systems, typical for such landscapes, are essential to biodiversity conservation and the provision of ecosystem services (Lomba et al., 2020; Strohbach et al., 2015). Intensive and traditional agricultural production, however, rests on homogenous landscapes, i.e. larger plots without landscape elements that could provide sufficient habitat structure or prevent soil erosion (Tscharntke et al., 2005).

Our research focuses on the eastern German Federal State of Brandenburg, where large-scale agricultural land use shapes the landscape. As in many other post-communist regions, large-scale agriculture persisted despite fragmented land ownership after restitution following German reunification (Hartvigsen, 2014). Along with the large-scale farming structure, Brandenburg's agricultural landscape is characterized by homogenization and production intensification, both of which are associated with a decrease in biodiversity and adverse environmental effects, i.e. a decrease in soil and water quality (Thomson et al., 2019). These trends continue despite the EU's efforts to increase financial support for sustainable land management practices within the Common Agricultural Policy (CAP). Concerns over whether these efforts have been able to impede adverse landscape structures lead to questions regarding how to quantitatively assess landscapes' functioning so as to preserve and enhance biodiversity, habitats and thus, ecosystem service provision.

Quantitative landscape metrics characterize and allow comparison of agricultural landscapes across space and over time (Uuemaa et al., 2013). Typically, the number, size, shape and arrangement of patches of different land use/land cover types are used to describe a landscape's

structure, composition and dynamics (Lausch and Herzog, 2002). Recent metrics also include the area under cultivation, mean patch size and Shannon's Diversity Index as an agrobiodiversity indicator (Uthes et al., 2020) to characterize agricultural land use and management intensity (Schlesinger and Drescher, 2018). Other measures of agricultural land management intensity rely on input use intensity, including labor or capital, management practices, output quantities such as per-hectare yields (Shriar, 2000), or the dependence on industrial goods such as machinery and fertilizer (Temme and Verburg, 2011; Zasada et al., 2013). A conceptual framework to quantify and analyze land use intensity proposed by Erb et al. (2013) integrated three dimensions: input intensity, output intensity and the associated system-level impacts of land-based production (e.g., changes in carbon storage or biodiversity). (Estel et al., 2016) summarized that, particularly in mapping indicators of cropland use intensity substantial progress has been made. Intensity indicators included yield gaps, fertilizer use, human appropriation of net primary production, field size or the extent of irrigated agriculture or tillage (Estel et al., 2016). The study by Estel et al. (2016) maps and characterizes cropping systems based on the MODIS Normalized Difference Vegetation Index (NDVI) time series and self-organizing maps. The results correspond well with indicators for agricultural intensity, such as nitrogen inputs or yields. Rega et al. (2020) combine the mapping of cropping systems with an indicator of management intensity to classify agricultural land across Europe. Many of these studies, however, have limited generalizability given restrictions on available data to small areas, regions or selected farms.

The Integrated Administration and Control System (IACS) dataset that is used to monitor and control the flow of payments for which farmers apply as part of the CAP offers promising applications to carry out plot-based characterizations of different types of agricultural landscapes. Several studies have successfully used this dataset to analyze agricultural land use change (Lüker-Jans et al., 2016; Tomlinson et al., 2018) and to characterize farms based on crop choice and land use (Lomba et al., 2017; Uthes et al., 2020). On a broader scale, landscape archetypes and zones on a European or global level have also been identified and discussed in several studies (Eisenack et al., 2019; Levers et al., 2018; Oberlack et al., 2019; Václavík et al., 2013). This research, however, did this far not consider detailed regional specifications.

The aim of this paper is to close this gap by first identifying and characterizing different types of agricultural landscapes based on an integrative approach that jointly acknowledges landscape structure, diversity and management derived from plot-based information, and second, by

depicting their spatial patterns. We illustrate our approach for the Federal State of Brandenburg and pose the following research questions:

RQ1: How can agricultural landscapes be characterized in terms of landscape structure, diversity and management on a small scale. What spatial patterns can be detected?

RQ2: How can regionally specific agricultural landscape types be identified? Which spatial concentration of those types exist?

Our analysis relies on IACS data for Brandenburg and uses metrics built from a combination of agricultural landscape structure, diversity and management indicators rather than single-variable metrics. We thereby include detailed regional specifications in contrast to existing classifications for Brandenburg, i.e. agro-ecological zones (*Landbaugebiete*), defined by site conditions and the resulting productivity (Landesamt für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung, 2016) or single-variable crop and livestock information provided by the Thünen Atlas (Thünen Institut, 2014). We are thus able to capture different dimensions of agricultural landscapes which may indicate or be used as a proxy for selected ecosystem services (ESS), for example habitat richness or biodiversity. While landscape metrics are most frequently applied to grids and administrative areas, we use hexagons, which have been shown to better capture spatially continuous phenomena, such as agricultural landscapes, due to their spatial smoothing effect towards the edges (Birch et al., 2007; Schindler et al., 2008).

The outcomes of this study provide important insights. First, integrated agricultural landscape characteristics can be used to develop environmental and agricultural policies that are better tailored to local and regional characteristics. Second, the results of this study can subsequently be used to prioritize areas and set the scope for measures regarding agricultural land use, particularly enforcing multifunctional agricultural landscapes. Last, our methodological approach allows transferability to other EU regions, where identification of different types of landscapes offers locally- and regionally-adapted designs of environmental and agricultural policy measures, environmental policy impact evaluation and landscape planning.

3.2 Material and Methods

3.2.1 Study region

The state of Brandenburg is located in north-eastern Germany, covers 29,640 km² and is a heavily agricultural state, with approximately 45% of its area comprised of agricultural land (Amt für Statistik Berlin-Brandenburg, 2016), making it an ideal setting to study landscape composition. 12% of Brandenburg's agricultural area is dedicated to organic agriculture, which is relatively high compared to other German states, and has been steadily increasing (MLUK, 2019). Nevertheless, the utilized agricultural area has remained constant, with about 77% cropland and 23% permanent grassland (Troegel and Schulz, 2018). Brandenburg completely surrounds Germany's capital city of Berlin (Figure 3.1), where land use and its composition are heavily influenced by strong urbanization trends such as demand for residential land in the suburban areas. Demand for regional food production in the neighbouring state has been growing, as has the use of cropland for renewable energy production (Gutzler et al., 2015), leading to considerable increases in maize production for subsidized biogas fermentation in Brandenburg (Federal Environmental Ministry, 2000).

Brandenburg's agricultural land exhibits a high share of low-quality soils; almost two-thirds are sandy and sandyloamy soils. According to Gutzler et al. (2015), this situation, paired with low rainfall (on average, less than 600 mm/ year), makes agricultural production challenging. This is one reason why Brandenburg farmers either produce in the organic niche, benefiting from the high prices paid in Berlin for regional, organic food, or apply a high level of technology, including heavy-duty machinery and intensive use of fertilizers and agrochemicals (Gutzler et al., 2015). Maize replaced rye as the main crop in 2013, followed by wheat and rapeseed (Troegel and Schulz, 2018). As in all eastern German states, agricultural in Brandenburg is dominated by large farm enterprises with an average size of approximately 250 hectares, four times the German average (Gutzler et al., 2015; Troegel and Schulz, 2018). Livestock production has been in continuous decline in Brandenburg; according to the most recent available agricultural census, its livestock density in 2010 was a low 0.4 livestock units (LU) per hectare in comparison to other federal states, such as Lower Saxony's 1.1 LU per hectare (Statistisches Bundesamt, 2019). We, therefore, focus on cropland and grassland in our analysis. Furthermore, in contrast to Uthes et al. (2020), we propose an areal characterization of landscapes instead of farming systems where livestock numbers are more relevant.

As a base for our indicator and cluster calculation, we created a hexagonal grid with a cell size of 10 km² (N = 2 836, Figure 3.1). The size of the cells captured the landscape level and the spatial configuration of plots within each cell (mean plot size = 7.9 ha). Since administrative areas vary in size and form, the hexagonal grid provides a smoother surface for analysis (Birch et al., 2007; Schindler et al., 2008) and has been applied in studies using landscape metrics for characterizing agricultural landscapes (Griffith et al., 2000). We selected only those cells that are located entirely within the Brandenburg state, including overlaps with Berlin administrative areas.

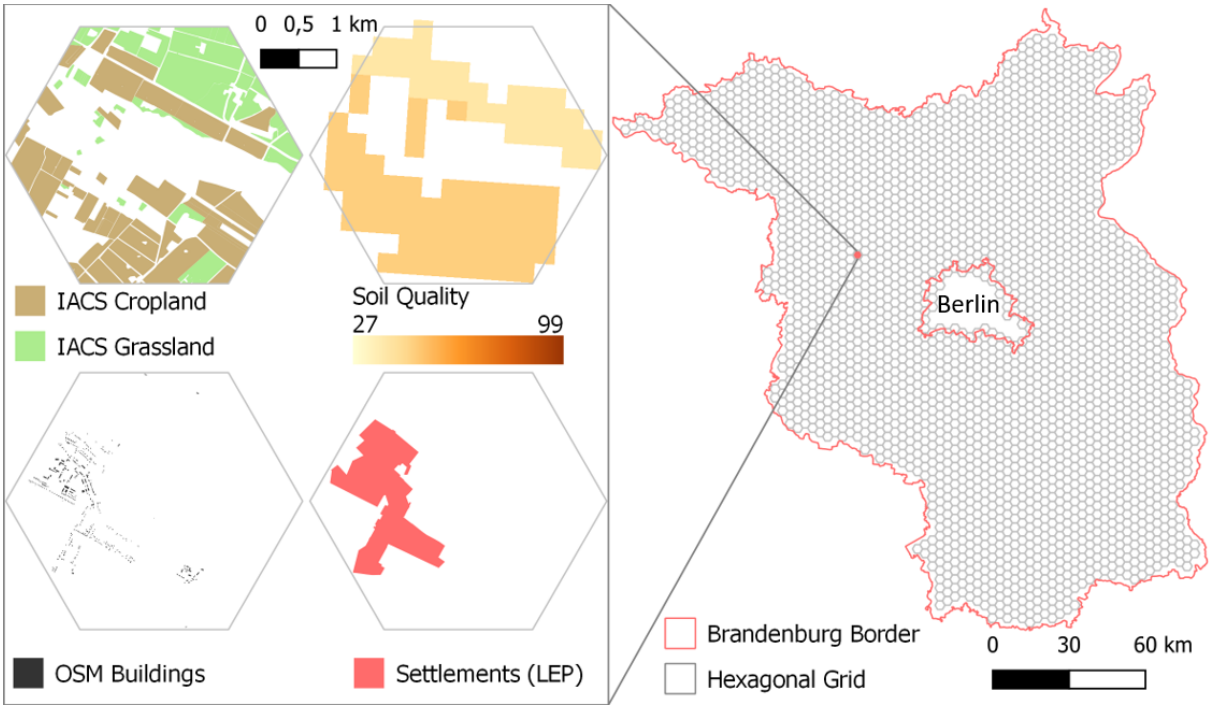


Figure 3.1: Input data source samples and hexagonal grid in the study area Brandenburg, Germany

3.2.2 Data

We used plot-based information on the cultivation of agriculture in Brandenburg in 2018 from the IACS to identify agricultural characteristics. Farms apply for area-based payments to ensure income support according to EU CAP regulations, managed and controlled in a standardized way in all EU member states through IACS. In Brandenburg, the baseline map for the registration is a digital cadaster of field blocks established in 2015. The field block cadaster covers the agricultural area in Brandenburg that is eligible for EU subsidies and is updated based on orthophotos. A field block is a coherent agricultural area surrounded by permanent borders (e.g. roads, paths, trees) with a predominantly uniform primary land use. One or more farmers can use a field block, meaning that the area of one field block may be split between

each farmer who applies for subsidies. As a result, the georeferenced agricultural land use data covers only those plots for which farmers applied for subsidies in 2018. The outlines of the plots are generally aligned with the underlying field blocks, but they may have been edited by the farmer due to the specific land use in a specific year. Hence, the size and outlines of plots registered for subsidies can change over time. In addition to agricultural use at the plot level, landscape elements located in a field block, such as hedges, rows of trees and single trees, are also registered. In Brandenburg, landscape elements were registered and located with a single point until 2016, but now they are digitized with spatial outlines (e.g. groups of trees). We, therefore, focused on the categories of grassland, cropland and landscape element, which were assigned based on cultivated crops (*Kulturart*) for 2018. These landscape elements include ecological priority areas for which farms can get extra support within the EU CAP. However, we did not include landscape elements in the final cluster analysis. All subcategories were then aggregated to the categories: cropland, grassland and landscape elements (Figure 3.1).

To account for specific types of arable land use, we identified plots that were likely to have been cultivated without crop rotation and used maize as a specific crop type. We also included information about whether a plot is under organic or conventional management, both of which are indicated in the IACS data.

In addition to IACS data, we used the OpenStreetMap (OSM) data and regional planning data (settlement locations) and soil quality (Figure 3.1). We used the OSM data for all building footprints in Brandenburg from September 2019 to assess the degree of urbanisation in each hexagon. OSM is an open-source, crowd-sourced mapping platform that has high coverage and good quality in countries such as Germany (Fan et al. 2014; Jokar Arsanjani et al. 2015). We used April 2019 settlement data from the *Landesentwicklungsplan Hauptstadtregion Berlin Brandenburg* for calculating the mean Euclidean distance to settlements for each cell. The Bundesanstalt für Geowissenschaften und Rohstoffe (2014) provides a soil quality rating (SQR) on a 0–100 point scale (Mueller et al., 2007), which indicates a rough estimate for crop yield potential. Soil quality points suggest the potential productivity and are an official measure in Germany that was constructed to combine pedologic, scientific and agronomic considerations within one measure. A low (high) number represents very low (high) productivity (BMJV, 2007; Scheffer et al., 2010).

3.2.3 Indicator Calculation, Metrics and Spatial Patterns

To answer RQ1, we selected a set of landscape metrics to characterize agricultural landscapes based on a literature review according to three categories (Table 3.1).

Landscape structure: median plot size (ha), edge density (calculated as a share of the total hexagon area in km/10 km²), number of buildings (N) and mean distance to settlements (km).

Landscape diversity: agriculture share of total hexagon area (%), Shannon Diversity Index (SDI), share of landscape elements in a total agricultural area (%).

Management: share of organic of total agricultural area (%), share of cropland of total agricultural area (%), share of maize of total agricultural area (%), soil quality (values from 0-100).

Table 3.1: Metrics to describe landscape structure, diversity and management with description of indicators, calculation of metrics and data sources

Metric	Indicator	Calculation	Data Source
Landscape structure			
Plot size	Spatial configuration of plots	Median plot size in each hexagon area (ha)	Integrated Administration Control System (IACS)
Edge density	Habitat diversity, fragmentation of agricultural landscape	Total plot edge length per hexagon area (km/10km²)	IACS
Number of buildings	Urbanity	Count building per hexagon area (N)	Open Street Map (OSM)
Distance to settlements	Urbanity	Mean Euclidean distance for each hexagon (km)	Settlement data from ‚*Landesentwicklungsplan Hauptstadtregion Berlin Brandenburg*‘
Landscape diversity			
Share of agriculture	Landscape heterogeneity	Share of agricultural area per hexagon (%)	IACS
Shannon Diversity Index (SDI)	Agro-biodiversity	$SDI = -\sum_{i=1}^{n} p_i ln p_i$ p_i= share (%) of crop/crop and usage i in total agr. area lnp_i= natural logarithm of p_i	IACS

Share of landscape elements	Habitat diversity	Share of landscape element area per hexagon (‰)	IACS
Management			
Share of organic agriculture	Sustainable agricultural production	Share of organically utilized area per hexagon (%)	IACS
Share of cropland	Potential agricultural intensity	Share of cropland area per hexagon (%)	IACS
Share of maize	Potential cropland intensity	Share of area under maize cultivation per hexagon (%)	IACS
Soil quality	Yield potential	Mean soil quality point per hexagon	Soil Quality Rating (SQR)

We calculated the respective indicator values for the year 2018 at the aggregated level of the hexagons. We focused on measures to describe agricultural land use, management, agricultural intensity and diversity and spatial configuration.

Plot size captures the spatial configuration of plots and is frequently used to characterize agricultural landscapes (Dengler, 2009; van der Zanden et al., 2016). We calculated median plot size within hexagons from the reported management units in the IACS data by using the centroid of the plots, considering each plot only once even though it might have overlapped between two cells.

The ecological role of habitat diversity and plot edges for farmland biodiversity (including functional biodiversity) has been demonstrated by several authors (Benton et al., 2003) (Burel and Baudry, 2005; Weissteiner et al., 2016). We, therefore, calculated edge densities and the SDI. Edge density characterizes the fragmentation of the agricultural landscape, i.e. with increasing edge density, the number of farmland patches increase and their patch size decreases (Su et al., 2014).

Organic agriculture is a production type in which mineral fertilizer and synthetic pesticide usage are subject to stricter regulations than in conventional agriculture (Gabriel et al., 2010). Because organic production is considered less harmful to the environment and key for more sustainable agricultural production, it has been included as a share of organic agriculture as an indicator.

To differentiate between cropland and grassland, we included the share of cropland of the total agricultural area, following the argument that most grasslands in eastern Germany are managed rather extensively (Matzdorf et al., 2008). Though grasslands can also be managed intensively,

particularly in regions with high livestock densities, Brandenburg is characterized by few ruminant livestock and rather extensively used grasslands under agri-environmental measures, whereby farmers receive additional compensation payments through the EU CAP for extensively-managed grasslands (Matzdorf et al., 2008).

We measured cropland intensity by the share of maize that is likely to be used for biogas and cultivated as a long-term, self-following crop, i.e. without crop rotation (Gutzler et al., 2015) (Lüker-Jans et al., 2016). We included all maize types (i.e., silage maize and corn maize) in our analysis. According to the German expert group for renewable energy (FNR, 2013), the expansion of maize monocultures (no mixed cultivation on a plot) is expected to be on par with the intensification of crop production (Vergara and Lakes, 2019). Areas with a high share of maize may indicate intensive production of crops for biogas, which often comes at the expense of food production areas (Grundmann and Klauss, 2014; Lüker-Jans et al., 2016).

