Conceptual and methodological challenges of ecosystem services mapping in urban regions

Von der Naturwissenschaftlichen Fakultät der
Gottfried Wilhelm Leibniz Universität Hannover

zur Erlangung des Grades
Doktorin der Naturwissenschaften (Dr. rer. nat.)

genehmigte Dissertation
von
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2023

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Tag der Promotion	16.03.2023

Zusammenfassung

Mit dem weltweiten Bevölkerungswachstum sowie veränderten Konsumverhalten ist der Bedarf an natürlichen Ressourcen und Energie gestiegen. Die zunehmende Urbanisierung und Verstädterung, die wirtschaftlichen Verflechtungen und die Globalisierung verschärfen die Situation und lassen die Nachfrage weiter steigen. Infolgedessen haben sich viele nicht nachhaltige Praktiken in der Land- und Forstwirtschaft, im Bergbau und in der Energieerzeugung entwickelt, die zu einer veränderten Flächennutzung, einem allgemeinen Raubbau an den natürlichen Ressourcen, einer ineffizienten Abfallwirtschaft und Umweltverschmutzung sowie Biodiversitätsverlust führen. Der Zustand unserer Ökosysteme verschlechtert sich schneller denn je, wodurch die Fähigkeit der Ökosysteme, lebenswichtige Ökosystemleistungen bereitzustellen, ernsthaft beeinträchtigt wird.

Mit dem Begriff Ökosystemleistungen werden alle Beiträge von Ökosystemen auf das menschliche Wohlbefinden zusammengefasst. Ökosystemleistungen können den Menschen direkt oder indirekt zugutekommen, sei es wirtschaftlich, materiell, oder in Form einer Stärkung ihrer mentalen und körperlichen Gesundheit. Da sich der Rückgang der Ökosystemleistungen negativ auf das menschliche Wohlbefinden auswirkt, fordern engagierte Umweltschützer*innen, Wissenschaftler*innen sowie zwischenstaatliche Organisationen zunehmend den Schutz und die Wiederherstellung der Ökosysteme und ihrer Leistungen.

Das Konzept der Ökosystemleistungen stellt ein sehr aktives Forschungsfeld dar, da es sich mit den gesellschaftlichen Herausforderungen im Zusammenhang mit dem Klimawandel, dem Verlust der biologischen Vielfalt, der Umweltverschmutzung, der nicht nachhaltigen Landnutzung und der Umweltgerechtigkeit auseinandersetzt. Trotz der wachsenden Anzahl an Forschungsaktivitäten wird das Konzept der Ökosystemleistungen in der Politik und Entscheidungsfindung bisher nur im begrenzten Maße genutzt. Zwei der Hauptfaktoren, die dafür verantwortlich sind, sind die anhaltenden konzeptionellen Herausforderungen und die Anwendungsbarrieren, die gegenwärtig mit den Ansätzen zur Bewertung und räumlichen Darstellung von Ökosystemleistungen verbunden sind.

Die vorliegende Dissertation hebt diese konzeptuellen und methodischen Unsicherheiten und Herausforderungen im urbanen Kontext hervor und betrachtet folgende Forschungsfragen näher:

1. Welche Trends lassen sich bei der Erfassung und Bewertung von Ökosystemleistungen in städtischen Gebieten beobachten?
2. Welche konzeptionellen Herausforderungen bestehen bei der räumlichen Erfassung von Ökosystemleistungsangebot und -nachfrage?
3. Mit welchen Problemen sind die derzeitigen Ansätze zur Erfassung und Bewertung von Ökosystemleistungen konfrontiert und wie können diese am besten überwunden werden?

Abstract

Global population growth and changes in consumer behaviour have led to an increased requirement for energy and natural resources. The rise in urbanisation, economic interdependencies and globalisation exacerbates the situation and further increases the demand. As a result, many unsustainable practices in agriculture, forestry, mining and energy generation have emerged, leading to land-use changes, a general overexploitation of natural resources, inefficient waste management and pollution. The state of our ecosystems and global biodiversity are deteriorating faster than ever and this is having a severe impact upon the ability of ecosystems to provide services.

Ecosystem services is a term used to cover all the contributions ecosystems make to human well-being. Ecosystem services can directly or indirectly benefit people, be it economically, materially or in terms of improving their mental and physical health. As the decline of ecosystem services has a negative impact on human well-being, dedicated environmentalists, scientists and intergovernmental organisations are increasingly calling for the protection and restoration of ecosystems and their services.

There is a very active research field engaged with the ecosystem services concept, which addresses the social challenges related to climate change, biodiversity loss, pollution, unsustainable land use and environmental justice. Despite the growing number of studies assessing and mapping ecosystem services, the ecosystem services concept has as yet only been able to have a limited impact upon real-world policy and decision-making. Two of the main factors responsible for this are the persistent conceptual challenges and application barriers currently inherent to ES mapping approaches.

This thesis emphasises these conceptual and methodological uncertainties and challenges in an urban context and considers the following research questions in more detail:

1. What are the trends in mapping and assessing ecosystem services in urban areas?
2. What are the conceptual challenges in mapping ecosystem service supply and demand in urban regions?
3. What issues do current ecosystem service mapping approaches face and how can these best be overcome?

Schlagwörter: Ökosystemleistungen; Räumliche Erfassung von Ökosystemleistungen; Stadtregion

Keywords: Ecosystem services; ecosystem services mapping; urban regions

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List of Abbreviations

BKG	Bundesamt für Kartographie und Geodäsie (Federal Agency for Cartography and Geodesy)
CICES	Common International Classification of Ecosystem Services
CLC	CORINE Land Cover
CORINE	Coordination of Information on the Environment
DEM	Digital Elevation Model
ES	Ecosystem Services
EU	European Union
EUROSTAT	European Statistical Office
FAO	Food and Agriculture Organization of the United Nations
FAU	functional urban areas
GIS	Geographic Information Systems
INCA	Knowledge Information Project on an Integrated system of Natural Capital and ecosystem services Accounting in the EU
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LEAFlood	Landscape vegetation and flood model
LULC	Land use and land cover
MEA	Millennium Ecosystem Assessment
NbS	Nature-based Solutions
NEA	National Ecosystem Assessment
NUTS	Nomenclature des unités territoriales statistiques (*engl.* territorial units for statistics)
ÖSKKIP	Ökosystemleistungen von Stadtregionen – Kartieren, Kommunizieren und Integrieren in die Planung zum Schutz der biologischen Vielfalt im Klimawandel (Ecosystem Services of Urban Regions – Mapping, Communicating, and Integrating into Planning to conserve biodiversity during a changing climate)
SBA	Service Benefitting Area
SCA	Service Connecting Area
SDA	Service Demanding Area
SDG	Sustainable Development Goals
SEEA - EA	System of Environmental Economic Accounting – Ecosystem Accounting
SPA	Service Providing Area
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations

Chapter 1

Introduction

Figure 1. Be it for walking, playing sports, picnicking or just relaxing - urban parks provide space for recreational outdoor activities. Photo: Jolanta Dworczyk

1. Introduction

1.1. General introduction and research objectives

The world has become increasingly urbanised. In the past 50 years, the world's population has more than doubled from 3.7 billion to 7.8 billion people (1970 – 2020, UN 2019a), and the worldwide percentage of people living in urban areas changed in the same years from 37 % to 56 % (UN 2019b). The United Nations World Urbanisation Prospects estimates and projects a population growth to 9.77 billion people in 2050 with roughly two thirds (68 %) living in urban areas (UN 2019b). There is a variety of reasons for the ongoing urbanisation. Cities provide economic and employment opportunities, health care and education, the attraction of an urban lifestyle and access to various cultural offers (Moore et al., 2003). Despite the fact that urban areas cover only a small amount of the global terrestrial area, they have far-reaching impacts on biodiversity, ecosystem condition and the climate system on local and global scales (IPBES, 2019; Kalnay and Cai, 2003; McDonald et al., 2008; Millennium Ecosystem Assessment, 2005a). For example, it has been estimated, that urban areas use up to 70 % of global energy and contribute between 70-80 % global energy-related emissions (Seto et al., 2014). Urban growth is often accompanied by a densification of inner-city areas and suburbanisation (Johnson, 2001; Nechyba and Walsh, 2004). This kind of urban development – also referred as urban sprawl – takes often place extensively and partly unregulated into rural areas (Johnson, 2001; Nuissl and Siedetop, 2021). In some local areas, this expansion of built-up areas has already directly and indirectly led to a loss of more than 80 % of natural habitats (Ke et al., 2018).

All over the world, cities are facing a series of environmental challenges that impact urban population safety, health and well-being (Grover and Singh, 2020). For example, urban areas are vulnerable to environmental extreme events (like heat waves, heavy rainfall events), whose intensity and frequency are expected to rise with climate change (IPBES, 2019; United Nations, 2015). But also other factors such as increased exposure to waste, air pollution, contaminated drinking water or noise, place human health at risk (Moore et al., 2003). Furthermore, sedentary and inactive lifestyles, social exclusion (Dahlberg and McKee, 2018; Li and Rose, 2017) or loneliness (Scharf and Jong Gierveld, 2008) have negative physiological and psychological impacts on the well-being of the urban population (Pacione, 2003). Currently, the COVID-19 pandemic has highlighted the urgent need for a transition to greener urban systems. Many countries around the world imposed severe restrictions to prevent the rapid spread of the COVID-19 virus, including the closure of cultural and recreational facilities, travel bans, lockdowns, and restrictive quarantines. These measures and restrictions changed the perception and use of nature. For example, public urban green spaces were one of the remaining places where leisure activities and social interactions were still allowed, which led to a significant increase in use (Venter et al., 2020). For many city dwellers, however, the benefits of urban nature were out of reach because they were either inaccessible or unavailable to them. In 2020, it has been estimated that only 45 % of the world's urban population had access to a public urban green space within 400 metres distance (United Nations, 2022b).

Policy-makers, practitioners, and researchers are giving increasing attention to a more sustainable, resilient, and liveable city. Global commitments such as the Sustainable Development Goals (SDG) (United Nations, 2022a), the Paris Agreement on Climate Change (United Nations, 2016), New Urban Agenda (United Nations Human Settlements Programme, 2022), or Sendai Framework for Disaster Risk Reduction (United Nations, 2015) are addressing many of the social and environmental challenges in urban areas. In the European Union (EU), sustainable urban development is targeted, among others, in the Urban Agenda for the EU (European Union, 2016), the Green Infrastructure Strategy (European Commission, 2019), the EU Biodiversity Strategy (European Commission, 2020, 2011), and the perspectives on Nature-Based Solutions (European Commission, 2015; Maes et al., 2016b; Szkop et al., 2021).

The concept of **Ecosystem Services (ES)** illustrates the human dependence on functioning ecosystems in good condition. ES describe ecosystems' direct and indirect contributions to human well-being (Potschin-Young et al., 2018). These contributions include natural services and goods that bring direct or indirect economic, material, health or psychological benefits to humans (The Economics of Ecosystems and Biodiversity, 2010). The ES concept thus emphasises the importance of ecosystems in a holistic manner: ecosystems provide humans with numerous provisioning (like food, raw materials), regulating and maintaining (like local climate regulation, pollination), and cultural ES (like nature-based recreation activities) (Potschin-Young et al., 2018, see Chapter 1.3).

In this context, the ES concept brings the opportunity to highlight and communicate the dependency of urban citizens on healthy ecosystems. Urban nature, urban green spaces and the adjacent rural areas can be understood as integral parts of urban areas where complex interactions, interdependencies, and feedbacks take place between people and their environment (Andersson et al., 2014; Maes et al., 2016b). However, many ES used in urban areas (such as drinking water, food, raw material, mediation of waste and toxins) originate in distant locations. Market goods and products in particular are transported or can flow through built infrastructures (like water pipelines, transportation routes) into urban areas. These products and goods can be provided by ecosystems surrounding cities or from even further distanced ecosystems (Kleemann et al., 2020; Schröter et al., 2018). However, with this spatial disconnection, urban dwellers are in danger of losing the direct links between the final ES and the ecosystems of origin (Gómez-Baggethun and Barton, 2013). Rapid urbanisation means that large parts of the world's population have less direct contact with nature (Soga and Gaston, 2016). Many people, especially children, often spend their leisure time with virtual activities, such as watching TV, playing computer games or using the Internet (Ballouard et al., 2011). Consequently, urban societies are increasingly losing awareness of human dependence on healthy ecosystems, which impacts how people interact with nature and diminishes the wide range of physical and psychological benefits from many ES (Soga and Gaston, 2016). This alienation, often termed as "extinction of experience" (Miller, 2005; Pyle, 1993; Soga et al., 2016), may lead to less attention to the conservation and protection of ecosystems, biodiversity and climate.

This "cycle of disaffection toward nature" (Soga and Gaston, 2016) can create serious problems, as a lack of available or poorly accessible ecosystems that provide ES has implications for human safety and health (McKinney and VerBerkmoes, 2020), sustainability (Seto et al., 2017), and/or environmental justice (Mullin et al., 2018). Combined with the challenges of climate change, this can increase environmental risks (such as extreme heat, floods) as well as tensions and conflicts within the urban population if the required ES are not accessible in desired quantities and qualities or are unequally distributed over space and time (IPBES, 2019). Therefore, policy, decision-makers, planners and urban citizens need to gain awareness of the multiple urban ES and related benefits (Andersson et al., 2014).

ES mapping is considered an important tool to support policies and decision-making processes related to sustainable urban and regional planning, environmental protection, climate adaptation, green infrastructure development and maintenance, and resource management (Maes et al., 2015). A wide range of ES mapping methodologies and assessment frameworks have been developed to address the growing interest of policy and decision-makers. Attention to the ES concept in research and practice has grown, particularly with its implementation in international treaties, strategies, and environmental accounting frameworks (European Commission, 2011; Millennium Ecosystem Assessment, 2005a; The Economics of Ecosystems and Biodiversity, 2010; United Nations, 2021; United Nations, 1992).

However, the impact of ES maps or ES mapping processes on policy and decision-making is still limited (Grunewald et al., 2021; Root-Bernstein and Jaksic, 2017). This is because scientists, practitioners, policy-makers, and users from other public and private sectors encounter numerous challenges with the mapping process, also described as "bottlenecks of ES mapping" (Palomo et al., 2018).

One important barrier can be identified in the ES concept itself. The ES concept consists of a plethora of terms and their definitions (see Chapter 1.3). The conceptual understanding and use of ES terminology differ among researchers and map-makers, leading to different ES mapping results, reduced comparability, and confusion (Honey-Rosés and Pendleton, 2013; Potschin-Young et al., 2018; United Nations, 2021). Another well-known barrier is the "limited availability or access to accurate, trustworthy, and affordable data in the required format and at an appropriate spatial or temporal resolution for the entire area of interest" (Palomo et al., 2018, p.7). This obstacle is closely related to the challenge of selecting an appropriate methodology with suitable indicators and data (Harrison et al., 2017; Jacobs et al., 2017; Palomo et al., 2018).