The SDI, as a measure of agrobiodiversity, is widely used (Uthes et al., 2020; Vaz et al., 2014). It considers the abundance of different crop types. We calculated the SDI for all listed cultivated plants within the IACS data (N = 158) according to the following formula:

$$SDI = -\sum_{i=1}^{n} p_i \, lnp_i$$

where

p_i = share (%) of crop/crop and usage i in total agricultural area

lnp_i = natural logarithm of p_i

The diversity measure equals minus the sum, across all crop types, of the proportional abundance of each crop type, multiplied by that proportion (Griffith et al., 2000).

According to Uthes et al. (2020), landscape elements such as hedge or tree rows are important features for a diverse landscape structure. We thus calculated the share of landscape elements in the total agricultural area within each hexagon.

We used the SQR as a measure for yield potential, which has often been used in land market analyses, such as those of Hüttel et al. (2016) and Ritter et al. (2015).

To assess the degree of urbanization, we calculated the number of buildings in each hexagon and the mean distance to settlements. According to Su et al. (2011), proximity to urban centers parallels the intensity of urbanization and the decrease in human influences on the environment. Additionally, Piorr et al. (2018: 13) emphasize that agricultural landscapes ‘differ in the way they are influenced by the proximity to urban areas, being part of functional urban-rural

linkages, urban pressures and opportunities', for example regarding the farming systems and the involvement of (urban) communities.

For visualization of the results, we classified the metrics share of agriculture, cropland, maize and organic agriculture by equal intervals in 20% steps. For the indicators related to the number of buildings, distance to settlements, soil quality, median plot size, edge density and the SDI, we used natural breaks (jenks) for classification.

To identify spatial patterns, we calculated the spatial autocorrelation values for all single metrics with continuous values. We used Global Moran's I statistics, which characterize the spatial dependency of values between the hexagons (Moran, 1950). We used all six neighbors of each hexagon (Queen's contiguity). The value of Moran's I ranges from -1 (perfect negative autocorrelation) to 1 (perfect positive autocorrelation), with 0 indicating spatial randomness (Moran, 1950).

3.2.4 Cluster Analysis to Identify Agricultural Landscape Types and Spatial Concentrations

To answer RQ2, we applied a two-step cluster analysis using selected metrics to identify different types of agricultural landscapes in Brandenburg.

Lausch and Herzog (2002) emphasize that when working with landscape metrics, one is confronted with the question of which indicators are relevant for the area and the problem under investigation. We, therefore, determined Spearman's correlation coefficients to reduce redundancies (Lausch and Herzog, 2002). After the Spearman correlation analysis, eight selected indicators showed values < 0.4 (Figure A 3.1). However, we relied on seven input variables for the cluster analysis, having excluded the share of landscape elements. This indicator was not included because the values are generally very low in the hexagonal grids, with low variance except for a few outliers (65% of all hexagons have a < 1% share), and if included in the cluster analysis, the results showed no variance within clusters. The final cluster analysis input indicators included soil quality, number of buildings, edge density, shares of organic agriculture, cropland and maize, and median plot size for each hexagon in 2018 (Figure 3.2).

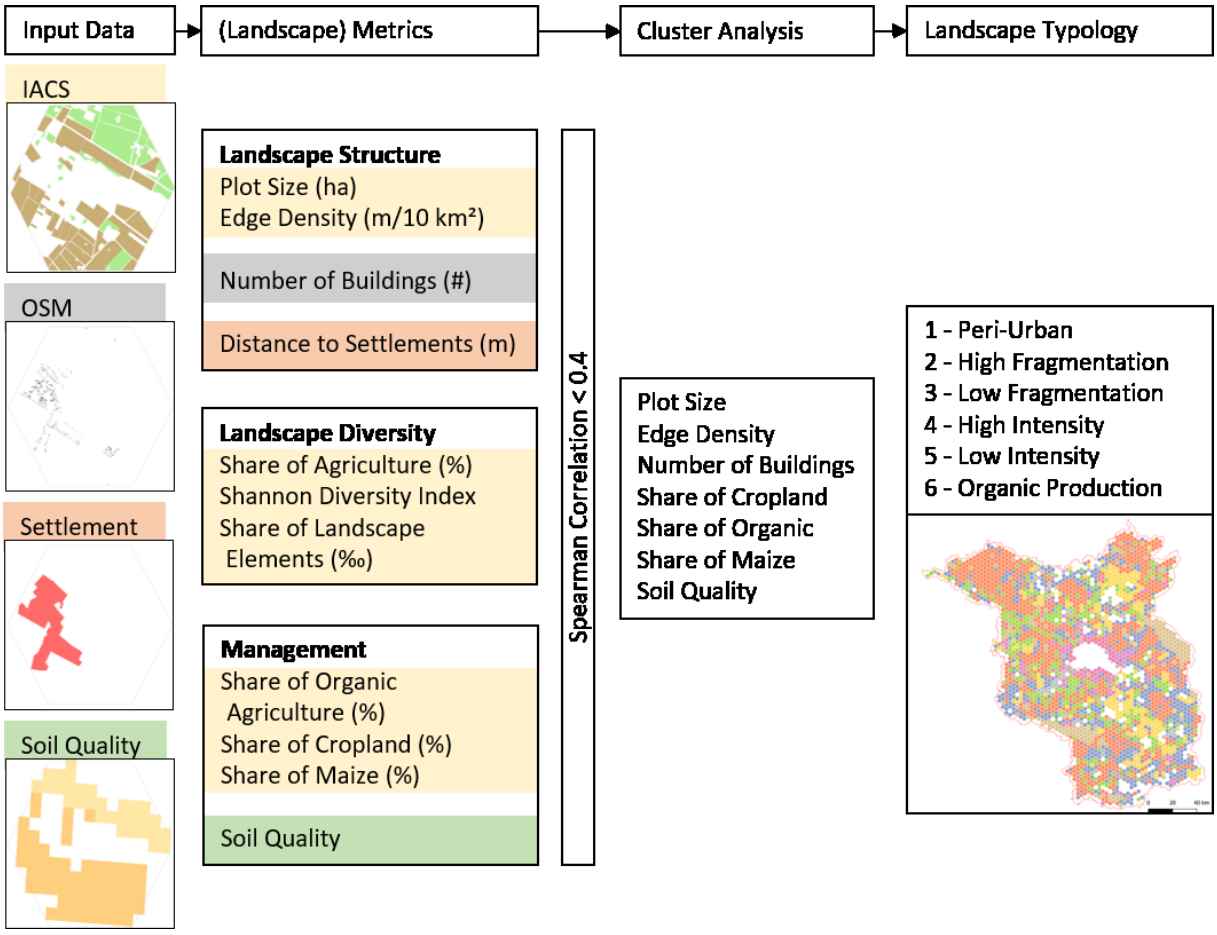


Figure 3.2: Workflow including data and processing steps from indicator calculation to cluster analysis for identifying agricultural landscape types

We followed the approach of Lüker-Jans et al. (2016), that characterised agricultural land use patterns using k-means clustering. Here, we applied a two-step cluster analysis because of its ability to deal with large datasets, including variables that are not normally distributed, and the possibility of automatically determining the optimum number of clusters (Chiu et al., 2001). In the first pre-clustering step, the Bayesian information criterion (BIC) was calculated for each cluster, which was then used to generate an initial estimate of the number of clusters. The second step refined the initial estimate by determining the greatest change in distance between the two closest clusters in each hierarchical clustering stage (Chiu et al., 2001). We note that 178 hexagons could not be clustered due to missing soil quality data in those cells; consequently, no type could be assigned.

For goodness assessment of the cluster number, the model fit was evaluated using the silhouette coefficient, which is a measure of the cohesion and separation of clusters. A value above 0.2 indicates a *fair* cluster quality (Tkaczynski, 2017).

Since the cluster values are categorical, we calculated the join count to determine the degree of spatial concentration or dispersion among a set of spatially adjacent polygons (Plant, 2012). To

calculate the join count for each cluster value, we set the reference cluster value to 1 and all other cluster values to 0.

3.3 Results and Discussion

3.3.1 Characteristics and spatial patterns of the agricultural landscape in Brandenburg

With respect to RQ1 and regard to the categories landscape structure, landscape diversity and management, we found the following results. For brevity, total values (min, max, median and standard deviation) for all hexagons are provided in Table A 3.1.

Landscape structure (Figure 3.3)

Most hexagonal cells show a rather low median plot size between 0.1 ha and 7.4 ha (N = 2347). However, median plot sizes can reach up to 27.0 ha to 46.9 ha (N = 9) which include both, cropland and grassland plots. The ecological value of certain plot sizes depends on the agricultural use; according to Crist and Peters (2014), larger and older plots of grassland might support greater biodiversity of insect species than do smaller plots. Other studies suggest that agricultural diversification–the compositional heterogeneity of crops within a landscape–supports an increase in both biodiversity and yields (Burchfield et al., 2019; Thomson et al., 2019).

Edge density represents the composition of plots. Hexagons that did not have strictly rectangular plot shapes showed higher edge density values. From this, we infer that such shapes might increase agricultural landscape diversity, in line with Uthes et al. (2020). Edges might operate as zones for ecologically valuable elements, such as hedges or tree rows.

Brandenburg contained many rural hexagons with a low number (0-421) of buildings (N = 2238). The highest settlement densities (number of buildings > 6041) were in cells adjacent to Berlin and to regional centers such as Neuruppin, Schwedt/Oder, Fürstenwalde, Cottbus and Jüterbog (N = 17). At the same time, most of the hexagons were characterized by short mean distances to the nearest settlement associated with high spatial autocorrelation (Moran's I = 0.51). Approximately 66% of cells showed a mean distance below 2 km.

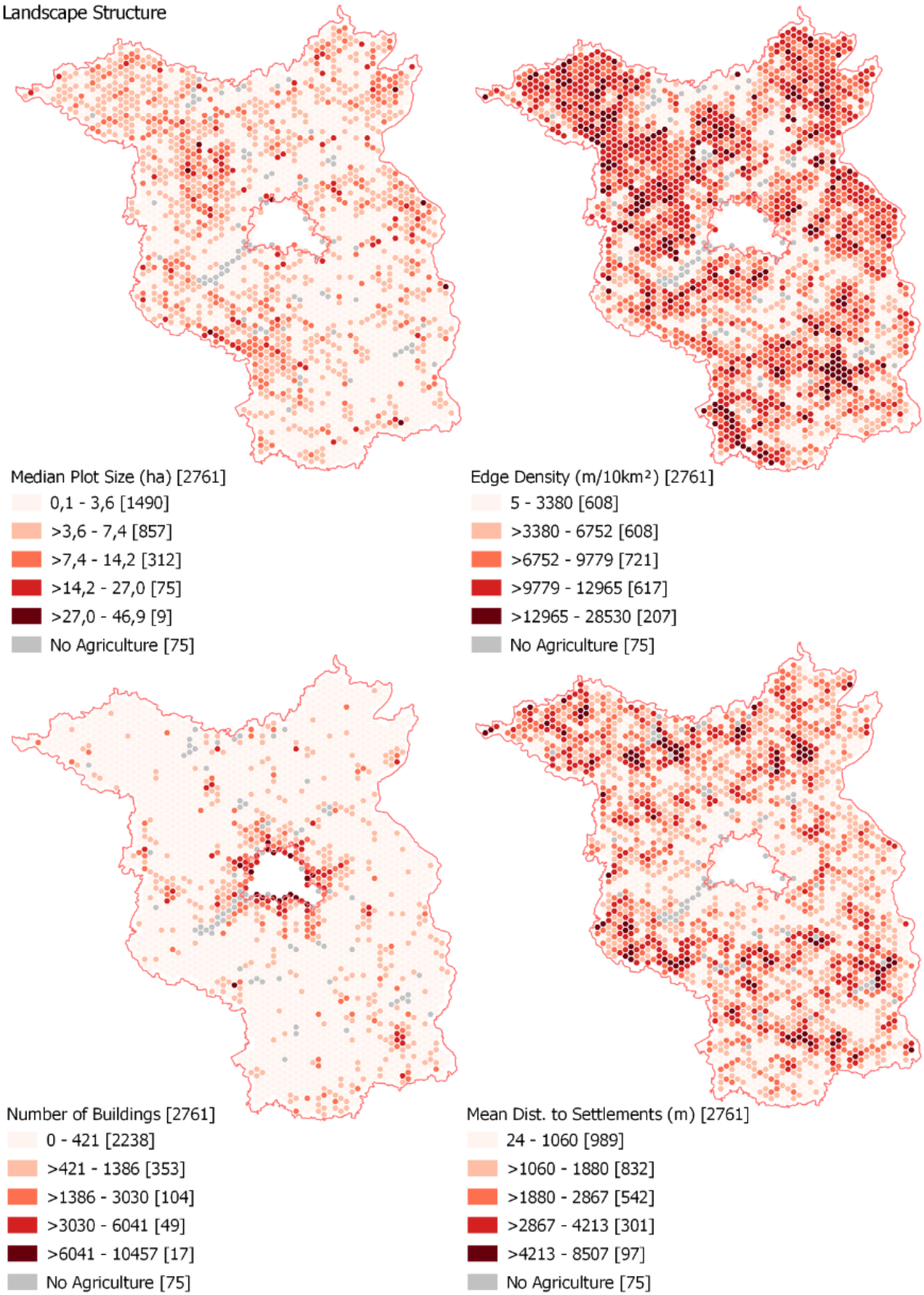


Figure 3.3: Maps for landscape structure indicators including median plot size (ha), edge density (m/10km²), number of buildings (#) and mean distance to settlements (m)

Landscape diversity (Figure 3.4)

The share of agricultural area per cell was evenly distributed between the 20% step-classes, with the exception of those with a very high agricultural share (> 80%,N = 349 of 2761). The highest agricultural shares were found in cells with the highest values for mean soil quality (> 62). Only 75 hexagons contained no agricultural land at all and were instead covered by forest, urban centers or water surface. The spatial autocorrelation analysis of agriculture share returned a Moran's I value of 0.59 indicating relatively high spatial concentration of hexagons.

The SDI, calculated as a proxy indicator for agrobiodiversity, showed low positive spatial autocorrelation (Moran's I = 0.37). Areas with a high share of organic agriculture, however, showed no explicitly higher values for the SDI.

The share of landscape elements was generally low in relation to the total agricultural area (between 0-1% for 73% of the hexagons) due to the chosen landscape scale. However, they perform a number of functions, such as serving as windbreaks, modifying the microclimate and assisting in soil retention and water purification (Stoate et al., 2009). They also enhance landscape diversity and connectivity, are explicitly acknowledged as important cultural features and have recreational, aesthetic and heritage value (van der Zanden et al., 2016).

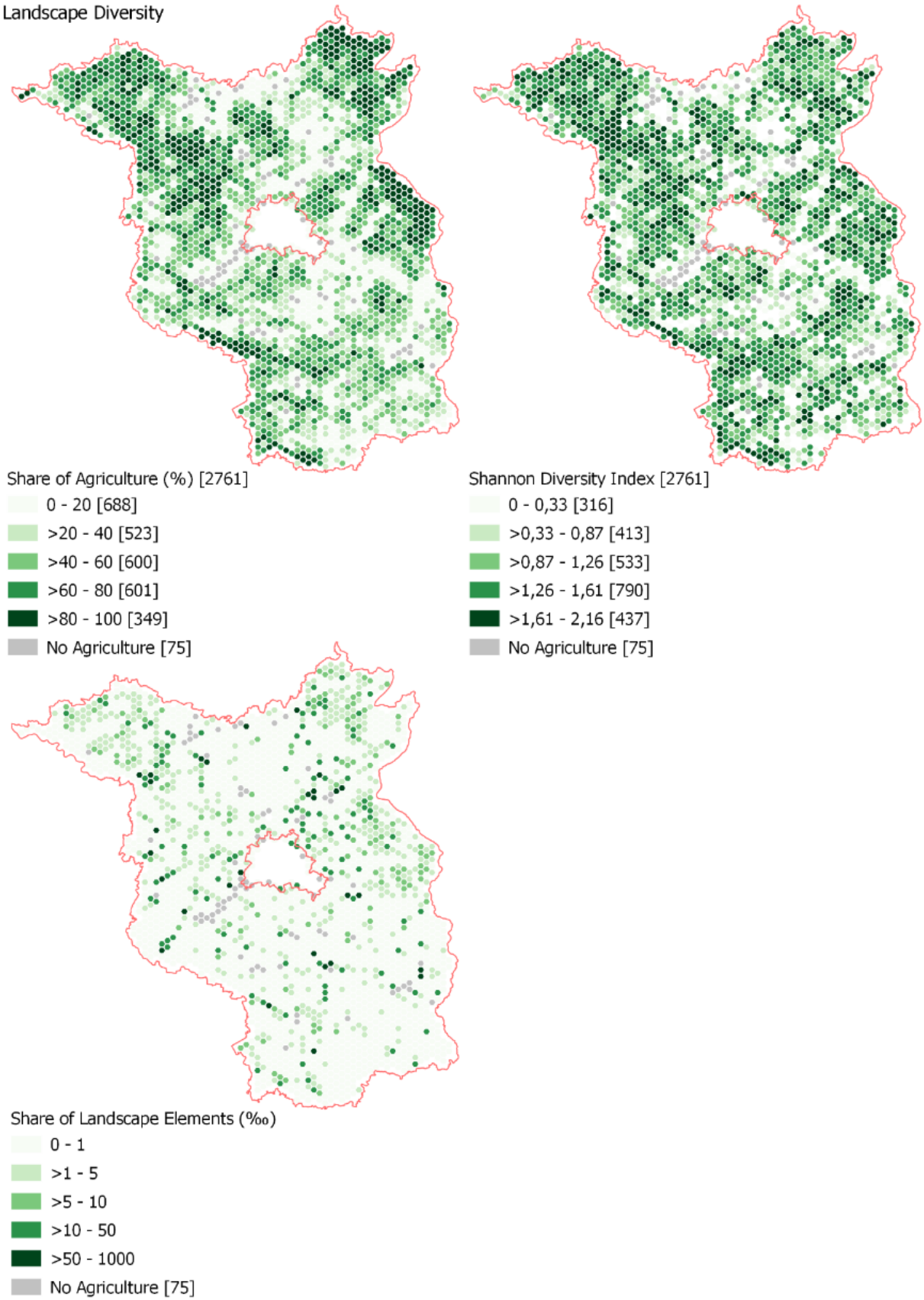


Figure 3.4: Maps for landscape diversity indicators including share of agriculture (% of total area), Shannon Diversity Index and Share of Landscape Elements (‰ of total UAA)

Management (Figure 3.5)

About 8% of hexagons showed values of more than a 60% share of organic agriculture with high spatial autocorrelation (Moran's I = 0.56). Best (2006) states that farmers' decision to switch to organic management is dependent on multiple factors, but might include socialization factors, such as neighbors' perceptions and social connectivity. The decision to switch is also influenced by higher uncertainties in yields leading to a fear of lower income and dependence on subsidies (Best, 2006).