That these "bottlenecks" directly affect the success of applications of the ES concept is evident when looking at the 2020 Biodiversity Strategy. Within this strategy, all member states of the European Union were called to conserve and restore ecosystems and their services. To achieve this goal, they needed to improve their knowledge of the status of their ecosystems and assess and map ES by 2014 (Target 2, Action 5 (European Commission, 2011)). However, this aim was only partially successfully achieved (European Commission, 2020). In retrospect, the completion of the target was hampered by *inter alia* conceptual and methodological difficulties within the ES concept (European Commission, 2020).

The overall objective of this dissertation is, therefore, to improve the conceptual and methodological understanding of mapping ES on urban and regional scales. Specifically, this thesis aims to answer the following research questions:

1. What are the trends in mapping and assessing ecosystem services in urban areas?
2. What are the conceptual challenges in mapping ecosystem service supply and demand in urban regions?
3. What application obstacles do commonly applied ecosystem service mapping approaches face and how can these best be overcome?

The following subchapters of **Chapter 1** (Introduction) provide further background information of the ES concept, describe the conceptual framework and introduce briefly the applied methods of this thesis. The objective and research questions are addressed in the five original articles that have been peer-reviewed (or are in the process of being peer-reviewed). The original articles are presented in **Chapters 2 – 6.** The **Synthesis (Chapter 7)** provides answers to the three research questions. Furthermore, this Chapter presents the main conclusions as well as an outlook for future research.

1.2. Short history of the ecosystem services concept

Our ancestors understood the importance of nature for human well-being. For example, Plato described the impact of healthy forests on fertile soil and drinking water availability (Daily, 1997). In human history, however, there are many examples where societies ignored the importance of healthy ecosystems or biodiversity and most likely disappeared due to overuse of natural resources, loss of biodiversity, and changing climatic conditions (Diamond, 2005, 2011; Fisher et al., 2009). Early scientific notions of the value of ecosystems can be found in the 17th century (Gómez-Baggethun et al., 2010). Famous (pre-) classical economists like Adam Smith or Karl Marx acknowledged and addressed the importance of nature for economic prosperity (Gómez-Baggethun et al., 2010). In the 19th century, George P. Marsh portrayed this economic importance in his 1864 book "Man and Nature", which Mooney and Ehrlich (1997) marked as one of the first mentions of modern concerns about ecosystem degradation.

The modern history of the ES concept begins in the 1970s. In 1977, Walter E. Westman proposed in his article to assess and enumerate the social value of the so-called *nature's services* (Westman 1977). The idea was to present ecosystem functions as beneficial services to increase public support for biodiversity conservation (Gómez-Baggethun et al., 2010). Ehrlich and Ehrlich (1981) were the first who introduced the term *ecosystem services*, which is still used today.

In the 1990s, scientists started to increasingly assess and quantify the economic values of ecosystem services (i.e. Daily, 1997). Particular interest generated, for example, an article by Costanza et al. (1997), which attempted to quantify the total economic value of the world's ES and natural capital. The Millennium Ecosystem Assessment (MEA) had a strong impact on political interest in the ES concept and boosted scientific research activities (Fisher et al., 2009; Gómez-Baggethun et al., 2010; Maes et al., 2020). More than 1300 scientists worldwide worked on the MEA, which provided scientific appraisal of the world's ecosystem conditions and trends and reported them in fifteen thematic reports (MEA, 2005b). The loss and degradation of healthy ecosystems and their services and the anticipated impact on future human well-being were key messages for decision-makers (MEA, 2005a). In order to be able to monitor these developments more closely and to support decision-makers in taking appropriate action, the scientists called for intensified research on the measurement, modelling and mapping of ecosystem services (MEA, 2005a). For this purpose, several ideas and initial proposals for action have been detailed in *A Framework for Assessment* (MEA, 2003). Back then, the scientists emphasised that the ES concept itself and the assessments were still in the initial stages of development and that more research was needed (Fisher et al., 2009). Since then, the concept has evolved from the ecological, socio-cultural and economic perspectives, and has also been reflected in the emerging definitions and methodological approaches (de Groot et al., 2017).

The ecosystem services concept has continued to be included in important positions on the policy agenda. In 2007, the international initiative *The Economics of Ecosystems and Biodiversity (TEEB)* was launched at the G8+5 Potsdam Meeting of Environment Ministers**.** One key objective was to highlight the global economic values of ES and biodiversity and to protect them more effectively from destruction and overexploitation. The findings of this initiative were published in a series of thematic reports (TEEB, 2010). TEEB also published a guidance manual for national or sub-national studies (TEEB 2013), enabling the publication of countrywide studies.

Back in 1992, the *Convention on Biodiversity (CBD)* was adopted at the United Nations Conference on Environment and Development. Article 6 of the CBD requires that *"national strategies, plans or* *programmes for the conservation and sustainable use of biological diversity [shall be developed or adapted] for this purpose […]"* (United Nations, 1992). With the Ecosystem Approach (CBD, 1998), a strategy for the protection of ecosystems has been on the CBD's agenda since 1995. The international commitments and strategies led to decisive action; the first development of a *European Community Biodiversity Strategy* in 1998 (European Commission, 1998). Shortly after the publication of the MEA reports, the European Commission included the ES concept in an EU Action Plan with the ambitious target of halting the loss of biodiversity by 2010 (European Commission, 2006).

The *EU Biodiversity Strategy 2020* was adopted (European Commission, 2011) for the decade 2011 – 2020. The second target of this strategy called all EU Member States to maintain and restore ecosystems and their services. Furthermore, all EU Member States were directed to improve their knowledge about the state of their ecosystems, map and assess ecosystems and their services and integrate the ES values into national and EU accounting and reporting systems by 2020 (Target 2, Action 5 (European Commission, 2011)). Today, the follow-up *EU Biodiversity Strategy 2030* is in place for the decade 2021 – 2030 (European Commission, 2021).

Since 2011, the EU working group *Mapping and Assessment of Ecosystems and their Services (MAES)* has supported the implementation of EU biodiversity strategies (Maes et al., 2013). MAES published several thematic reports with definitions, typologies of ecosystems, methodological frameworks and tested indicators for assessing and mapping ecosystem condition and ES (European Commission, 2022). Furthermore, the working group has contributed to integrate the importance of green infrastructure and ES into policies at EU and national level (European Commission, 2019)

The *Knowledge Information Project on an Integrated system of Natural Capital and ecosystem services Accounting in the EU (KIP INCA)* supports the MAES implementation by establishing a coherent EU approach for ecosystem accounting, which is consistent with internationally agreed standards (EU, 2019).

An important internationally agreed standard is the *System of National Accounts (SNA).* In its first version, natural capital, which describes the Earth's natural assets including their related ES, was hardly considered. Therefore, the SNA was extended, alongside others, including the *System for Environmental and Economic Accounts*, which has been in use for accounting natural resources like timber or minerals (La Notte and Dalmazzone, 2018). As policy interest in the ES concept grew, experiments on how to integrate ES into those existing systems were undertaken (UN, 2019). Recently in 2021, the UN adopted the *System for Integrated Environmental and Economic Accounting - Ecosystem Accounting (SEEA EA)*, which focuses on biophysical information about ecosystems, ES, and changes in ecosystem extent and condition (UN, 2021).