Most of the agriculturally used areas were characterized by a high share of cropland (53% of hexagons show values > 80% cropland share), and cells with a low share of cropland had low soil quality. In contrast, the maize share was below 20% in 1,955 of 2,761 cells (71%), with low spatial autocorrelation (Moran's I = 0.30).

Brandenburg's mean SQR ranges between 37 and 79 which indicates generally rather low soil quality and thus yield potential. Mean soil quality shows low values of spatial autocorrelation (Moran's I = 0.33).

To identify types of agricultural landscapes and cover systematic patterns, reduction of dimensionality was necessary and subsequently implemented as the two-step cluster analysis.

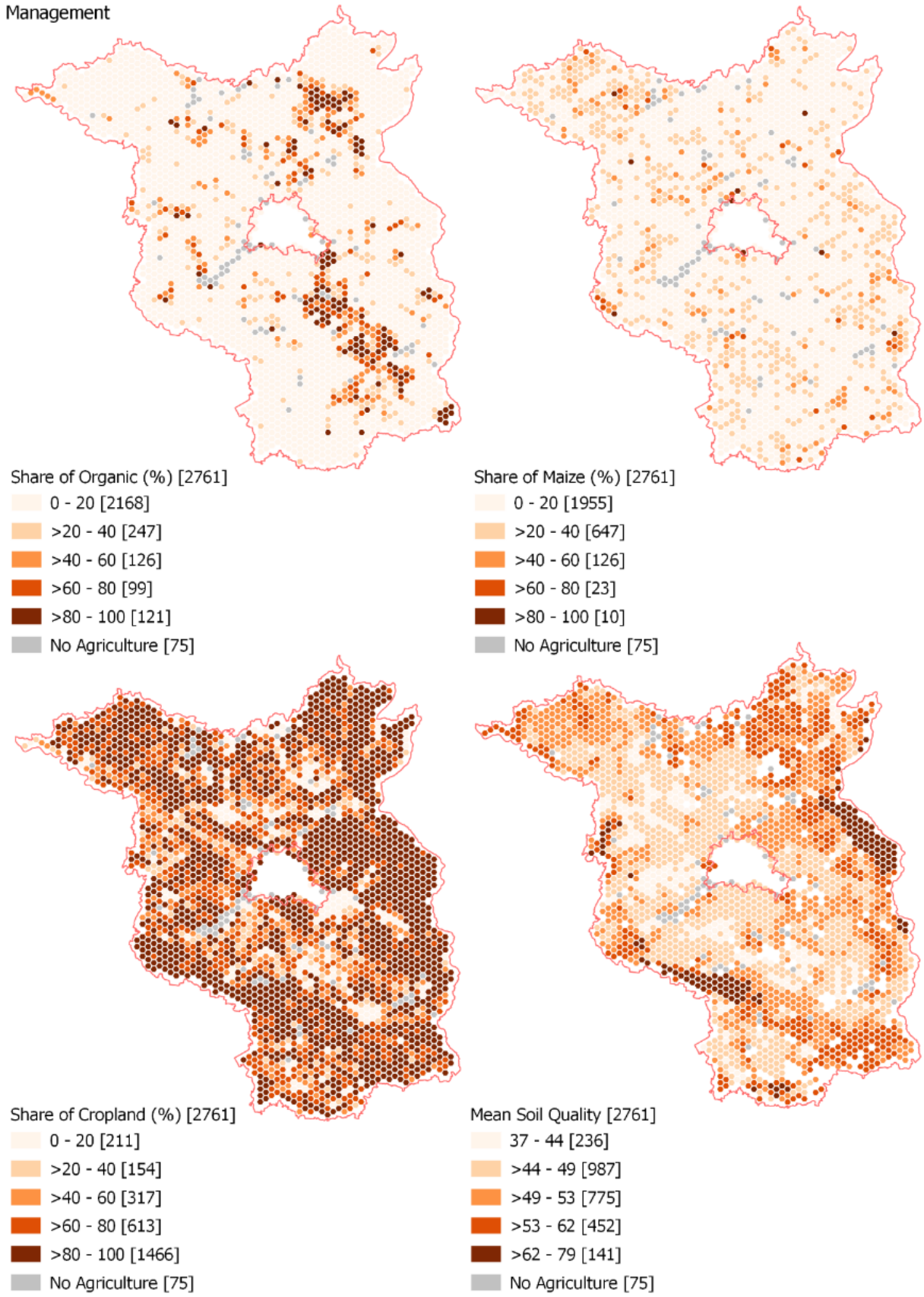


Figure 3.5: Maps for Management indicators including share of organic, share of maize, share of cropland (% of total UAA) and mean soil quality (points)

3.3.2 Types of agricultural landscapes and spatial patterns

In this section we answer RQ2, identifying types of agricultural landscapes and their spatial concentrations. The twostep clustering analysis returned the most optimal results with a cluster number of six, with a relatively low BIC value of 7 894.076 and the highest distance measure of 1.546 (Table A 3.2). The silhouette measure of cluster cohesion and separation indicates a fair quality (0.3) of the resulting number of six clusters. Based on the cluster analysis, we identified six different types of agricultural landscapes in Brandenburg: peri-urban, high fragmentation, low fragmentation, high intensity, low intensity and organic production described in more detail in Figure 3.6. Median values of clusters are summarized in Table 3.2 and Figure 3.7. The map in Figure 3.8 shows the spatial distribution of clusters in Brandenburg. For the join count, results with significance level $p > 0.01$, and thus cells with only one or two total neighboring hexagons, were excluded. We identified a high positive spatial autocorrelation for the high intensity (N = 98) and organic production (N = 95) clusters. That is, one agricultural landscape type was likely located next to another agricultural landscape of the same type. The spatial clustering of high-intensity agriculture that we found in our results may be attributed to the underlying spatial clustering of high soil quality.

Table 3.2: Centroid of clusters with the lowest (italic) and highest (bold) values

	Cluster centroid						
Cluster	**Soil Quality**	**Number of Buildings**	**Edge Density (km 10km^2)**	**Median Plot Size (ha)**	**Organic Share (%)**	**Maize Share (%)**	**Cropland Share (%)**
1 – Peri-urban	49.4	**3206.2**	5.0	*3.0*	7.6	10.1	68.9
2 – High fragmentation	49.4	194.7	**10.4**	4.4	5.1	18.4	83.7
3 – Low fragmentation	51.3	197.4	*4.1*	3.5	5.3	19.3	86.7
4 – High intensity	**62.8**	*173.9*	7.9	**11.2**	*3.2*	**20.5**	**93.7**
5 – Low intensity	*47.2*	207.8	8.3	4.5	12.9	7.2	*35.7*
6 – Organic production	50.4	244.6	6.3	3.2	**68.9**	*4.8*	72.1
Combined	50.8	374.8	7.7	4.6	13.5	15.1	75.6

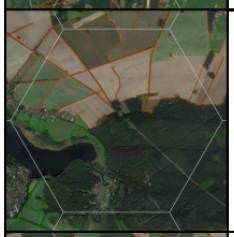
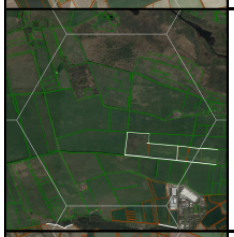
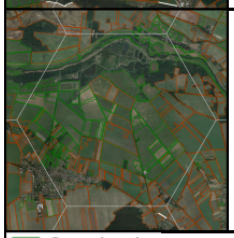
Sample Image	#	Name	%	Description
	1	Peri-Urban	5.8	Characterised primarily by a high mean number of buildings (3,206), the lowest mean share of agricultural area (24.5%) and a relatively low edge density (mean: 5.0 km/10 km2). The lowest average median plot size (3.0 ha) and soil quality (49.4) in this cluster were smaller than in other clusters, as noted by Weissteiner et al. (2016). The shares of maize and cropland also tended to be lower than in the other clusters.
	2	High Fragmen-tation	31.6	High fragmentation and a high mean of agriculture share (66.0%). This goes along with a high share of cropland (83.7%) and maize (18.4%).
	3	Low Fragmen-tation	22.4	Characterised by low fragmentation of the agricultural landscape, a low mean agriculture share (25.5%) but a high share of cropland, relatively high soil quality and low edge density. The landscape in this cluster was not dominated by agriculture, but rather other types of land cover, such as water or forest.
	4	High Intensity	8.9	Showed the highest mean agriculture share (66.3%), high-quality soil (62.8), larger mean plot sizes (11.2 ha) with large shares of cropland (93.7%) and maize (20.5%).
	5	Low Intensity	15.6	Mainly included grasslands, with a mean agriculture share of 44.5%, and had a comparably low mean soil quality (47.2) and a low share of cropland (35.7%). In contrast to other clusters (except Cluster 6), the mean organic share in this cluster was relatively high (12.9%).
	6	Organic Produc-tion	11.2	Represents organic farming, and was characterised by a low share of cropland and maize, smaller median plot sizes (3.2 ha) and a mean agricultural share of 32.5%.
Grassland Cropland Google Satellite	Data Sources: IACS 2018 Google Satellite			

Figure 3.6: Description of agricultural landscape types derived from two-step cluster analysis with exemplary satellite imagery for each type (Google)

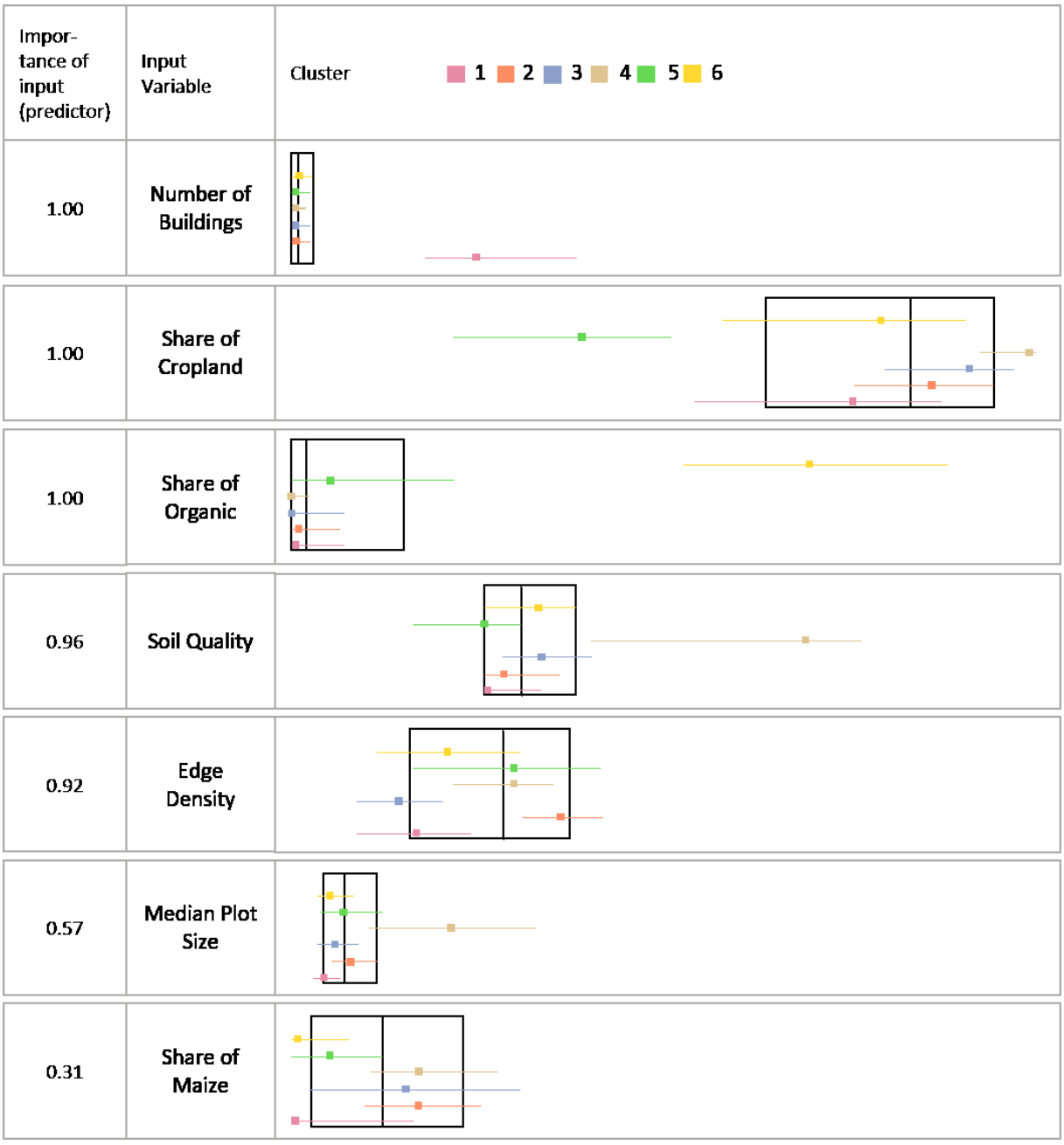


Figure 3.7: Comparison of input variables' value of importance and statistic values for clusters; colorbars represent clusters (1–6) with median and 25% and 75% quantile, white boxes represent the combined values showing median, 25% and 75% quantile

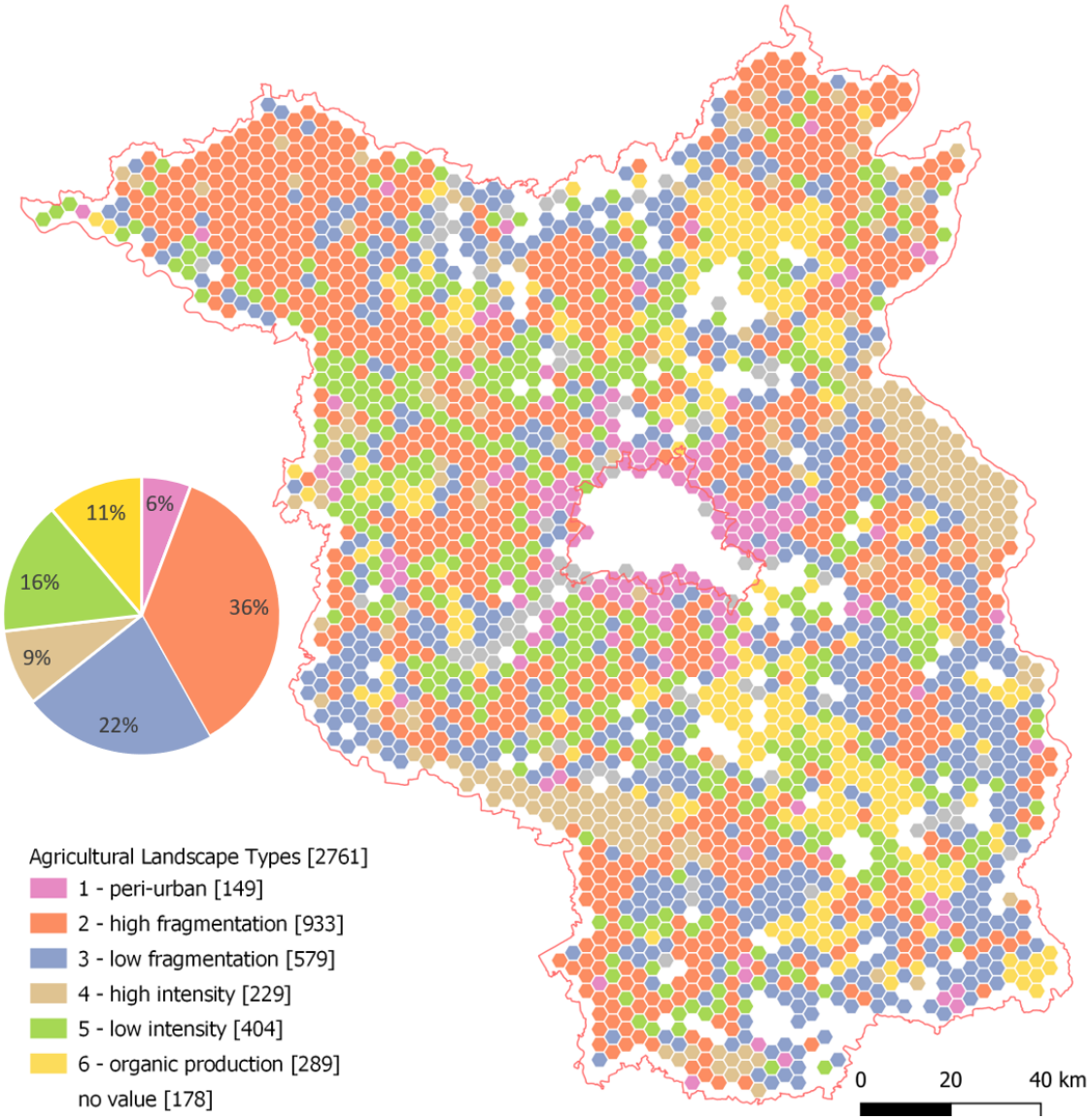


Figure 3.8: Map of agricultural landscape types in Brandenburg, Germany in 2018

We found that hexagons with a high percentage of organic farming had lower median plot sizes (cluster 6, Figure 3.7), which is in line with the studies of Best (2006) and Caporali et al. (2003). As shown by the study of Bichler and Häring (2003), land with high shares of organic agriculture tends to show higher shares of grassland and lower shares of maize (Figure 3.7), especially in Brandenburg where there is a low livestock density. Edge density tends to be higher in areas with a high share of organic farming and a low share of maize. In contrast to other studies, we could not find significantly higher soil qualities in areas under organic production; however, agglomeration effects of organic farming have been noted (Schmidtner et al., 2012). One reason for this finding could be that organic agriculture is possible even in close proximity to nature preserves, which cover larger coherent areas in Brandenburg

(Venghaus and Acosta, 2018). The low fragmentation (N = 34) and low intensity (N = 43) clusters did not show a high degree of spatial autocorrelation and were distributed across the state. The peri-urban (N = 54) and high fragmentation (N = 71) clusters showed medium spatial autocorrelation and seemed randomly spatially distributed over the state, whereby the peri-urban cells were concentrated around Berlin.

The increase of maize cultivation in Brandenburg in recent years has led to areas with larger plot sizes, hence the lower edge densities and potentially intensive management (represented by clusters 3 and 4, N = 808 which accounted for 30% of all hexagons). Lüker-Jans et al. (2016: 2) emphasize that 'intensive land use is connected to landscapes with rather favorable site conditions for arable cultivation such as relatively flat and fertile land', which corresponds with our findings, particularly for cluster 3 low fragmentation and cluster 4 high intensity. Consistent with Lüker-Jans et al. (2016), using k-means clustering, we identified similar agricultural types based on cropland share, with maize as a focal crop. However, in contrast to our hexagons, which provided a smooth, homogeneous surface that enabled unambiguous identification of neighborhoods for the study area, Lüker-Jans et al. (2016) analyzed metrics on a municipal level, which resulted in a higher variance in shape and size than grid-based analysis.

3.3.3 General Discussions

Other studies which identify landscape types consider similar indicators such as plot size, share of cropland, built-up or linear landscape elements (Levers et al., 2018; Tieskens et al., 2017; van der Zanden et al., 2016). In relation to the European archetypes by Levers et al. (2018), our identified types are in line with the intensity classifications for Brandenburg (i.e., large share of cropland or as landscape mosaic). However, our clusters considered additional, region-specific plot-based information with a focus on agricultural landscape structure, diversity and management characteristics. Similar to van der Zanden et al. (2016)and Tieskens et al. (2017), who also take into account landscape composition, structure and management indicators but on a European level, our types range from small to large farming scale as indicated by median plot sizes, and can be further differentiated by edge density (potential linear elements) and land management intensity (approximated by the share of cropland and maize). Several studies showed that Brandenburg is characterized by agriculture under medium to large scale arable land (Andersen et al., 2013; Levers et al., 2018; van der Zanden et al., 2016). In addition to the identification landscape types, our study analyzed the spatial patterns of characteristics and

types showing that particularly high intensity and organic farming tend to be spatially concentrated.

Our results complement and broaden information about agricultural landscapes, such as the agri-ecological zones of Brandenburg (*Landbaugebiete*), that have been given a suitability rating for crop production potentials (*Ackerzahl*; Landesamt für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung 2016) and the maps available in the Thünen Atlas, including the distribution of crop types or grassland on a municipal scale (Thünen Institut, 2014). Using a plot-based analysis, we add new information to the existing data regarding composition, configuration, diversity, and management, including intensity, which may become relevant also from a perspective of resilience and climate smartness of landscapes. Earlier typologies of Brandenburg's agriculture have been based mainly on farmers' decisions and referenced renewable energy production (Venghaus and Acosta, 2018). These authors considered farmers as decision makers as the designers of agricultural landscapes; however, the explicit landscape composition scale as we do here was not considered explicitly. In this study, we used different metrics as inputs for typologizing agriculture on a landscape level and thus complement the results of Uthes et al. (2020) and Venghaus and Acosta (2018), who focused their analysis on the farm level.

Our approach innovatively integrates different metrics into a new land use typology, which we consider an improvement over the use of single indicators (e.g., soil quality). The newly provided information improves the understanding of the agricultural landscape structure in Brandenburg and helps identifying regions specified support measures may be required. Additionally, the region-specific types can be used for monitoring changes over time or assessing changes after, for example, policy measures have been implemented from an outcome-based perspective. Resulting changes may for instance include the frequency and spatial distribution of identified types, but may also generate new types that are not included in the six used in this study.

Agricultural production in particular creates pressure on the environment whereby appropriate farming systems help preserve landscapes and habitats (Lütz and Felici, 2009). From the European policy perspective, the supply of ecosystem services and biodiversity conservation within farmland is fostered by the EU Biodiversity Strategy to 2020 and within the CAP's greening measures (Weissteiner et al., 2016). Typologizing the agricultural landscape in Brandenburg allows for the comprehensive assessment of the potential prioritization of areas for the supply of environmental measures, such as the implementation of green infrastructures

to support landscape diversity and connectivity supported by multifunctional agriculture (Oberlack et al., 2019). Through typologizing agricultural landscapes, along with estimates of the provision of ESS by type offers a step forward towards landscape-type functioning assessment. Exemplarily, Type 3 (low fragmentation) and Type 4 (high intensity) could indicate low habitat diversity due to large median plot sizes, low edge density and a high share of cropland and maize. Contrary, Type 2 (high fragmentation) and Type 5 (low intensity) indicate a potentially higher habitat diversity through a comparably low share of cropland and agriculture in general as well as through high edge densities. At the same time, in agricultural landscapes with a high share of organic agriculture (particularly Type 6) the farming systems are potentially offering enhanced ESS, for example biodiversity, soil quality or pollination services, and at the same time show low environmental impacts of agricultural production (Bavec and Bavec, 2015). Based on this approach, likewise, typologizing could be combined with climate smartness assessments, and help policy makers in defining and evaluating respective agricultural landscape feature goals.

Although our results are shown for an exemplary case study of Brandenburg, Germany, the methodology can be applied to other regions where sufficient data is available such as other regions in Germany and the EU. The integration of metrics via cluster analysis may result in different (number of) typologies in other areas, which is, however, one advantage of utilizing small-scale region-specific data rather than generalized types. The landscape focus enhances a more integrated assessment of agricultural landscapes than the focus on pure farm size and farm-based characteristic. Furthermore, a typology based on landscape structure, diversity and management is independent of the area of application and can thus be ubiquitarily applied as a general framework for the characterization of agricultural land.

3.3.4 Limitations and Further Research

Similar to Lomba et al. (2017), Uthes et al. (2020) and Lüker-Jans et al. (2016), we were able to show the potential of IACS data for analyzing agricultural land use. Future backing through remote sensing data, such as crop type mapping (Griffiths et al., 2018), crop yield mapping (Lobell et al., 2015) or landscape pattern analysis (Weissteiner et al., 2016), would increase the potential for this approach to be applied to areas in which frequent land use monitoring is not available. In this study, we did not consider the temporal dimension of land use, e.g. crop rotation and crop diversity over time. Applying our proposed method to different time slices would make it possible to address changes in the set of indicators and the resulting clustering.

This would reveal processes that occur in the agricultural landscape and could help identify how changes in boundary conditions would impact the composition of a landscape. In Brandenburg, two prominent examples of such processes are the increase of maize in the crop portfolio and the construction of biogas plants in direct response to implementation of the Act on Granting Priority to Renewable Energy Sources in 2000 (Federal Environmental Ministry, 2000). Such developments would be revealed by an analysis with multiple time periods of IACS data. Furthermore, our results do not represent a full set of potential agricultural landscape types, for example across the whole EU under different landscape structure, diversity and farmland management characteristics. We argue, however, that the methodological approach is highly transferable to other regions in the EU, where IACS data are available; missing soil quality assessments could for instance be replaced by increasingly available remote sensing data.

A common problem in ecological analyses of spatial indicators is the spatial scale and the unit of analysis known as the Modifiable Area Unit Problem (MAUP) (Wu, 2004) which is not quantitatively analyzed within this study. Scale dependence (of metrics and number of clusters) could be addressed by performing a sensitivity analysis of, for instance, changing grid cell size in future studies. In earlier studies, however, landscape metrics have proven to be a suitable tool for landscape analysis, even though there are limitations when it comes to up- and down-scaling of the generated results (Schlesinger and Drescher, 2018).

3.4 Conclusions

This paper focuses on the methodological suitability of standard and landscape metrics as an input for cluster analysis within a hexagonal grid. One of the advantages of using IACS data is the potential to transfer the approach to other study regions in which similar monitoring data are available.

Our findings reveal six different types of agricultural landscapes and their respective spatial patterns. We conclude that Brandenburg is characterized by highly fragmented agriculture and a high degree of spatial clustering of intensive agriculture and organic production. The chosen landscape metrics derived from IACS data have proven to be adequate for improving the understanding of agricultural landscapes. The approach could potentially be applied for measuring agricultural landscape structure and diversity in terms of plot composition and configuration at the EU level since IACS data are available across the EU. Our paper proposes an approach at the landscape level, which, according to Thomson et al. (2019), provides a

fundamental connection between the diverse array of relevant socio-economic and biophysical conditions and processes and can inform particularly regional decision-making.

In addition to performing spatio-temporal analysis, future work should address the relations among different types of agricultural landscapes and land price development, ownership patterns and trade-offs, for example between food and energy production, particularly on different units of analysis in regard to decision-making units.

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Appendix

Figure A 3.1: Spearman correlation coefficient matrix of indicators (blank = not significant)

Table A 3.1: Total values (all hexagons) for landscape characteristics in Brandenburg, Germany 2018

Category/Indicator	**Min**	**Max**	**Median**	**Standard Deviation**
Landscape Structure				
Plot size (ha)	0.1	46.9	3.4	4.1
Edge Density (m/10 km²)	4.8	28529.9	7632.4	4135.6
Number of buildings	0.0	10475.0	103.0	924.2
Distance to settlements (m)	23.6	8506.6	1416.3	1130.2
Landscape Diversity				

Share of agriculture (%)	0.0	96.4	45.34	27.4
Shannon Diversity Index	0.0	2.2	1.2	0.6
Share of landscape elements (‰)	0.0	1000.0	0.0	35.3
Management				
Share of organic agriculture (%)	0.0	100.0	1.8	24.0
Share of maize (%)	0.0	100.0	11.0	14.7
Share of cropland (%)	0.0	100.0	82.1	27.2
Soil quality	37.0	79.0	50.0	6.1

Table A 3.2: Automatic clustering. Six clusters show a relatively low BIC and high distance measures. Bold values indicate relatively low BIC and high distance measure resulting from two-step cluster analysis for the number of clusters = 6

# of Clusters	BIC	BIC change[a]	Relations of BIC changes[b]	Relations of distance measures[c]
1	12639.288			
2	10915.973	−1723.315	1.000	1.269
3	9581.095	−1334.878	0.775	1.664
4	8822.853	−758.241	0.440	1.349
5	8289.365	−533.488	0.310	1.274
6	**7894.076**	**−395.289**	**0.229**	**1.546**
7	7677.336	−216.740	0.126	1.074
8	7483.168	−194.168	0.113	1.086
9	7313.045	−170.124	0.099	1.069
10	7160.902	−152.143	0.088	1.273
11	7065.035	−95.867	0.056	1.206
12	7004.337	−60.698	0.035	1.188
13	6970.704	−33.633	0.020	1.024
14	6940.408	−30.297	0.018	1.041
15	6915.647	−24.760	0.014	1.285

a. The changes were based on the previous number of clusters in the table.

b. The change rates are relative to the change in the two cluster solutions.

c. The distance measurements are based on comparison of the current number of clusters with the previous number of clusters.

Chapter 4

Ecosystem Service Relationships and Scale Sensitivity of Agricultural Landscapes in Brandenburg, Germany

Agriculture, Ecosystems & Environment (under review)

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Abstract

Agricultural landscapes determine the provision of ecosystem services (ESS). The spatial heterogeneity of ecosystem services (ESS) is sensitive to both scale and unit of analysis (UoAs), but not enough is known about the scale sensitivity of the ESS relationships themselves. This study examines the spatial patterns and sensitivity to scale and UoAs between agricultural production and habitat provision services in Brandenburg, Germany. Using bivariate maps, we incorporate fine-scale plot-based data and land cover data to identify ESS indicators and their spatial patterns. We compare a set of different UoAs across different spatial landscape scales. To evaluate agricultural production, we use mean area-weighted maize plot density. To capture habitat provision, we use mean shortest distance to (semi-) natural habitats. We identify spatial patterns as a very strong spatial autocorrelation of agricultural production. Differences in the scale sensitivity between grid-based and administrative UoAs reveal that administrative units are more sensitive. At the landscape scale, conflicts between ESS dominate, whereas at the farm level there is an equal distribution of ESS conflicts and co-benefits. Our findings emphasize the importance of the landscape perspective in analyzing ESS and their relationships.

4.1 Introduction

Agricultural landscapes provide multifunctional ecosystem services (ESS). The Millennium Ecosystem Assessment (2005) defines ESS as the key benefits to human societies provided directly and indirectly by the ecological functioning of nature. Heterogenous agricultural landscapes combine fuel, food and fiber production with habitat provision (Rallings et al., 2019). Several studies suggest that landscape heterogeneity contributes to the environment and ecosystem functioning with benefits for society (Fahrig et al., 2011; Hendrickx et al., 2007; Musvoto et al., 2018; Weibull, 2003). According to Stein et al. (2014), it even could encourage species richness.

Other studies note that landscape homogeneity threatens natural habitats (Wätzold et al., 2020) (Burel and Baudry, 2005; Tscharntke et al., 2005); in particular, the intensification of large-scale agricultural land management reduces landscape heterogeneity (Cramer et al., 2017; Lütz and Felici, 2009). In some areas, however, local diversity in agroecosystems may compensate for the adverse environmental effects and decreased eco-functionalities (Tscharntke et al., 2005), and stabilize or increase yields (Burchfield et al., 2019).

The challenge for policy-makers and agricultural landscape experts is to find a balance between the diversity of ESS relationships. Typically, conflicts of interest are caused by trade-offs, where one ESS is reduced due to another service's increased use or supply, and synergies, where multiple services are enhanced at the same time (Bennett et al., 2009; Lee and Lautenbach, 2016). The terms trade-off and synergy consider truly causal interactive mechanisms between ESS (Vallet et al., 2018). This study categorizes ESS relationships by conflict and co-benefit. Conflict indicates a static negative association between ESS (Mouchet et al., 2014), and co-benefit indicates a high occurrence of multiple ESS at the same time.

Certain indicators are the fundamental units of ESS relationship analysis (Kanter et al., 2018), and their combinations aid in identifying ESS relationships between agricultural production and habitat provision. Key indicators include yield measure (Kanter et al., 2018; Burchfield et al., 2019), extent of habitat area (Fahrig et al., 2011), species richness (Brandt and Glemnitz, 2014; Verstegen et al., 2019; Weibull, 2003) and the distance to (semi-) natural habitat (Burel and Baudry, 2005; Devictor and Jiguet, 2007; Rüdisser et al., 2012). We use proxies and models when data are unavailable, for example on yields, or number of species (Kanter et al., 2018). Spatial configurations and concentrations of agricultural plots capture landscape heterogeneity; the larger and spatially concentrated the agricultural plots, the more homogeneous the landscape.

Spatial scale (i.e., resolution) and unit of analysis (UoA) (Bai et al., 2020; Cui et al., 2019; Purtauf et al., 2005; Roces-Díaz et al., 2018) are especially challenging. One challenge is to solve the Modifiable Area Unit Problem (MAUP) (Wu, 2004), i.e., spatially aggregating area-based data. Recent studies of spatial analysis use different levels of spatial resolution within a dataset, such as administrative (municipality, county), grid-based or (sub-)watersheds (Hou et al., 2018; Qiu et al., 2018). Another UoA of major importance is the farm level (Herzog et al., 2017; Kremen and Miles, 2012; Stoeckli et al., 2017; Uthes and Matzdorf, 2013). We note that many ESS involve processes which occur at much larger scales, for instance pollination by non-domesticated bee species, nutrient retention in landscapes, soil retention, carbon sequestration, flood control, sustained water yield, and biodiversity conservation (Dale et al., 2013). Balancing between the diversity of ESS relationships and making use of the knowledge obtained fosters the dialog between stakeholders (Vallet et al., 2018) required to support sustainability and improve yields.

This study presents an empirical analysis of the spatial scale and UoAs effect on ESS relationships demonstrated by two services, agricultural production and habitat provision, as a proof of concept using spatial metrics as indicators at the landscape level. We select the state of Brandenburg in eastern Germany, which is characterized by large farm sizes, low soil fertility and subsidies for agricultural energy production. We propose to answer three research questions:

RQ 1) What are Brandenburg's characteristics and spatial patterns of agricultural production and habitat provision?

RQ 2) What are the conflicts and co-benefits between the two ESS and how are they distributed in space?

RQ 3) What are the effects of choice of scale and UoAs on the two ESS and their relationships?

4.2 Material and Methods

4.2.1 Framework

Before turning to the case study, we present our methodological framework in the following. We use spatial metrics, particularly distance and density measures, to approximate two ESS. We create bivariate choropleth maps to see the relationships between two ESS. We classify each indicator into three classes based on quantiles and combine them for a total of nine classes

as shown in Figure 4.1. In these bivariate maps, each ESS follows a single-color hue with increasing saturation from low to high values (red and blue). The color matrix consisting of nine classes is then created by overlaying the two single color schemes. Hence, the class representing both ESS as high has the darkest color. Classes 3 and 7 which indicate very low values in one ESS in combination with very high values in the other denote a strong conflict. Class 9, which indicates a high-high relationship, denotes a strong co-benefit. Classes 4 and 6 denote a somewhat strong conflict. Class 5 denotes a medium co-benefit whereas class 1 indicates the lowest co-benefit for both ESS.

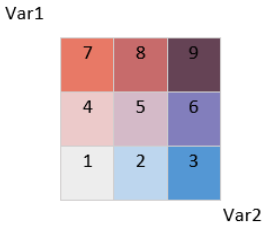

Figure 4.1: ESS relationship analysis classification derived by combining 3 quantiles of each input variable

Next, we use two different methods to detect the spatial patterns of ESS indicators and their relationships. First, we use Spatial Autocorrelation measured by the global Moran's I for single indicators with continuous values ranging from -1 to 1, where 0 indicates random spatial distribution and -1 or 1 indicate negative or positive spatial clustering, respectively (Moran, 1950). We note that the calculation of Moran's I for measuring spatial concentration for the categorical relationship classes values is not suitable (Plant, 2012). Therefore, we use the second method known as join count. For each of the relationship classes (1-9), each reference value is set to 1 and the other values to 0. Subsequently, neighboring units with the same value as the reference unit are counted. We use Queen's contiguity (corners and edges) to define neighborhoods for both methods.