Also of importance is the independent *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)*, which was established in 2012. One key objective was and is to provide policy and decision-makers, businesses and the public with scientifically credible and objective assessments about biodiversity, ecosystems and their services. Since its establishment, IPBES has published thematic reports from local to global level with up-to-date assessments and recommendations for action to be taken for protecting and enhancing sustainability (IPBES, 2019).

This Chapter presented key initiatives, working groups and platforms that shaped and boosted ES research. Although there are numerous research activities on the ES concept, theoretical-conceptual questions and methodological implementation difficulties still exist, which will be introduced in more detail in the following Subchapters 1.3 and 1.4.

1.3. Conceptual framework of the ecosystem services concept

The following section describes the conceptual framework of the ES concept in more detail. Unless specified otherwise, this thesis follows the definitions from the MAES glossary (Potschin-Young et al., 2018). The MAES glossary reflects the various research contributions to the ES field from different scientific fields. It has a strong focus on mapping and assessing ES. This glossary is however not used by all researchers working on the ES concept. Moreover, some of the terms are still subject to scientific debate.

As already described above, ES can be understood as the ecosystems' direct and indirect contributions to human well-being (Potschin-Young et al., 2018). A number of different ES classification systems exist, pursuing the common basic objective of describing how ecosystems support human well-being and health (United States Environmental Protection Agency, 2015). Well-known examples of ES classification systems are, for example, MEA (2005b), TEEB (2010), Boyd and Banzhaf (2007), the National Ecosystem Service Classification System (Newcomer-Johnson et al., 2020), or the Common International Classification System of ES (CICES). CICES provides the EU with a comprehensive and hierarchical structural system for the standardised classification, mapping and accounting of ES. Therefore, this thesis used the structure of CICES. Following CICES Version 5.1, ES can be classified in three categories (or sections): provisioning ES, regulating and maintaining ES, and, cultural ES (see Figure 2).

Provisioning ES include all material and biotic energetic outputs from ecosystems. They include all "material goods and products from ecosystems that can be exchanged or traded, as well as consumed or used directly by people in manufacturing" (Haines-Young and Potschin, 2013, A2). This section includes, for example, food, fibres or other raw materials.

Regulating and maintaining ES comprise ecosystem functions that affect other elements and processes of ecosystems which deliver direct benefits to humans. Furthermore, these ES cannot directly be consumed but affect the human health and well-being (Haines-Young and Potschin, 2013; Naturkapital Deutschland – TEEB DE, 2016; Potschin-Young et al., 2018). Local climate regulation, air quality regulation, and pollination are examples of this section.

Cultural ES include all the non-material and normally non-consumptive outputs of ecosystems that have symbolic, cultural or intellectual significance and affect people's physical and mental states. Those services are primarily regarded as the physical settings, locations or situations that give rise to changes in people's physical or mental states, and, whose character are fundamentally dependent on living processes. They can involve individual species, habitats and whole ecosystems. The settings can be semi-natural and natural (i.e., cultural landscapes), which depend on *in-situ* living processes (Naturkapital Deutschland – TEEB DE, 2016; Potschin-Young et al., 2018). This section includes, for example, nature-based recreation activities, nature-based aesthetics, and environmental education.

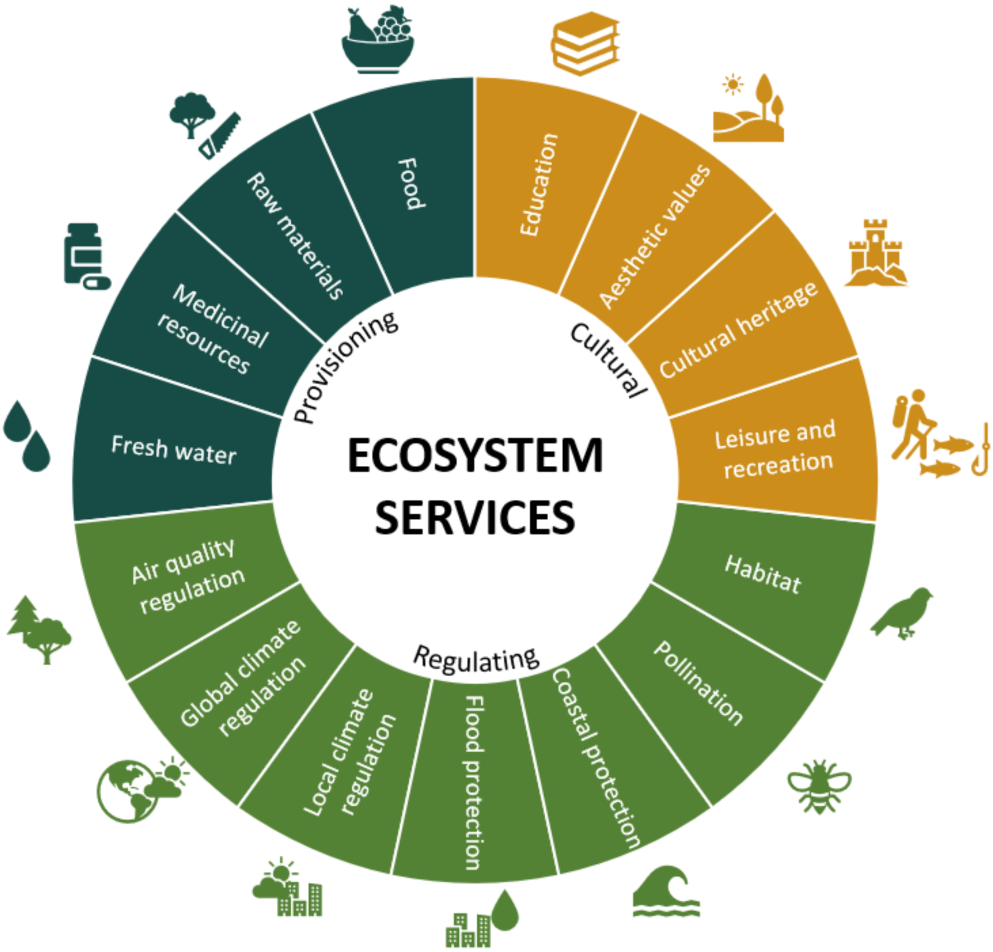

Figure 2. Graphical overview of ecosystem services within the three main categories, adapted after WWF, 2016, p 51.

The section **abiotic services** include all abiotic materials and goods (such as water, mineral substances), and energetic outputs (wind energy, solar energy). These services are not directly produced by an ecosystem but are important for human well-being too (Haines-Young and Potschin, 2018).

Those three sections (or four, if abiotic services are included) are divided into 'divisions', 'groups' and 'classes' (Dworczyk and Burkhard, 2020). The latest version, CICES lists in total around 90 different ES on the class level (Haines-Young and Potschin, 2018).

1.3.1 Ecosystem services cascade model

The **ES cascade model** (see Figure 3) is a helpful conceptual model and has been widely used to explain the key components of the ES concept (de Groot et al., 2010; Haines-Young and Potschin, 2010; Heink and Jax, 2019; Maes et al., 2016a; Potschin and Haines-Young, 2017). In addition, the model can be used to visualise the interrelationships and interactions between the environment and humans and thus communicate society's dependence on ecosystems (La Notte et al., 2017).

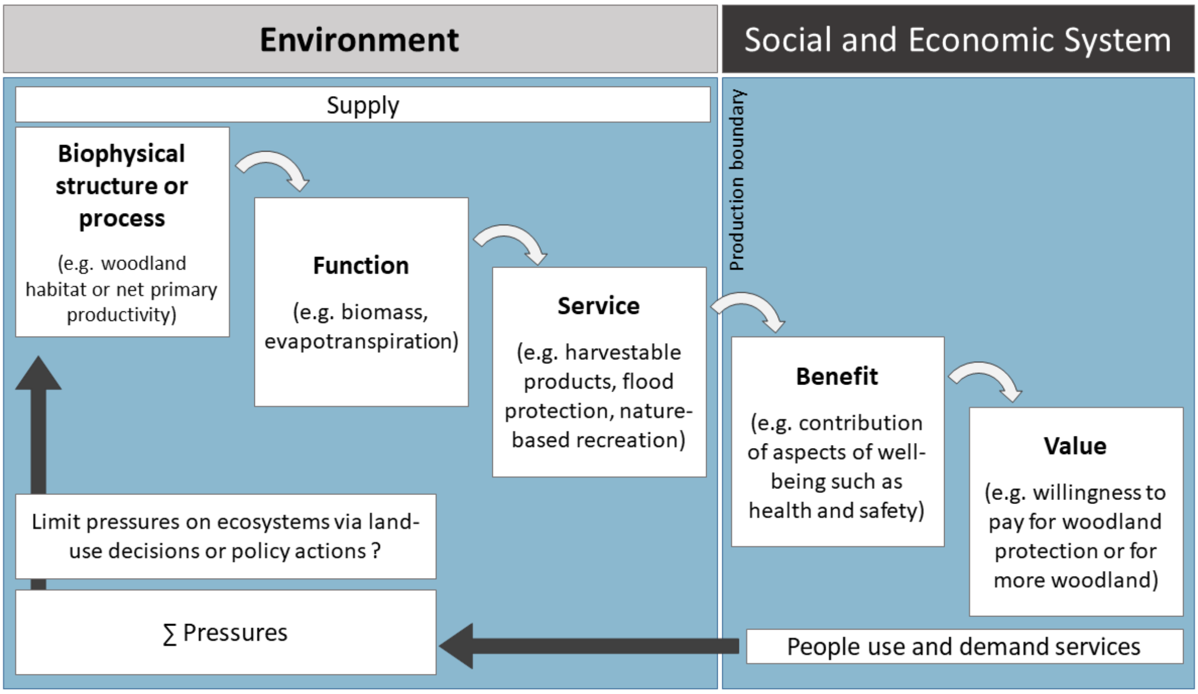

Figure 3. The ES cascade model (adapted after Potschin and Haines-Young, 2017, p. 39).

The model can be structured like a 'production chain' (Potschin and Haines-Young, 2011) or 'pathway' (Potschin and Haines-Young, 2017), visualising different 'steps' from the environment (left side) to elements of human well-being (right side). Five elements are important: 1) Ecosystems' biophysical structure and processes, 2) ecosystem function, 3) ecosystem services, 4) benefits, and 5) values. The environment supplies manifold biophysical structures, processes and functions, which are the basis for ES. The **biophysical structures of an ecosystem** include all biotic or abiotic characteristics of that ecosystem (including human-made elements) and their composition and distribution. **Ecosystem processes** comprise "any change or reaction, which occurs within ecosystems, physical, chemical or biological" (Potschin-Young et al., 2018). In distinction, **ecosystem functions** are defined as the "subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services" (Potschin-Young et al., 2018). Finally, the "contributions of ecosystem structure and function – in combination with other inputs – to human well-being" (Burkhard and Maes, 2017) are referred to as **ecosystem services (ES)**. The ES lead to a "positive change in 'well-being' from the fulfilment of needs and wants" (Potschin-Young et al., 2018), also called **benefits**. These benefits can be used and **valued** by different groups in different ways (e. g. in monetary or non-monetary dimensions). The ES are at the centre of and connected to the environment and socio-economic systems.

The cascade model attempts to highlight **final ES** (Haines-Young and Potschin, 2018). Services are final if they occur as an outcome of an ecosystem and if they have a direct impact on human well-being. In contrast, intermediate ES cannot be used directly by people, as they represent more or less an ecosystem function or process. Those ES support other ES rather than existing in isolation and should be excluded to avoid double-counting in respective valuation studies (Potschin-Young et al., 2018; United Nations, 2021).

However, it often depends on the context whether the service is considered to be 'final' or 'intermediate' ES. Boyd and Banzhaf (2007) used water quality as an example to explain the difference.

Water quality can be understood as a final service if water is used directly as drinking water. However, water quality can also be only an 'intermediate' component that is important for the provision of, for instance, fish (Potschin-Young et al., 2017).

The boundary between final and intermediate ES can also be called the **production boundary** (Potschin-Young et al., 2018). The production boundary was initially used in economics and represents the point where the ES crosses the boundary between the environment and the socioeconomic system (Potschin and Haines-Young, 2017). This boundary is particularly relevant in ecosystem services accounting (Eigenraam and Obst, 2018; United Nations, 2021).

The ES cascade also represents the interactions of the socio-economic system with the environment. People use and demand ES, which can affect ecosystems and the supply of ES if the pressures caused by the social and economic systems are not minimised via sustainable land use decisions or appropriate policy measures (Fisher et al., 2009; Haines-Young and Potschin, 2018).

Many ES are the result of **co-production** processes, in which ecosystem structures and functions are intentionally maintained or enhanced by land use decisions or management measures. Such anthropogenic measures can for instance include planting of trees. agricultural activities or protecting wildlife habitats (Fischer and Eastwood, 2016; Resque et al., 2021). Strategies to improve or enhance the state of urban ecosystems and their services can also be found in the concept of **Green Infrastructure** (European Commission, 2013). The term 'green infrastructure' describes a strategically planned network of natural and semi-natural areas with different natural features at different scales that are designed to maintain and enhance ES (European Commission, 2019). Measures or actions, which are "inspired by, supported by or copied from nature" (European Commission, 2015, p.15) and aim to promote the conservation, enhancement, and restoration of ES and biodiversity are also referred to as **nature-based solutions (NbS)** (European Commission, 2015; Kabisch et al., 2016). The concept of NbS builds on the ES concept, but addresses stronger global societal challenges that arise in connection with climate change, for example in urban areas (Cohen-Shacham et al., 2016; Kabisch et al., 2016).

1.3.2 ES supply, demand and flow

Several aspects of ES can be assessed and mapped. Figure 4 illustrates interactions and connections between an ecosystem and socio-economic system and highlights aspects of ES, which can be mapped separately.

ES properties ("attributes which characterize an ecosystem, such as its size, biodiversity, stability, degree of organization, as well as its functions and processes" Potschin-Young et al., 2018, p. 19) and **ES condition** ("physical, chemical and biological condition or quality of an ecosystem at a particular point in time" Potschin-Young et al., 2018, p. 18) are the basis for the provision of ES. **ES potential** highlights the natural provision of ES. Human inputs (e.g. fertiliser, management practices) are not included (Maes et al., 2020). With ES potential, the amount of ES that could be provided naturally can be assessed and measured (Potschin-Young et al., 2018). **ES supply** describes "the provision of a service by a particular ecosystem, irrespective of its actual use. It can be determined for a specified period of time (such as a year) in the present, past, or future" (Burkhard and Maes, 2017, p. 368). The amount or quality of ES supply depends as well on the ES properties and conditions, but is also influenced by human inputs (e.g. land-use decisions). **ES flow** can be defined as "the amount of an ecosystem service that is actually mobilized in a specific area and time" (Potschin-Young et al., 2018 p. 23). This exchange can include matter, energy and/or information (Kleemann et al., 2020) and the mobilisation can occur through trade, transport, travel, political decisions or ecological phenomena (Schröter et al., 2018). The supplied ES provides several benefits for people. **ES demand** examines the extent to which a society, groups of people, or individuals need or desire ES to meet their basic needs (such as food, safety, social life) and to enhance their quality of life (Dworczyk and Burkhard, 2021; Wolff et al., 2017).