We refer to scale as spatial analysis scale (or methodological scale), which denotes the unit size used for aggregation (Westerholt et al., 2015). We represent landscapes at different spatial scales and apply various UoAs. We consider two groups of landscape UoAs: 1) hexagonal grids and 2) administrative units related to the 'Nomenclature of Territorial Units for Statistics' (NUTS). To the latter, we add the farm-level as the smallest unit. A farm-based analysis introduces issues due to plot configuration, i.e., the plots of one farm can be scattered over space, or different farmers can own or rent single plots within a field block (Fischer and Biederbeck, 2015).

Each cell in the hexagonal grid contains equal areas and each cell has a uniform and unambiguous connectivity, having six neighbors share an edge, and neighboring cell centers are equidistant from the reference cell center (Sahr, 2011). Even though administrative units have non-uniform areas and no neighborhood relationships, they are widely used as an aggregation level in agricultural research (Gutzler et al., 2015; Plogmann et al., 2020; Schmidtner et al., 2012; Vaz et al., 2014), and they often correspond to decision-making entities.

To analyze scale sensitivity for the two landscape UoA groups, we analyze variances of indicators (data differentiation), and Spearman correlation coefficients (data consistency) between ESS (Purtauf et al., 2005; Wu, 2004) for 10 km², 20 km², and 50 km² hexagon scales. For the correlation analysis, the null hypothesis says there is no significant correlation between ESS. We compute p-values for the Spearman correlation using the asymptotic t-approximation and calculate all statistics across all UoAs separately for each spatial scale. We use ANOVA to examine the significance of differences in mean values of ESS indicators across the scale levels. We test between the two groups of UoAs and within single groups. The null hypothesis is that no differences in the mean values (concerning the test variable) exist.

4.2.2 Study region

Our study region is the federal state of Brandenburg in northeastern Germany, covering 29,640 km² (Figure 4.2). Agricultural land comprises approximately 45% (Amt für Statistik Berlin-Brandenburg, 2016) and the overall utilized agricultural area (UAA) has remained relatively constant since 2013, with about 77% cropland and 23% permanent grassland (Troegel and Schulz, 2018). Large farm enterprises with a size of approximately 250 ha, four times the German average (Gutzler et al., 2015; Troegel and Schulz, 2018) dominate. Surrounding Berlin, Brandenburg's farms supply the city with food crops and maize for biogas fermentation (Lupp et al., 2014). Brandenburg is vulnerable to climate change and the cascading effects on ecological systems include productivity losses with socioeconomic implications (Reyer et al., 2012). Given that nearly two-thirds of its soils are sandy and sandy-loamy, and rainfall on average less than 600 mm/year, Brandenburg's farms tend to grow niche organic crops, or rely heavily on fertilizers and agrochemicals (Gutzler et al., 2015).

4.2.3 Data

To compute the indicator values, we used plot-based information on the cultivation of crops in 2018 from the Integrated Administration and Control System (IACS), which collects data from farmers who register for area-based payments to ensure income support according to EU CAP regulations. Brandenburg's baseline map for registration is a digital cadastral map of field blocks established in 2015 covering the agricultural area eligible for EU subsidies. A field block is a coherent agricultural area surrounded by permanent borders (e.g., roads, paths, trees) with a predominantly uniform primary land use. Since more than one farmer can use a field block, the area of one field block may be split between the farmers who apply for subsidies. The outlines of agricultural plots generally align with the underlying field blocks, but may change over time due to a specific land use in a specific year, i.e., plot sizes and outlines. Registering farmers cite only the crop cultivated on May 31, the IACS annual registration date. While it is not possible to derive information on crop diversity and rotation for individual plots within one year, specific information on the crop cultivated on every single plot is available. Specifically, we extract maize plots for a part of our analysis. We also use two of seven land cover classes, perennial and seasonal high vegetation, based on Sentinel-2 imagery and LUCAS samples covering Germany with a resolution of 10 x 10 m (Weigand et al., 2020). Figure 4.2 shows the seven land cover classes and agricultural land uses in one location in Brandenburg.

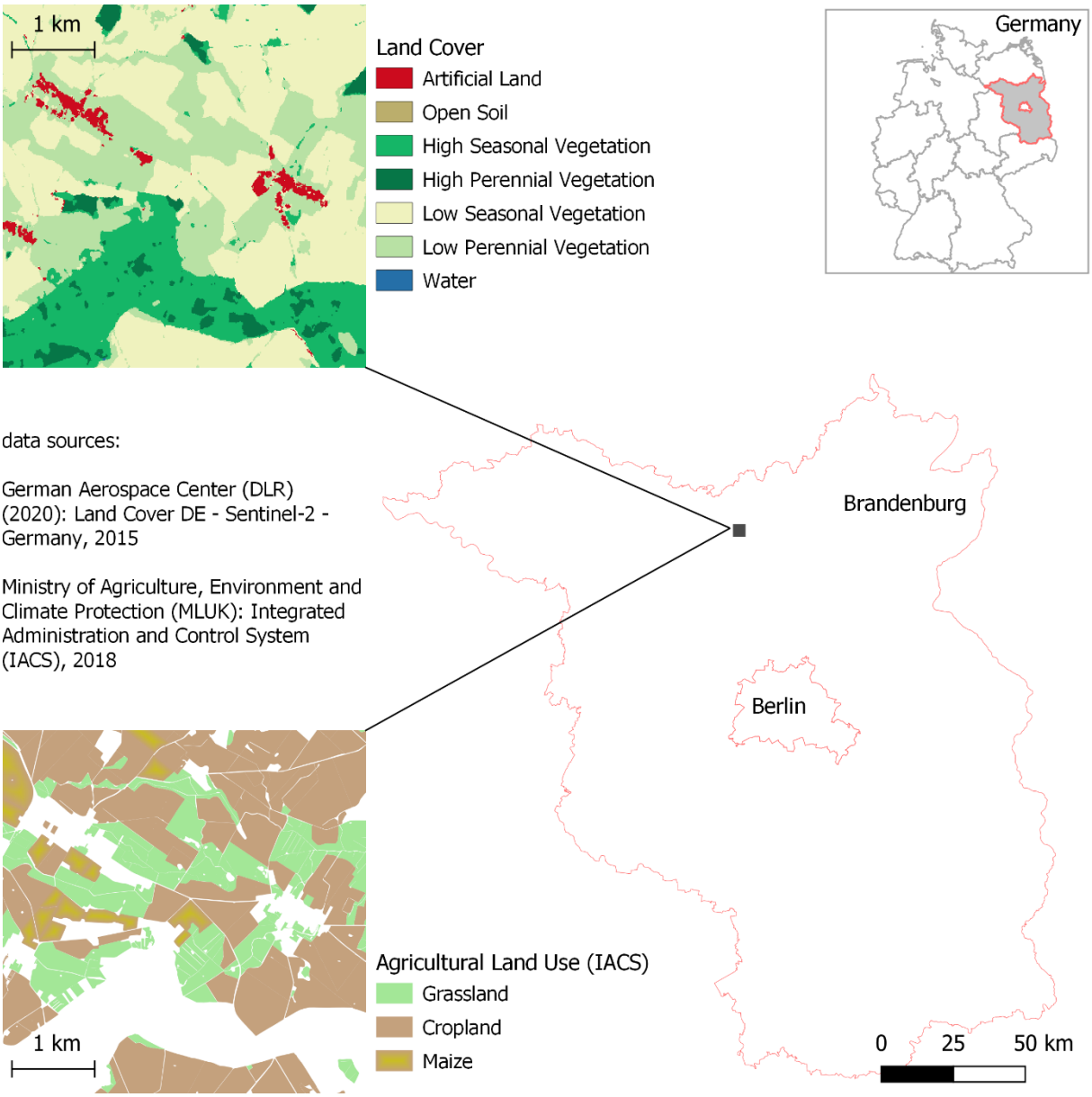

Figure 4.2: Land cover classes (top) and agricultural land uses (bottom) in one location of the study area

4.2.4 Indicator Selection and Calculation

As stated (see Introduction), we choose agricultural production and habitat provision to investigate scalability and any relationships between the two ESS in the study region. This section gives the details of our methodology as shown in Figure 4.3 below. We begin by describing our two ESS.

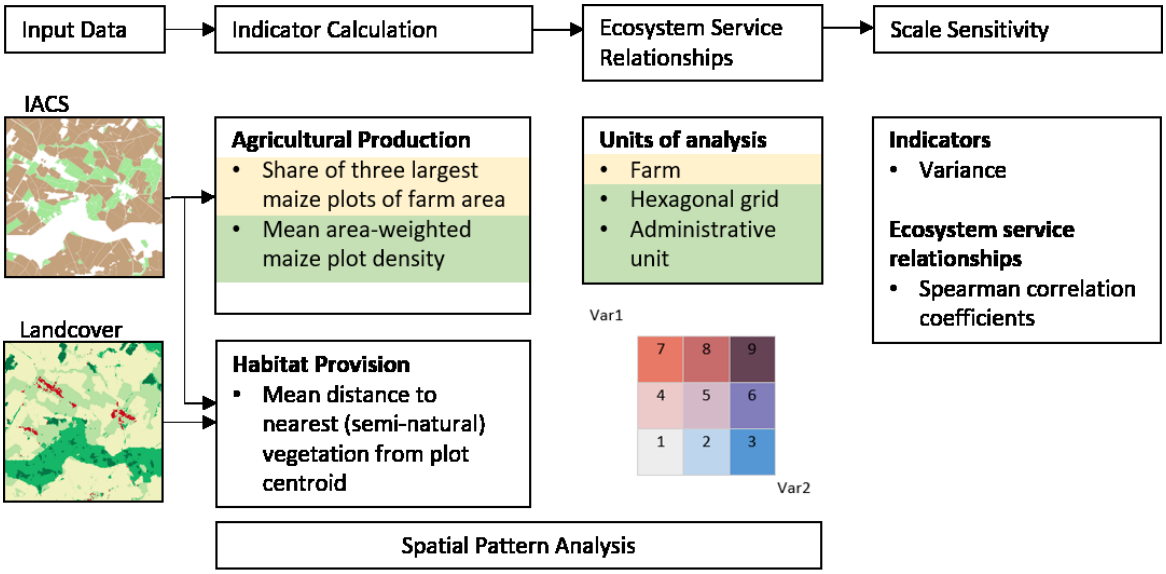

Figure 4.3: Methodological workflow including data processing, indicator and ecosystem service relationship calculations for different units of analysis and scale sensitivity

Agricultural production

Agricultural production determines a landscape's configuration. In response to the increased pressure of farms to improve economic efficiency, farms may prefer larger plot sizes to benefit from economies of scale and their spatial concentration to reduce the operating costs (mainly transportation) of field crops (Rodríguez and Wiegand, 2009). Since 2013 maize has become the main crop in Brandenburg (Troegel and Schulz, 2018). Its intensive cultivation includes monoculture in self-rotation, late seeding and lengthy periods of open soil. Maize, however, erodes soil because it does not root deeply and supports soil structure (Lupp et al., 2014). Crop rotations with a high share of maize also degrade soil (Lüker-Jans et al., 2016). Harvesting the whole plant for silage does not contribute to carbonization. We use spatial concentration of maize plots as a metric to approximate agricultural production because the yields are not available on plot level.

Habitat provision

Habitat provision considers the quality of a landscape for different animal and plant communities. A mosaic of crops and uncultivated patches and the distance from (semi-) natural habitats (Billeter et al., 2008) have a significant impact on species richness (Stein et al., 2014;

Weibull, 2003). In fact, agricultural production may as well benefit from landscape heterogeneity by increasing yields in diverse landscapes (Burchfield et al., 2019).

Calculating ESS indicators

We use spatial metrics to calculate the two ESS indicators as reported in Table 4.1. For agricultural production, we calculate the area-weighted Kernel density of maize plots based on plot centroids and aggregate the mean value to the set of UoAs and scales. Area-weighted density measures extend the single metrics of plot size or percentage of a specific crop in the UoAs to represent spatial concentration. Vizzari and Sigura (2015) note that Kernel density results are very useful for uncovering structural features which a parametric approach might not reveal in the data. To obtain the optimal processing environment regarding the spatial reference, we derive the Kernel density output cell size automatically. The cell size is the shorter of the width or height of the output extent in the output spatial reference divided by 250. The output spatial reference is the administrative boundary layer of Brandenburg leading to an output cell size of 1000 x 1000 m. We specifically compute the default search radius (bandwidth) to the input dataset using a spatial variant of Silverman's Rule of Thumb that is robust to spatial outliers (Silverman, 1986). To identify the spatial distribution of plots at farm level, we consider agricultural production using an adjusted indicator. For each farm, we calculate the share of the three largest maize plots of the total farm's utilized agricultural area (hereafter, 'farm maize share'). The farm-level analysis only considers farms cultivating maize and neglects 1856 of total 6034 of Brandenburg farms.

For habitat provision we use the high vegetation (perennial and seasonal) land cover classes representing (semi-) natural vegetation patches (Billeter et al., 2008; Cushman et al., 2008). They include broadleaved and coniferous woodland and permanent fruit trees (Weigand et al., 2020). We use proximity measures to capture structural diversity within the landscape (Burel and Baudry, 2005) and calculate the Euclidean distance to the nearest (semi-) natural vegetation from plot centroids. We aggregate the values as mean values of plot-centroids in one spatial unit for all UoAs and scales. For the calculation of *high* habitat provision, we reverse the values of mean distance to nearest vegetation, i.e., short mean distances correspond to high habitat provision.

Table 4.1: Overview of ecosystem service indicator calculation

Ecosystem service	**Indicator**	**Indicandum**	**Processing**	**Data Source**
Agricultural Production	<u>Farm Level</u> share of three largest maize plots of total farm utilized agricultural area (UAA) (%) <u>Landscape level</u> Mean density of maize plots (N/km²)	Landscape configuration and spatial concentration of agriculture	Plot-based $share = \frac{\sum_{i=\max(N)}^{\max(N-2)} m}{a} * 100$ where m = maize cultivated plot area a = total farm UAA N = total number of maize plots Area-weighted kernel density of maize plot centroids $density = \frac{1}{(radius)^2} \sum_{i=1}^{n} [\frac{3}{\pi} \times pop_i \left(1 - \left(\frac{dist_i}{radius}\right)^2\right)^2]$ for $dist_i < radius$, where i = 1, … ,n are the input points only included if within the radius distance of the (x,y) location pop_i is the weight of point i $dist_i$ is the distance between point i and the (x,y) location	IACS
Habitat Provision	Mean nearest distance to vegetation (m)	Landscape structural diversity	Plot-based Euclidean distance from plot centroid to nearest (semi-) natural vegetation $distance = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$, where x1, y1 are the coordinates of one point and x2, y2 are the coordinates of the other point	IACS, Landcover (Weigand et al., 2020)

Units of analysis and scales

As mentioned, farm level represents the operating unit of agricultural plots, administrative units and hexagonal grids serve as landscape levels of aggregation. We use three different spatial scales for each landscape UoA as shown in Figure 4.4). Administrative units include district (cadastral unit), municipality (Local Administrative Unit), and county (NUTS 3). We select comparative sizes of grids for the respective administrative units; the units of the 10 km² grid (N = 2782) correspond to the district (N = 2370, average area = 13 km²), and the 50 km² grid (N = 517) to the municipality (N = 417, average area = 71 km²). Due to the small sample size of counties (N = 18, average area = 1648 km²), we use an intermediate hexagonal scale of 20 km² (N = 1365) instead of an equivalent.

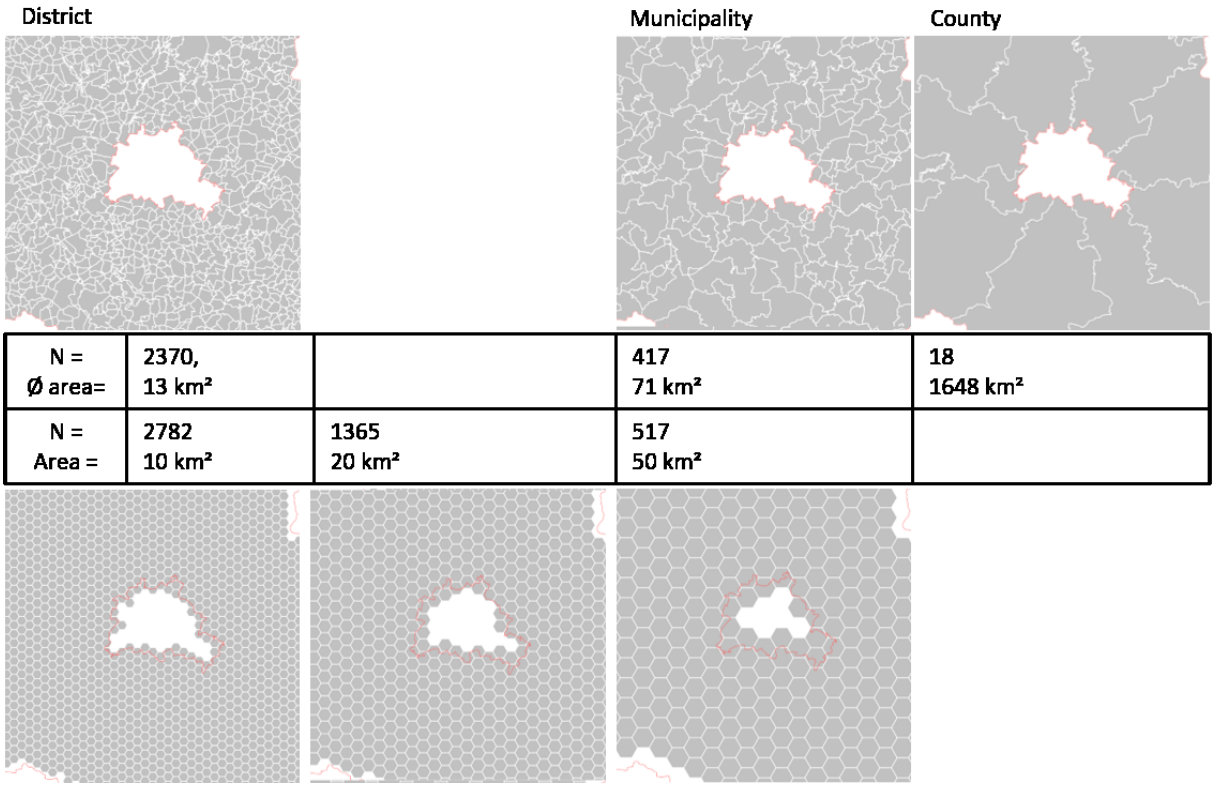

Figure 4.4: Comparison of units of analysis: administrative and hexagonal grid with scales (average area) and sample size (N) in Brandenburg

4.3 Results

4.3.1 Characteristics and spatial patterns of agricultural production and habitat provision

Figure 4.5 shows the results of our calculations for the two ESS. Non-aggregated values of maize density range from 0 to 33 per km² with a mean value of 3.78 per km². The highest densities are in northwestern and eastern Brandenburg, whereas the lowest are around Berlin. Plot-based values for distance to (semi-) natural vegetation range from 0 to 1957 m with a mean value of 170 m. The highest distances are in southwestern and northeastern Brandenburg, whereas the shortest are in the northwest and the south-central (Spreewald).

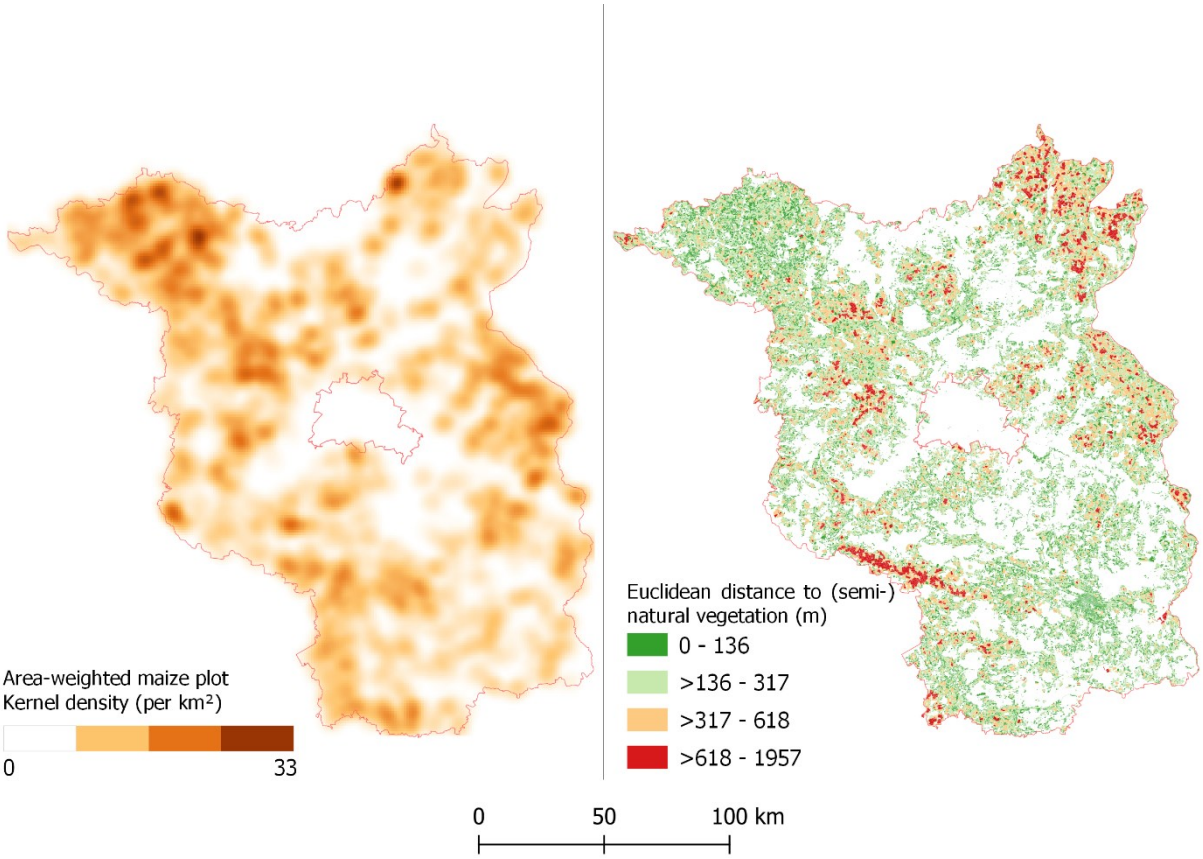

Figure 4.5: Left: area-weighted maize plot Kernel density (per km²); Right: plot-based Euclidean distance to (semi-) natural vegetation in Brandenburg

At farm level, maize share (three largest plots) ranges from 0.1 to 100% with a mean value of 18%. Consequently, for the majority of maize farms, they represent the minority of overall UAA (see Figure A 4.1 and Figure A 4.2 for the aggregated values of both ESS for both groups of UoAs across scales).

Maize plot density has a relatively similar data distribution for hexagonal UoAs with a decreasing maximum with increasing scale as shown in Figure 4.6, whereas administrative

UoAs have larger differences in data distribution. ANOVA results indicate a statistically strong significant difference of mean values between both UoA groups (p = 2.26e-05). Therefore, we reject the null hypothesis of equal data distribution between groups of spatial units. Within groups of UoAs, the grid-based units have no significant differences (p = 0.359), whereas the administrative units have strong significant differences in mean values (p = 0.00121).

The results are similar for habitat provision as shown in Figure 4.6. Administrative UoAs have more irregular data distributions. ANOVA results indicate a relatively weak significant difference between all UoAs (p= 0.016). Therefore, we reject the null hypothesis of equal data distribution between grid-based and administrative units.

Testing within single groups of UoAs finds no significant difference between mean values for the hexagonal grid (p= 0.656). Therefore, we cannot reject the null hypothesis if testing within administrative UoAs only (p= 0.224).

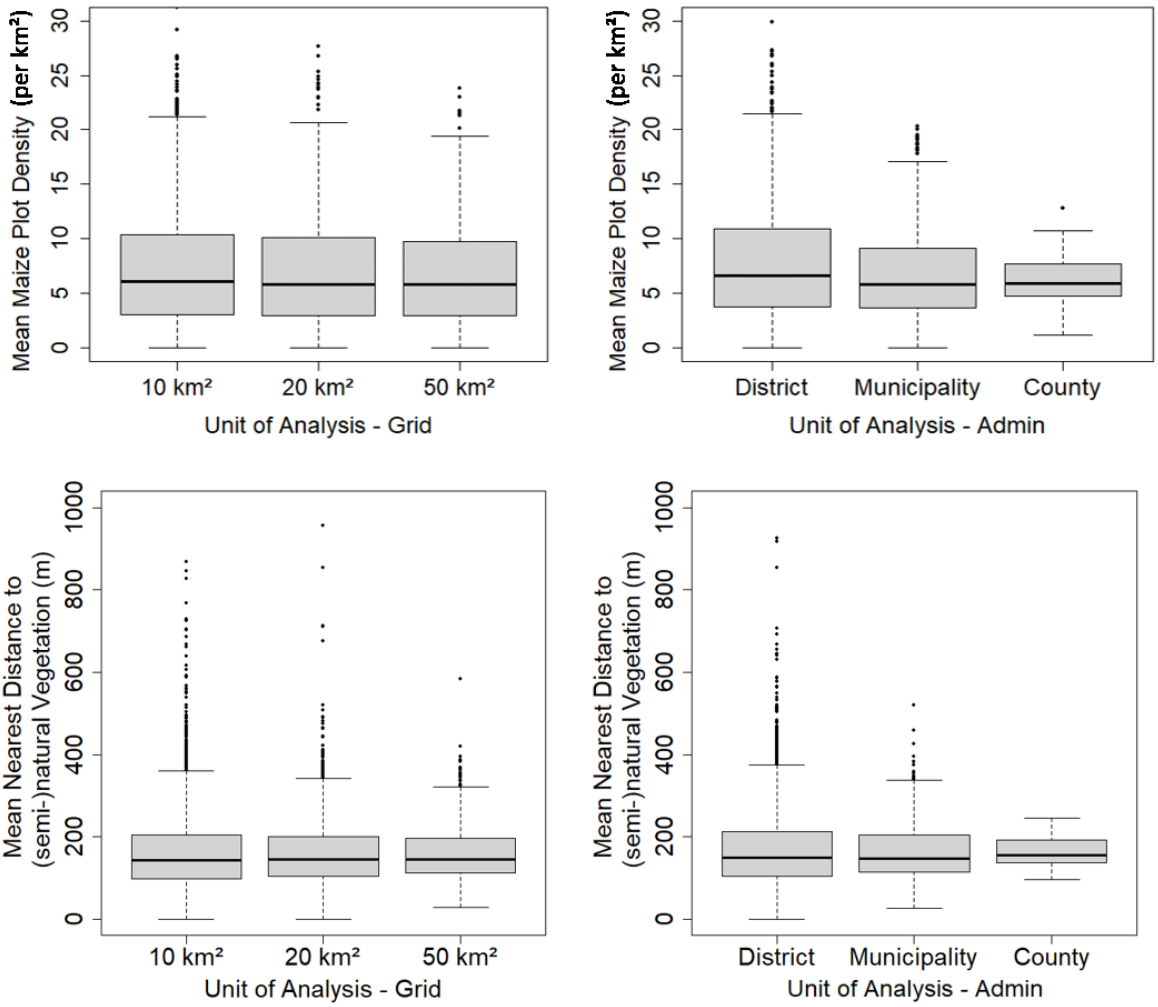

Figure 4.6: Boxplots of agricultural production (indicator mean maize plot density) and habitat provision (indicator mean nearest distance to semi-natural vegetation) across Unit of Analysis and scales

Spatial patterns of agricultural production indicate a very high spatial autocorrelation across all UoAs and scales with the highest Moran's I at small scales (district 0.8 and 10 km² grid 0.85). The Moran's I decreases with increasing scale for both grid-based and administrative UoAs. Spatial autocorrelation results for the county level are not representative due to the small sample size. The Moran's I of habitat provision indicates lower spatial concentration than agricultural production with the highest values of 0.56 for the 10 km² grid and 0.54 at the district level. Values of spatial autocorrelation decrease with increasing scale for the administrative UoAs, but remain relatively constant for the hexagonal grid. High spatial autocorrelation values for both ESS indicators and across UoAs and scales indicate that neighboring units are likely to show similar indicator values (spatial clustering).

4.3.2 Ecosystem service relationships and spatial patterns

We characterize ESS relationships by the conflicts and co-benefits which we identify according to the 9 classes of our bivariate choropleth maps. At farm scale, all relationship classes are equally distributed unlike grid-based and administrative UoAs as shown in Figure 4.7. Across all administrative and grid-based units, the high-low and low-high classes 3 and 7, respectively (the conflict classes), have the highest shares of all classes, with values up to 22%. These results show that ESS provision is stronger for either agricultural production or habitat provision (a conflict) but seldom at the same time (co-benefit).

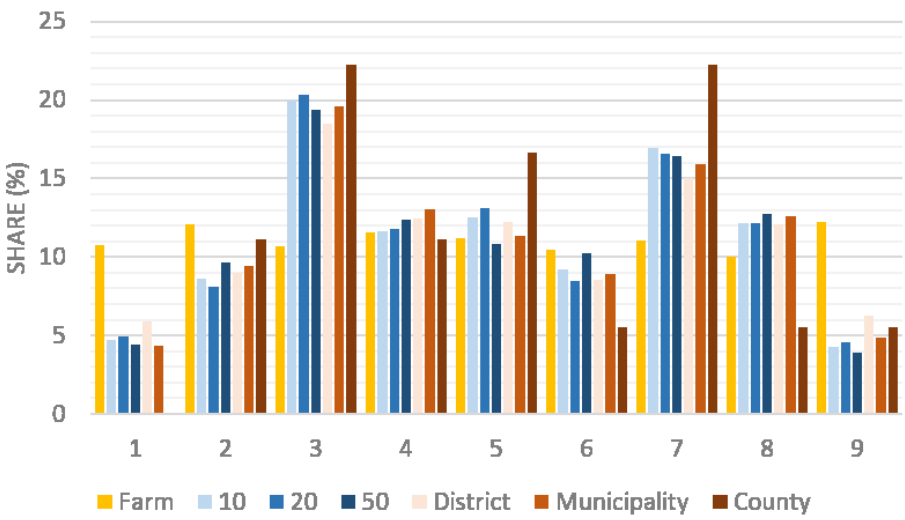

Figure 4.7: Relative share (%) of ecosystem service relationship classes (1-9) across all units of analysis and scales

At the landscape levels, we find patterns of co-benefits, i.e. high-high values across all scales too, though this class (9) shows the lowest frequency, spatially concentrated in the northwestern

region of Brandenburg, located in Prignitz county (Figure 4.8). Thereby, maize plot densities are high (class 7-9) in ~80% of hexagons at 10 km² scale. Farm-level results, however, show a majority of farms (~60%) with low to medium maize shares (class 1-6) in this region. To summarize, in Prignitz county, farms may be diverse in crop cultivation but the spatial concentration of the maize plots is high relative to the rest of Brandenburg.

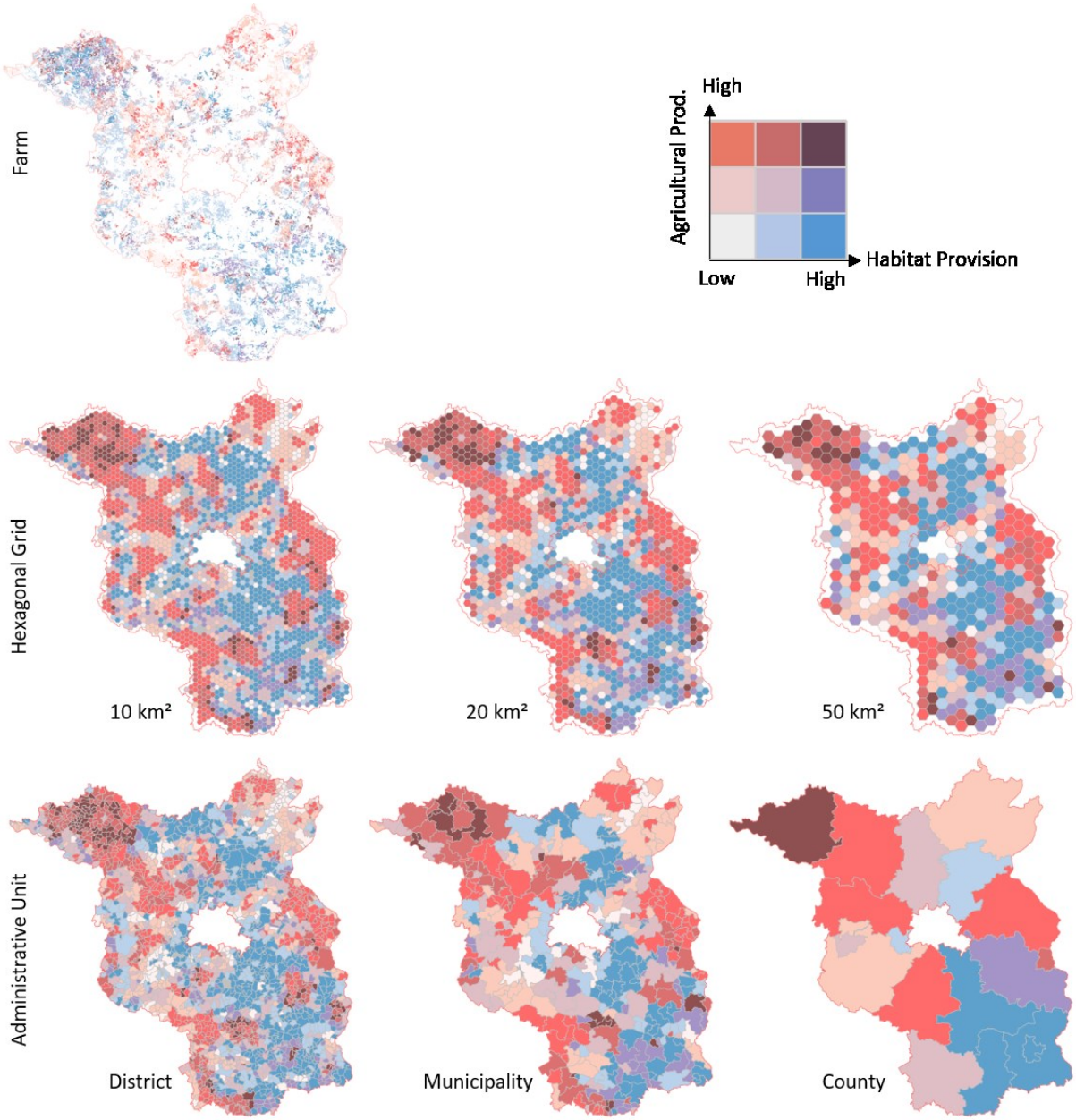

Figure 4.8: Maps of ecosystem service relationships (conflicts and co-benefits) at farm, grid-based and administrative units of analysis across scales

The results of the join count indicate only 5 of 20 units (25%) can be considered as cores of actual clusters for the 50 km² UoA class 9 (co-benefits) as the highest join count. We note similar values for 20 km² and municipality (Table A 4.1) with approximately 20% of the ESS units as cores of spatial clusters concentrated in northwestern Brandenburg. Results of the join

count also suggest that class 5 is least likely to cluster spatially across all UoAs and scales having the lowest join count values in relation to the total number of cases for the class. Overall, there is no strong tendency of conflicts and co-benefits spatially clustering across UoAs and scales. The comparison of join counts between groups of UoAs, however, have different and irregular tendencies. At the district level, join count values appear higher than at 10 km² grid level, but not for all classes. District level class 3 (high-low) and 10 km² class 7 (low-high) have the highest join count values.

4.3.3 Scale sensitivity and Units of Analysis

At the county level, variances for mean maize plot density range from 29 per km² for the 10 km² grid to 8 per km². The mean shortest distance to (semi-) natural vegetation ranges from 10475 m at the district level to 1741 m at the county level. For both ESS there is decreasing variance with increasing scale as shown in Figure 4.9. Comparing between UoA groups, administrative units have stronger decreasing variance with increasing scale. This trend is also noticeable in the Spearman correlation coefficients. We reject the null hypothesis and find positive correlations between agricultural production and habitat provision for all UoAs and scales except county level. Correlation between ESS have the highest values of 0.48 ($p < 2.2e-16$) for 20 km² and 50 km² grids. Whereas coefficients for grid units are relatively constant, the increase is stronger for administrative units with 0.36 ($p < 2.2e-16$) at district level and 0.46 ($p < 2.2e-16$) at municipality level as shown in Figure 4.9. Spearman correlation for the county level shows no significant results with $p= 0.055$. These results also demonstrate that administrative spatial units are more sensitive to scale than regular hexagonal grids when analyzing ESS relationships.