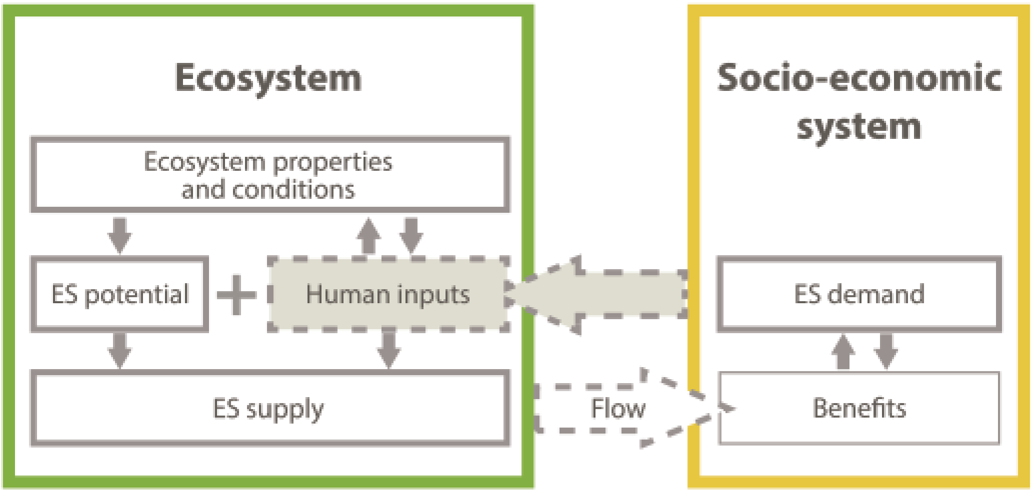

Figure 4. Simplified illustration of the cascade model to highlight the aspects of ES delivery, which can be mapped (Syrbe et al., 2017, p 149).

ES assessments allow the identification of areas that show a particularly high or low supply of ES. In the case of an assessment of multiple ES, **trade-offs** or **synergies** can be analysed and visualised. **Trade-offs** arise from land use decisions and management practices, which increase the magnitude of one particular ES. This intensification compromises, however, the provision of other ES (Potschin-Young et al., 2018; Rodríguez et al., 2006). A well-known example of this is the intensification of agriculture areas for increasing the ES crop production. Intensive agriculture has, however, negative impacts on the supply of other ES such as pollination or water quality. **ES synergies** occur when multiple services are enhanced simultaneously (Potschin-Young et al., 2018; Raudsepp-Hearne et al., 2010). This identification of ES that appear together in a landscape (ES bundles) is considered as a helpful tool for communicating the importance of multifunctional landscapes (Raudsepp-Hearne et al., 2010) and to illustrate the effects of human activities.

A comparison between the demanded and the supplied ES can be used to determine whether an imbalance (**ES mismatch**) exists (Geijzendorffer et al., 2015). For each individual ES, it is possible to examine *"1) the extent to which people need or demand these ES to meet their basic needs and improve their quality of life, and 2) the extent to which nature can meet these needs in a sustainable way"* (Dworczyk and Burkhard, 2021, p. 2). As already explained above, when ES demand exceeds ES supply, the respective ES may not be used sustainably, or may show unmet demand in certain areas. Unmet demand can directly negatively impact human well-being (e.g., health, safety).

However, the above-mentioned aspects and terms can be understood, interpreted and used differently within ES research (Honey-Rosés and Pendleton, 2013; Potschin-Young et al., 2018; United Nations, 2021). In many cases, the direct link between ES supply and ES demand is not clear, especially when long distances exist or when the benefits of the respective ES have time-lag effects (Wei et al., 2017). Also, the spatial location of ES demand is challenging as it can vary greatly depending on the needs or desires of stakeholders, population subgroups, or individuals (Wolff et al., 2015).

The multifaceted nature of ES has resulted in a 'supply-demand knowledge gap' (Elmqvist et al., 2013). The supply-demand knowledge gap points to the fact that the research on the (potential) supply of ES has progressed further than the research on the demand for ES (Luederitz et al., 2015; Wolff et al., 2015). This imbalance is still noticeable today in ES research (Campagne et al., 2020).

1.4. Spatial-structural approaches

The spatial relationships and connections between areas that supply and benefit from ES can be visualised in different ways, such as by using images, schematic illustrations or maps (such as in Fisher et al., 2009; Goldenberg et al., 2017; Rioux et al., 2019; Syrbe and Walz, 2012; Walz et al., 2017). These tools are helpful to understand, identify and communicate the complex spatial information of each ES potential, supply, flow and demand. This knowledge can help to identify suitable spatial scales, indicators and data needed for ES studies. It can also help to identify whether natural or anthropogenic barriers, sinks or depletion regions or other disturbances have an impact on the provision, distribution and accessibility of ES (Dworczyk and Burkhard, 2021).

In ES research literature, spatial-structural approaches have been used to visualise the spatial relationships between **Service Providing Areas (SPA)** and **Service Benefitting Areas (SBA)** and the space between them, the **Service Connecting Areas (SCA).** The empirical understanding between those areas have been discussed, adapted and updated in several articles (see Chapter 3).