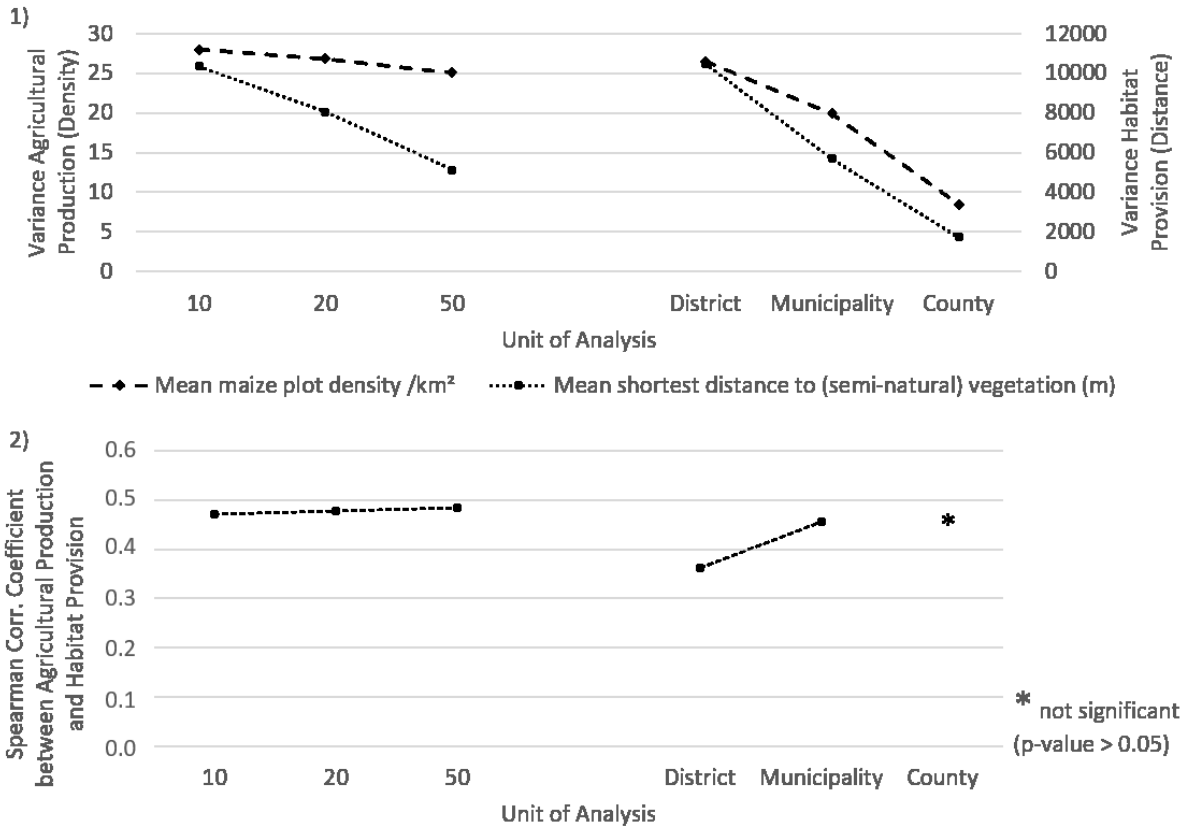

Figure 4.9: Top: variance (data differentiation) and bottom: Spearman correlation coefficients (data consistency) representing sensitivity of units of analysis and scales

4.4 Discussion

As mentioned in the introduction, we rely on proxies and models when data are unavailable, e.g., on yields, or number of species (Kanter et al., 2018). Using an area-weighted maize density metric offers the possibility of using an integrated measure of plot size and spatial distribution. We agree with Vizzari and Sigura (2015) who suggest that density analysis provides the most direct assessments.

Investigating the extent of maize production in Brandenburg enabled us to identify the benefits and conflicts between two important ecosystem services, agricultural production and habitat provision. High values of spatial autocorrelation suggest that agricultural production of maize is highly spatially concentrated in Brandenburg which is in line with the study of Vergara and Lakes (2019). With more than 50% of the agricultural plots in Brandenburg having distances larger than 300 m to (semi-) natural vegetation, our results support the need for smaller plot sizes and the integration of semi-natural habitat emphasized by (Tscharntke et al., 2021). The relatively high spatial autocorrelation values across all UoAs and scales also support spatial

clustering of habitat provision and identifying spatially clustered regions with low habitat provision in order to allocate more (semi-) natural vegetation. We note that Tscharntke et al. (2021) particularly stressed that the amount of semi-natural habitats in an agricultural landscape enhances species richness by linking croplands and natural areas, although rising land prices and housing pressure make it difficult to purchase and maintain semi-natural habitats.

Our analysis of spatial concentration of maize plots and habitat provision proves that co-benefits exist in regions with particular landscape compositions and configurations. Although we find that conflicts dominate in Brandenburg's agricultural landscape, at the same time areas with the highest maize plot density show the shortest distances to high vegetation. The co-benefits, however, only occur in a minority of cases and are spatially concentrated in the northwestern region of Brandenburg. Immerzeel et al. (2014) noted that habitat losses often relate to landscape homogenization; in Brandenburg, the majority of high habitat provision pairs with low agricultural production.

Our landscape-level analysis of the two ESS relationships highlights three significant differences compared to farm-scale analysis. First, ESS indicators on landscape level can be integrated independently of land ownership in a spatially continuous method. Second, ESS conflicts dominate at the landscape level, whereas conflicts and co-benefits are equally frequent at the farm level. Three, single farms can have a heterogeneous structure, but at landscape level, multiple farm areas can have a homogenous structure. Multi-scale analysis also produces granular insights. For instance, a single farm can be homogeneous in terms of habitat diversity but the landscape can be heterogeneous when homogenous, but differently producing farms, with diverse spatial patterns combine at landscape scale. Simultaneously, landscapes can be homogenous despite heterogenous production structures at the farm scale.

The differences in ESS relationships at farm and landscape levels support integrating a landscape perspective into policy and planning, rather than targeting individual farmers, although habitat provision is more effective in larger ranges than the average farm size (Franks, 2011). In 2020 the German Advisory Council on Global Change WBGU) emphasized the need for governance and planning at the landscape level. According to the FAO (2015), understanding various scales of ESS management provides insights into the availability of management functions and the types of institutions required to secure ecosystem services, e.g., farm cooperatives for farm-scale functions and eventually payments for landscape-scale functions.

Regarding scale dependency, our results are in line with Purtauf et al. (2005). Variances decrease with increasing scale, following the principles of aggregation, i.e., the higher the aggregation level, the larger the spatial unit, and the higher the correlation coefficient between two variables (Bahrenberg et al., 2010). ESS relationship trends are similar on all UoAs although increasing scale removes heterogeneity from spatial patterns, especially for the ESS indicators characterized by a more scattered distribution (lower Moran's I) as suggested by Roces-Díaz et al. (2018). We agree with the use of fine-scale spatial data when available to identify conflicts and co-benefits. If the main objective is identifying broad patterns of ES, intermediate levels, such as municipality are generally adequate, as they conserve many of the properties of assessments conducted at finer scales, and are more directly relevant for policy-making and assessment (Roces-Díaz et al., 2018; Wrbka et al., 2004). The county level, at least in Brandenburg, however, is suitable to a limited extent due to a small sample size and lack of detailed information on ESS relationships and spatial patterns. According to Turner and Gardner, 2015b) there is no single correct scale; the choice depends on the questions asked and the processes studied. Hence, agricultural policy-makers should consider all scale effects carefully.

In our study, the administrative UoAs are more prone to irregularities reflected by higher differences in variances of ESS indicators and spatial autocorrelation values. Additionally, the group of grid-based UoAs shows fewer differences in variance within the group, at least for habitat provision. The regular spatial surface is one reason why grids based on hexagons gained more popularity in recent years (Birch et al., 2007; Griffith et al., 2000; Stough et al., 2020). Hexagons are more suitable for spatial autocorrelation analysis because they provide a regular grid with equal number of neighbors for each hexagon. Contrary, administrative units are characterized by irregular neighborhood relationships which might also affect Moran's I values.

Our findings provide detailed complementary information to, for example, European-level studies, to cover the level from field to landscape as suggested by Overmars et al. (2014) in particular, when information on a local level is required. Our analysis integrates plot-based agricultural data and spatial metrics to measure ESS provision in agricultural landscapes in a spatially explicit manner. Accounting for spatial information explicitly can help us better describe and understand ESS relationships (Cord et al., 2017). Cord et al. (2017) suggest that spatially-explicit methods deserve more attention in the future, as they can directly address spatial interactions between the study location and its surrounding area and allow considering

neighboring effects of ESS and their relationships. Our findings may be relevant for multiple actors on different (spatial) levels regarding not only farm-based decision making but a landscape's multifunctional provision of services.

The methodological framework is transferable to other regions, particularly in the EU where local scale agricultural data (IACS) and high-resolution remote sensing land cover data are available. We follow the suggestion of Roces-Díaz et al. (2018) using small scale data and aggregating it as indicators to larger spatial scale, ranging from field to landscape. The identical base of assessing ESS using observational data for all UoAs removes some uncertainties when upscaling the indicator in our study. The data-driven classification leads to regionally comparable results which are, however, different for each unit of analysis and scale since quantiles can differ quantitatively.

This study is limited as follows. The data-driven classification of indicators using quantiles for each different UoAs and spatial scale allow only for a spatially explicit comparison of the results for Brandenburg and not between other regions due to the differences in the class boundaries. Considering indicators which allow for clear thresholds like nitrogen input would enable a standardized classification of ESS indicator values.

4.5 Conclusion

This study proposed a methodological framework to quantify and map ecosystem service relationships in agricultural landscapes, and to analyze the spatial patterns and effects of spatial unit and scale on the relationships. The framework used spatial scales from local, sub-regional and regional levels within grid-based and administrative units. An application to a case study of agricultural landscapes in Brandenburg, Germany, confirmed that using plot-based data helped to aggregate spatial metrics to the landscape level and was also beneficial for farm-level analysis.

This study found that conflicts between ESS dominated at landscape level and that conflicts and co-benefits occurred equally at farm level. The results affirmed the need to include agricultural landscapes managed by multiple farmers in agricultural planning and decision-making. Regional variability in the results highlighted the continued importance of landscape scale analyses in assessments of ecosystem services and their relationships across time and space. This study also noted that semi-natural elements enhanced landscape complexity and habitat quality. We believe that the proposed methodological approach is transferable to regions where fine-scale data are available, such as the European Union. The use of spatial metrics to

approximate ecosystem services allows for an integrated analysis of landscape structure regarding the simultaneous provision of food, fiber, fuel and habitat.

Based on this study we suggest several research avenues worth pursuing. Developing an edge-based metric combined with connectivity metrics would extend the habitat provision indicator. Using a larger sample size, i.e., a comprehensive, multi-dimensional set of ESS, would capture the details unnoticed in small datasets. Expanding the time scale of ESS relationship analysis would assist in testing, implementing and monitoring the effects of the policy measures proposed. More research would identify the relationships between the relationships and interactions of multiple ecosystem services across time and space. Agricultural policy would benefit from, trade-off analyses considering ESS causal relations and incorporating the services' improvement potential, e.g., via eco-efficiency analysis, or spatial optimization.

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Appendix

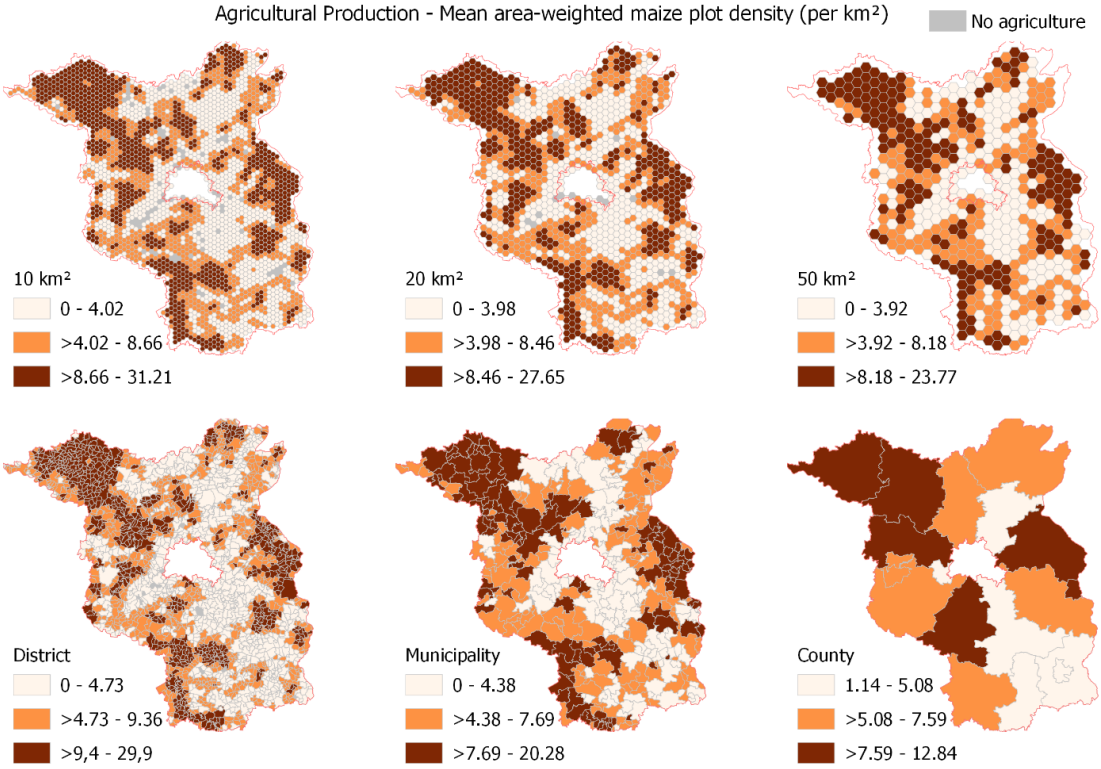

Figure A 4.1: Maps of mean area-weighted maize plot density (per km²) across UoA and scales classified by 1/3 and 2/3 quantiles

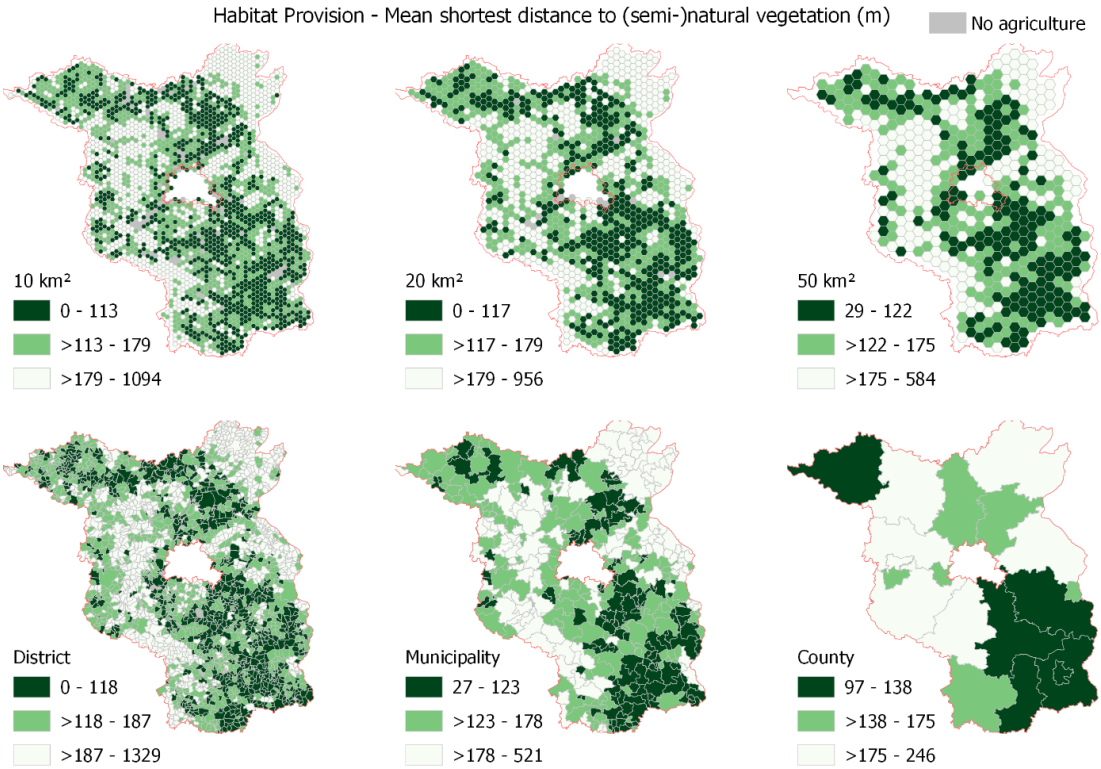

Figure A 4.2: Maps of mean shortest distance to (semi-) natural vegetation (m) across UoAs and scales classified by 1/3 and 2/3 quantiles

Table A 4.1: Results of spatial autocorrelation for single ecosystem service indicators mean area-weighted maize plot density (agricultural production) and mean shortest distance to (semi-) natural vegetation (habitat provision) using Moran's I (top) and ecosystem service relationships (bottom) using join count; classes 3 and 7 indicate strong conflicts and class 9 indicates strong co-benefits between ecosystem services

Moran's I		
	Mean distance	**Mean density**
10 km²	0.56	0.86
20 km²	0.52	0.77
50 km²	0.55	0.64
District	0.54	0.81
Municipality	0.47	0.61
County	0.47	0.13

Local join count p = 0.01, 999 permutations										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**SUM**
10 km²	7	26	56	39	18	19	91	43	7	306
N	115	223	517	316	339	266	470	339	119	2704
%	6.1	11.7	10.8	12.3	5.3	7.1	**19.4**	12.7	5.9	11.3
20 km²	2	8	31	17	1	6	41	20	12	138
N	64	106	272	160	177	117	226	167	62	1351
%	3.1	7.5	11.4	10.6	0.6	5.1	18.1	12.0	**19.4**	10.2
50 km²	1	1	12	3	1	1	15	2	5	41
N	23	50	100	64	56	53	85	66	20	517
%	4.3	2.0	12.0	4.7	1.8	1.9	17.6	3.0	**25.0**	7.9
District	23	9	84	39	11	24	56	38	19	303
N	135	202	425	288	291	202	355	284	151	2333
%	17.0	4.5	**19.8**	13.5	3.8	11.9	15.8	13.4	12.6	13.0
Municipality	1	0	5	8	0	3	6	6	4	33
N	18	38	80	54	47	38	66	53	20	414
%	5.6	0.0	6.3	14.8	0.0	7.9	9.1	11.3	**20.0**	8.0
County	0	0	0	0	0	0	0	0	0	0
N	0	2	4	2	3	1	4	1	1	18
%	/	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Chapter 5

Synthesis

5.1 Summary

The overarching aim of this thesis was to better understand landscapes and their spatial patterns that arise from underlying environmental and LUCC processes. The first research question targeted the description and analysis of land use and ESSs of landscapes. The second research question aimed to analyze the contribution of the landscape perspective to understanding land systems. The landscape perspective was the focus for two study regions where literature synthesis and expert knowledge were used to identify and fine-scale spatial data were used to map spatially explicit metrics and indicators for landscape and ESS analysis. Considering spatial metrics in particular and integrating spatial pattern analysis for two different types of landscapes focused on obtaining region-specific knowledge on landscape dynamics.