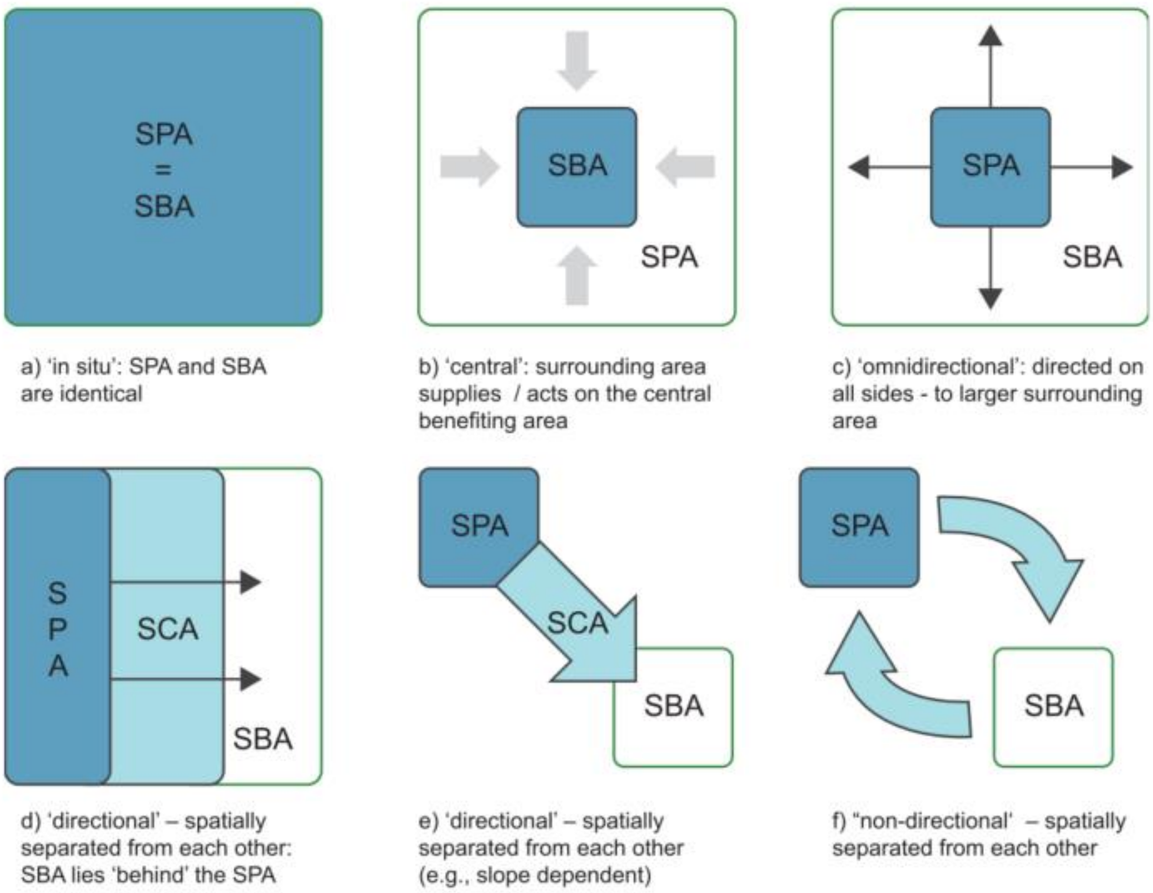

Figure 5. Spatial-structural approach from Walz et al. (2017). The figure shows the types of spatial relations of Service Providing Areas (SPA), Service Benefitting Areas (SBA), and Service Connecting Areas (SCA) without separate consideration of areas where the demand for ES arises or are not met.

In existing spatial-structural approaches, such as in Walz et al. (2017), the SBA are the areas where people simultaneously demand and benefit from ES (see Figure 5). However, the extent to which people demand ES might be greater than the extent to which nature can provide ES. For example, Baró et al. (2015) assessed in an ES mismatch analysis that the amount of green infrastructure in five case study areas was insufficient to abate the concentration of air pollutants to a healthy level according to environmental quality standards. Furthermore, many city dwellers cannot benefit from the ES of urban nature at home, as green areas in the vicinity are lacking or inaccessible due to barriers (e.g. property rights) (United Nations, 2022b). In order to be able to analyse the distribution of ES and their (un)accessibility and (un)availability, the **Service Demanding Area (SDA)** and the SBA should be considered separately. Existing spatial-structural approaches need to be adapted and supplemented with the SDA to emphasise and communicate this point.

1.5. Methodologies

The following subsections provide an overview of the various methodologies applied in this thesis. The literature reviews (Chapters 2 and 3) provided a sound scientific knowledge basis for addressing the research questions mentioned above. It also revealed conceptual questions, especially on ES demand and ignited the idea of adapting the existing spatial-structural approaches (Chapter 3). This adapted version has been used in Chapters 4 and 6. Chapters 4 and 6 mapped selected ES with a) an expert-based ES matrix approach, simple GIS mapping methods and models, and b) a comprehensive model. Chapter 5 complements the work with information from scientists and practitioners investigating the ES concept's implementation capacity in spatial planning and decision-making processes in urban contexts. This information has been assessed via discussions, questionnaires, and semi-structured interviews (see Chapter 5).

1.5.1. Literature review

The literature selection and review were based on the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement, which describes a systematic review process (Moher et al., 2009) (see Figure 6).

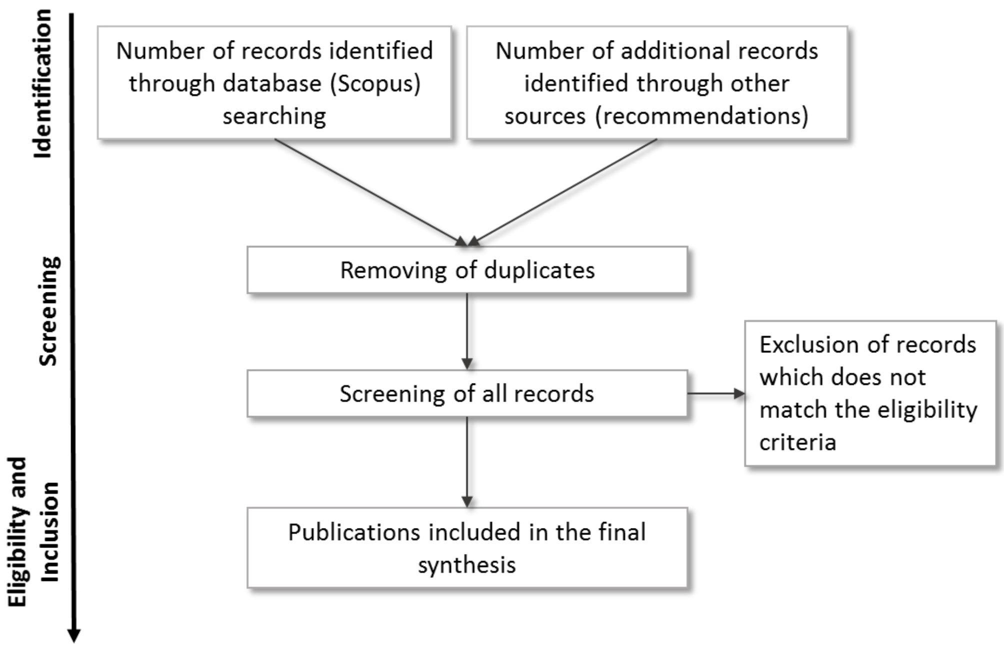

Figure 6. Schematic illustration of used systematic review process, followed the literature review flow diagram from Garcia Rodrigues et al. (2017, p. 6) and the PRISMA statement (Moher et al., 2009, p. 3).

This methodology has been applied in numerous other ES review studies (e.g. Garcia Rodrigues et al., 2017; Sieber et al., 2018). The systematic review process consists of several steps: First, peer-reviewed scientific articles are identified in scientific data bases like Scopus with keywords in a Boolean search. Other recommended articles can be included in the first list. Next, the initial relatively large number of records are reduced by the removal of duplicates and by screening the records. All records which do not match the eligibility criteria are excluded from the final list of records. The final list is then used for the literature review (see Chapter 2 and 3).

1.5.2. Mapping ecosystem services

ES assessment and mapping are needed to proceed from the conceptual framework described in Chapter 1.3 to the practical integration of ES into policy and decision-making (Burkhard and Maes, 2017; Maes et al., 2020). There are many existing methods for assessing and mapping ES. Appropriate methods can come from different scientific disciplines (e.g. sociology, environmental economics and natural sciences) (Harrison et al., 2017).

For mapping and assessing ES, there are approaches that: a) link ES values to land use and land cover classes, b) rely on expert knowledge, c) use known relationships between ES and spatial information from literature or statistics, d) use primary data (e.g. form field surveys), or, e) are based on more complex modelling (Grêt-Regamey et al., 2017). These approaches have their advantages and disadvantages, and the suitability of a method depends on many factors. Decisive factors are, for example, the objectives of the research project, the scale of the case study region and the availability and quality of the needed input data.