This thesis employed different approaches to address the overall research aim. Metrics and indicators were used to conceptualize landscapes and their spatial patterns and dynamics with regard to explicit spatial features. The *gradient* approach (Chapter II) delivers insights into spatial dynamics of peri-urban landscapes. The *clustering* approach (Chapter III) conceptualizes agricultural landscapes by typologizing them, and the ESS *relationship maps* (Chapter IV) identify conflicting or benefiting services in agricultural landscapes. The insights gained from these analyses were used to answer the two research questions of this thesis.

Research Question I*: How can land use change and ecosystem services of landscapes be described and analyzed?*

Two different kinds of landscapes were the focus of the analysis, which considered two different study regions with suitable characteristics. For peri-urban landscapes (Chapter II), a mixed-methods approach was applied. Local expert knowledge supported the identification of relevant metrics and indicators categorized as socio-economic, ecological, and political frameworks. For the study region, data availability, particularly primary data from official sources, was limited. The available, open, fine-scale spatial data were used to map metrics for a subset of the identified indicators. The results obtained yielded specific peri-urban dynamics, which can be summarized as *decreasing*, *increasing*, *random*, or *not changing* distributions along the peri-urban gradient in Dar es Salaam (i.e., with increasing distances to the city center).

Agricultural landscapes could be analyzed using fine-scale agricultural spatial data with detailed information on crop type and management practices. Indicator identification focused on the categories of landscape structure, diversity, and management, as well as the relationship between ESS agricultural production and habitat provision. Statistical pattern analysis via clustering (Chapter III) derived an appropriate number of clusters (i.e., agricultural landscape types). The clustering landscape indicators led to the identification of *six agricultural landscape types* in Brandenburg, characterized by different degrees of urbanity, intensification, fragmentation, and management type. Spatial pattern analysis suggested different degrees of spatial autocorrelation, whereby intensely cultivated and organic landscapes are likely to be spatially clustered. The agricultural landscape types allowed for the integration of various indicators from different categories, within which the set of indicators itself remains flexible and needs to be locally or regionally adapted with regard to specific spatial features and the landscape under consideration.

The combined (bivariate) consideration of ESSs instead of single ESS analysis allowed for the quantification of *conflicts* and *co-benefits* between ESSs (Chapter IV). The scale sensitivity of selected landscape ESSs revealed differences between the single ESSs and UoAs. Therefore, the administrative UoAs are more sensitive to the scale, with higher differences in terms of variance on different spatial scales than the hexagonal grids. In addition, the landscape and farm levels (as operational units for agricultural production) showed substantial differences in ESS relationship distributions, whereby conflicts are dominant at the landscape level, and conflicts and co-benefits are equally distributed at the farm level. The study demonstrated exemplarily the benefits of ESS relationship analysis and its sensitivity to the scale and UoAs and provided a sample for the spatial patterns of these relationships. Strong co-benefits tend to occur spatially clustered in Brandenburg, but overall, ESS relationships show no strong tendency of spatial clustering. These findings can provide a starting point for causal analysis on ESS relationships and their spatial patterns.

In general, the studies revealed that fine-scale spatial data can be beneficial for landscape-level analysis. Incorporating landscape and spatial metrics aggregated at the landscape level allowed for the determination of indicators covering ecological, economic, and social categories with a focus on spatially specific characteristics.

***Research Question II**: How can the landscape perspective contribute to our understanding of land systems?*

The results from research question I offered new insights into landscape dynamics and spatial patterns. Single indicators of landscape dynamics and ESSs could be combined through different methodological approaches and spatial pattern analysis. The landscape perspective removes the focus on single actors or stakeholders because multiple actors interact in a landscape. Spatially explicit approaches allow for region-adapted outcomes with regard to differences in landscape dynamics and structure while still allowing for conceptualization. In Dar es Salaam, expert interviewees emphasized the need for an integrative perspective in policy and planning with a particular focus on peri-urban landscapes as urban-rural interfaces characterized by highly dynamic spatio-temporal patterns. Similarly, the conceptualization of agricultural landscapes provided insights into combined ecological and socio-economic characteristics of landscapes. Differences in the scale sensitivity of different administrative and hexagonal units showed the importance of a careful choice of spatial scale and UoA.

5.2 Main conclusions and discussion

Each of the core research chapters provided answers to the two research questions of this thesis. Based on these results, the following conclusions emerged, which facilitate a better understanding of landscapes and their spatial patterns and thus address the overarching aim of this thesis.

Spatial metrics used within the studies were revealed to potentially assist indicator creation. Fine-scale spatial data availability has increased in recent years, especially in the form of remote-sensing products often available as open data. For the particular case of agricultural landscapes and ESSs, Bethwell et al. (2021) emphasized the common indication of agricultural productivity through yield numbers and its drawbacks. Such indication may be problematic for several reasons, including the disregard for the role of significant anthropogenic contributions to ecosystem service co-generation, external environmental effects, and strong dependence on site conditions. Furthermore, yield data are mostly only available for aggregated spatial units, particularly administrative units, but rarely at the plot level. However, the plot level, or incorporating fine-scale spatial data in general, can improve the landscape-level analysis by integrating local and site-specific characteristics. In particular, where primary information is

not available, spatial metrics may serve as proxies. Using spatial metrics can improve indicators of, for example, agricultural production, by integrating geometry (e.g., plot size) and their spatial concentration through density analysis. In a few studies, spatial ESS supply concentration was indicated by assessing hot or cold spots (Burkhard et al., 2014; Früh-Müller et al., 2016). Additionally, ESS relationships are of importance because a landscape (or any natural unit) can only supply a limited amount whereby ESSs interact and influence each other. As suggested by Bethwell et al. (2021), looking at these complex interactions (ESS conflicts and co-benefits and the consequent trade-offs and synergies) should be considered as one possibility for the indication of ESSs. The landscape perspective therefore delivers new insights into, for example, ESS relationships detached from actors, management units, or administrative boundaries. It may provide a more holistic picture of land systems while accounting for regional variability. However, as suggested by Turner and Gardner (2015b), landscape structure does not equate to landscape function, which implies the necessity to demonstrate and test pattern–process relationships.

The conceptualization of landscapes through explicit narratives might support the adoption of shared conceptualization between different actors, which allows for new knowledge and shared frameworks (Cullum et al., 2017). Thus, the landscape perspective allows for the locally and regionally adapted design of environmental and agricultural policy measures, leading to outcome-oriented environmental policy impact evaluation and landscape planning. However, landscapes themselves are not decision makers but rather the spatial entity where multiple actors and decision makers interact. Furthermore, the spatial consequences of decisions are often not taken into consideration, leading to external effects elsewhere other than those in the area that the decision itself focused on (e.g., via the passing on of environmental pollution, biodiversity loss, water shortages, or erosion) (Arts et al., 2017). The landscape perspective could reduce these shortcomings of, for instance, agri-environmental policies targeting individual land managers (Franks, 2011) by serving as a joint level of coordination for various actors. Thereby, the increasing demand for multifunctional landscapes through integrated land sharing is reflected in both research (Fischer et al., 2017; Killion et al., 2018; Mander et al., 2007; Stürck and Verburg, 2017) and policies (European Union, 2020; WBGU, 2020).

One challenge that arises from the landscape perspective and spatially explicit analysis is the inherent vagueness of landscape units (Cullum et al., 2017). The conceptualizations that frame

scientific understandings of landscapes are human constructions and are thereby provisional and subject to revision. In addition, when determining a landscape's extent and resolution, the appropriate scale depends on the question being asked and the processes being studied. Cushman et al. (2008) emphasize that a lack of concordance in spatially explicit landscape structure components raises the possibility that there are no fundamentally important aspects of landscape structure and that structure patterns are instead peculiar to specific landscapes. However, the methodological approaches suggested within this thesis can be transferred to different study regions. The flexibility of the presented methods allows for modifications to match various contextual settings or data situations. Open spatial data have become widely available (e.g., through *OpenStreetMap*). The data quality of such data sets, however, has to be considered carefully (Jokar Arsanjani et al., 2015).

While, in addition, the validation of (ESS) indicators derived from (spatial) metrics remains uncertain (Schulp et al., 2014; Seppelt et al., 2011), indicators could be compared to primary data information, if available, or with outputs of earth observation data or via field validation. Again, different mapping approaches (i.e., spatial scales and UoAs) can lead to different spatial patterns of ESS supply. Additionally, differences between results of landscape dynamics or ESSs can be caused by indicator definition and input data (Schulp et al., 2014). Schulp et al. (2014) emphasize that due to the lack of independent data on ESS provision, ESS maps cannot be properly validated, and appropriate measures for map quality are missing. Overall, the challenges in terms of ESS indicator validation and their presentation indicate a careful application of results for decision making and the need to clearly describe the indicators and methods used as well as the related uncertainties (Schulp et al., 2014). One possibility suggested by Groot et al. (2002) is to implement the standardized reporting of ESS assessment studies.

Overall, the findings of this thesis stress the importance of open spatial data availability as well as its potential to support indicator development for analyzing landscapes and ESSs. In combination with spatial pattern analysis, the landscape perspective can deliver additional insights into land systems and facilitate integrative metrics combining ecological, economic, and social dimensions to monitor and support sustainable land management.

5.3 Implications

This thesis reveals novel insights into the analysis of landscapes and their underlying environmental and land use processes based on exemplary peri-urban and agricultural landscapes. The results provided answer the two overarching research questions, thereby filling previous knowledge gaps in the conceptualization of landscapes via indicators, spatial metrics, and patterns. Emerging from the results of this thesis, it is possible to distinguish between implications for research and science and policy.

The insights, methods, and data generated in the context of this thesis have the following scientific implications. The mapping of spatial metrics and indicators at the landscape level can contribute additional information to, for example, the monitoring of SDGs. They can be used as proxies where primary data or information is missing. Landscape sciences focus on regional and place-based problems and solutions and thus need to play an instrumental role in sustainability research and practice (Wu, 2019). Multiple data sets can be combined for the identification of landscape and ESS indicators; for example, the agricultural survey data in Brandenburg can be complemented by land cover data in order to consider land use information other than that related to agriculture. When combining different spatial data sets, their original extent and resolution are equally relevant. Data mismatches should be considered carefully and adjusted to the appropriate scale and research subject. By integrating fine-scale data from open spatial data or remote-sensing data products, it is possible to apply them globally. The benefits of integrating spatial analysis by using spatial data and providing spatial metrics allows for the conceptualization of landscapes and can integrate multidimensional indicators with regard to explicit spatial features. To identify indicators for landscape and ESS analysis, suitable metrics need to be identified. In addition, the indicandum of each indicator should be declared since different indicators can contribute to various indicanda, and distinct indicanda can be depicted through different indicators (Heink and Kowarik, 2010). When focusing on the landscape perspective, a particular definition of spatial scale is missing due to the inherent vagueness of landscapes (Cullum et al., 2017). Suitable spatial extents and UoAs for landscape analysis have to be identified and, if possible, tested for their sensitivity to the applied methods, derived indicators, and the robustness of the resulting findings. Whereby administrative UoAs often correspond to decision-making entities, hexagonal grids serve as regular surfaces with neighborhood relationships characterized by an equal number of and equal distances to neighboring single units (i.e., cells) (Birch et al., 2007).

Policy and planning play a major role in governing land systems where multiple actors interact. To develop better tailored and regionally adapted strategies towards a sustainable future, (spatial and non-spatial) data provision and the usage of this data should be enforced and publicly available for research purposes, for example. In order to enhance sustainable pathways for land systems, policies should aim at integrating ecological, economic, and social dimensions. The landscape perspective supported by spatial analysis may enhance that integration. A lack of spatial targeting, as well as the insufficient consideration of conflicts and co-benefits (or, respectively, trade-offs and synergies), between ESSs among policy objectives has also been criticized (Früh-Müller et al., 2019). In order to encourage land users to support climate change mitigation and adaptation, to protect and improve the environment and landscapes and their features, and to conserve natural resources, soils, and biodiversity, the landscape perspective can support the coordination of better-tailored strategies towards these goals that address multiple land users.

5.4 Outlook

This thesis contributes to the understanding of spatial dynamics of landscapes and ecosystem services by applying a set of methods for landscape conceptualization and spatially explicit analysis. The insights and challenges presented in this thesis translate into some important topics for future research that should be pursued to advance landscape research in more detail.

The analysis within this thesis focuses on spatial dynamics at one point in time. A spatio-temporal approach allows for including temporal dynamics of landscapes and ESSs. By adding a temporal component to land use classifications, the potential to enhance land system sustainability can be demonstrated (Killion et al., 2018). Similarly, a temporal dimension can be added to spatial pattern analysis. Hot and cold spot analysis via *space-time cubes* allows users to set a series of parameters and then identifies trends and defines whether the hot or cold spot is persistent, increasing, or decreasing. Regarding temporal aspects of ESS supply and demand, the identification of hot moments is equally as important as that of spatially relevant hotspots (Burkhard et al., 2014). Trend analysis and the resulting insights allow for scenario development and modeling, which assist the development of strategies to obtain sustainable

pathways for land systems. Scenarios are powerful tools to envision how nature might respond to different pathways of the future (Rosa et al., 2017).

ESS relationships play an important role in understanding land use change at the landscape level and, consequently, scenario development. Cord et al. (2017) point out that only a few studies have analyzed ESS relationships over time, possibly due to the lack of monitoring data. Besides the investigation into static relationships (i.e., conflicts and co-benefits), truly causal interactive mechanisms between ESSs should be analyzed (i.e., trade-offs and synergies) (Vallet et al., 2018). Optimization techniques have been especially prevalent in terms of their application to ESSs with regard to trade-offs and synergies (Kaim et al., 2018). For instance, Pareto-based methods simultaneously generate multiple Pareto optimal solutions and are able to provide the whole Pareto frontier, indicating possible trade-offs. Optimizing land use patterns with respect to multifunctional uses provides useful information and solutions to problems applicable to multiple spatial scales (Seppelt et al., 2013). To deal with the inherent vagueness of landscapes, Cullum et al. (2017) propose a fuzzy logic approach for landscape classification. In general, a balance has to be found between sustaining and accounting for local and regional characteristics and necessary generalization or conceptualization. Fuzzy logic could also be implemented in optimization modeling using rather vague information, including metrics which are difficult to validate.

Another method accounting for ESS trade-offs is eco-efficiency analysis, which has been considered as a meaningful index for assessing how efficient economic activities are in terms of resource-use and environmental pressures (Coluccia et al., 2020). Measuring eco-efficiency provides policymakers with important information for developing policies focused on sustainable management and the efficient use of natural resources in the agricultural sector. Eco-efficiency is usually applied at the farm level, but studies have proceeded to transfer it to the landscape level (Coluccia et al., 2020). Sustainable development is one of the most important objectives of the CAP, which has a key role in facing the challenges of the new paradigm of the sustainability of agriculture. Desirably, the CAP can contribute to the achievement of several SDGs.

Causal relationships are linked to analyzing drivers of LUCC. In land systems, and hence landscapes, human and environmental systems interact through land use. A large body of

literature already exists on the drivers of LUCC, including various spatial scales, ranging from the local to regional and global levels (Lambin et al., 2001; Plieninger et al., 2016). Scale remains an important research focus in landscape sciences, with new approaches being investigated, such as one that looks at the scaling of patterns in geographic space as opposed to the scaling of patterns in pattern metric space (Gustafson, 2019). It is also critical that metrics are conceptually linked to process or theory, accounting for the scale of that process, and these putative links should be tested (Wu et al., 2004). Further knowledge gaps remain both with respect to the magnitude of associations between potential drivers and LUCC outcomes as well as with regard to the often context-dependent interactions between LUCC drivers. Given the lack of universal system theories, and following Meyfroidt et al. (2018), this can be achieved by developing middle-range theories linking inductive and deductive approaches for theory development.

Identifying opportunities to align social and environmental needs is a transdisciplinary challenge. The ESS analysis within this thesis could be extended using multiple ESSs, including social, ecological, and economic dimensions and actor participation through discussions and knowledge exchange. In general, indicator data-oriented approaches help ground the broad and, in many cases, vague SDGs in more concrete and measurable terms, but acquiring the data necessary to monitor the indicators on national or global scales is a significant and fundamental challenge. As Chapter II of this thesis demonstrated, mixed qualitative and quantitative research approaches can be highly beneficial for each other. Where data availability is limited, landscape and ESS dynamics can be identified through actor participation via, for example, expert interviews or surveys. Furthermore, limited data availability can be supplemented through data derived from citizen science, which is gaining increasing popularity (Ferretti, 2019; Fraisl et al., 2022). Ultimately, this knowledge can help to address future challenges for land systems and to guide a more sustainable future land use.

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Eidesstattliche Erklärung

Ich erkläre, dass ich die Dissertation selbständig und nur unter Verwendung der von mir gemäß § 7 Abs. 3 der Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt-Universität zu Berlin Nr. 42/2018 am 11.07.2018 angegebenen Hilfsmittel angefertigt habe.

Saskia Wolff
Berlin, den 31.3.2022