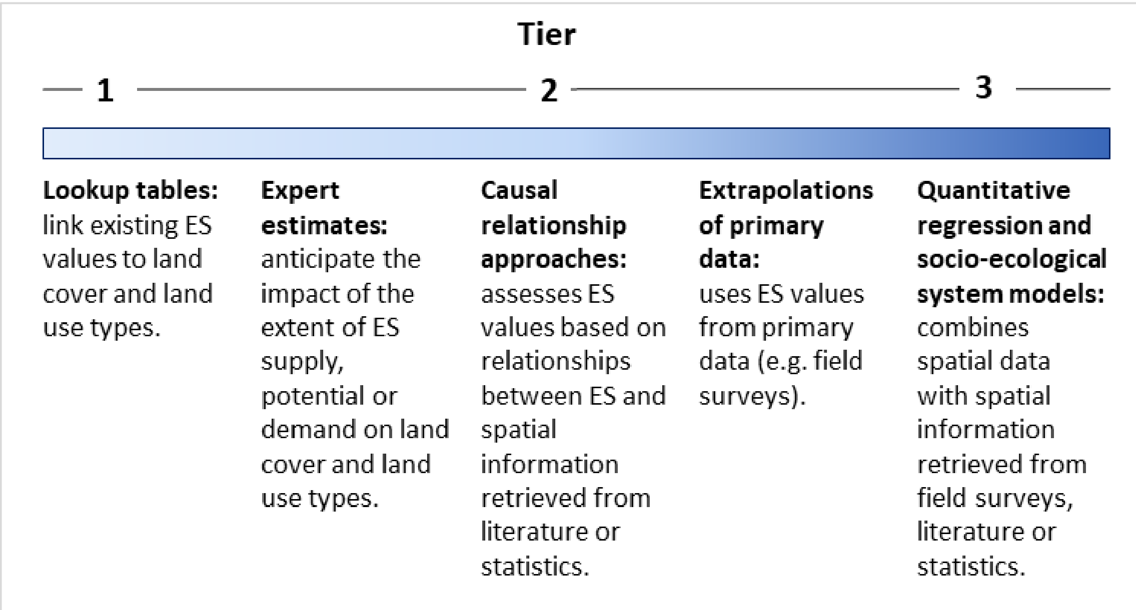

Figure 7. Tiered approach for ES mapping, adapted after Grêt-Regamey et al. (2017).

Guidance to choose suitable methods provides the *tiered approach for ES mapping* (see Figure 7). This approach classifies the methods and models into three different tiers according to their complexity, resource availability (e.g. time, data, knowledge) and mapping purposes (e.g. raising public awareness *vs*. scientific research) (Campagne et al., 2020; Grêt-Regamey et al., 2017; Grêt-Regamey et al., 2015). Relatively quick-to-apply methods (tier 1) can be used for instance for communication and awareness raising, as they can provide a simple overview of ES issues. More complex methods (tiers 2 or 3) provide results with higher spatial resolution and should be chosen if more in-depth analysis of the underlying interactions between ES components and/or socio-ecological processes are needed (Grêt-Regamey et al., 2017; Grêt-Regamey et al., 2015). For this study, supply and demand for selected ES have been mapped with the ES matrix approach, simple GIS mapping with proxy indicators and data, plus models (InVEST[1] and LEAFlood[2]) (see Chapters 4 and 6).

1.5.3. Ecosystem services matrix approach

The ES matrix approach is based on lookup tables, in which ES values are linked to appropriate geo-biophysical spatial units. The ES values can be generated using the range of mapping methods and data sources (like expert estimates, literature or statistical data, primary data, results from quantitative regression or socio-ecological system models). The ES values are classified into a relative scale, which can, for example, range from 0 to 5 and represent the lowest/highest value of ES supplied or demanded. Thereafter, ES maps using the same categorisation scale and colours can be generated. This standardisation allows comparisons between individual ecosystem services (columns), geospatial units, and results from different mapping methods (Burkhard, 2017).

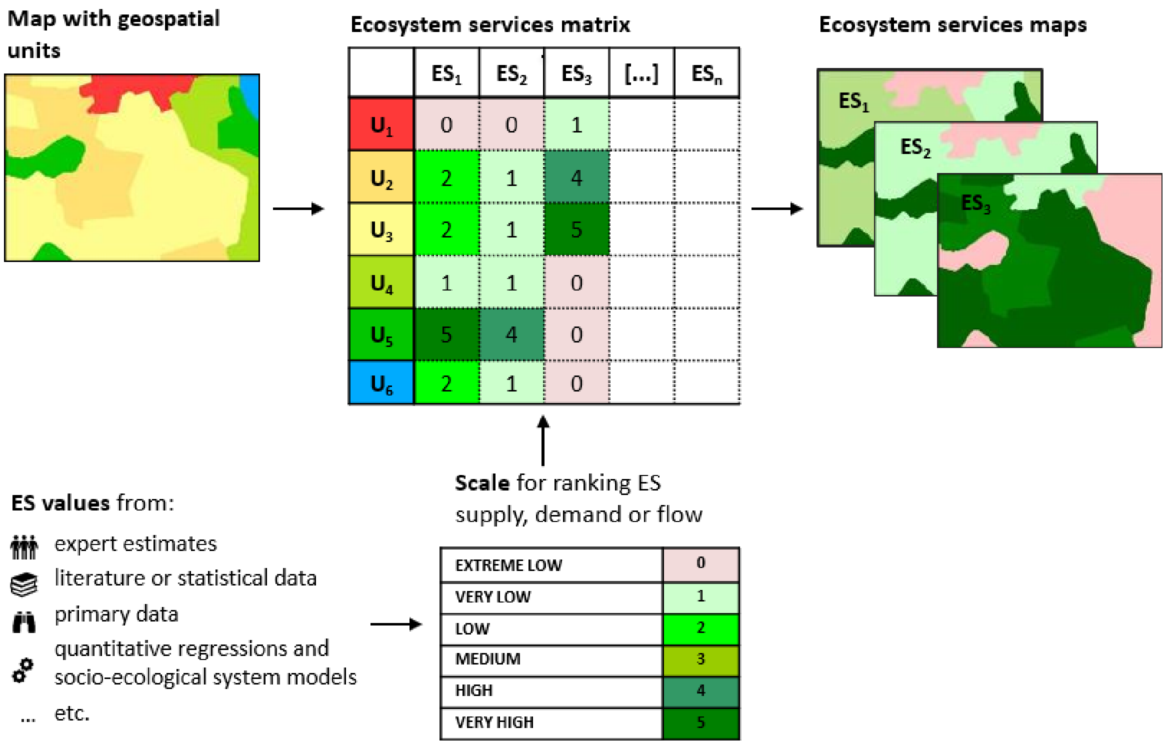

Figure 8. Schematic concept of the ecosystem services matrix approach (adapted from Burkhard, 2017; Jacobs et al., 2015). For the implementation of the ES matrix approach, a map/spatial data with appropriate geospatial units and ES values for each individual ES are needed. The ES values can be collected using different methods and data sources. These values are classified using a relative scale (in this example: 0 (extreme low) to 5 (very high)). Thereafter, ES maps using the same scale and colours can be generated. This allows comparisons between individual ecosystem services (ES) (columns) as well geospatial units (U).

The *expert-based ES matrix approach* describes a participatory scoring process, in which expert estimates are collected within the ES matrix approach. This method can be either conducted in workshops, focus group discussions, individual interviews or online. The participants get information material about the scoring process and explanations about the selected ES, ES component (e.g. supply

[1] InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs models (The Natural Capital Project, 2021).
[2] LEAFlood - Landscape vegetation and flood model (Wübbelmann and Förster, 2022)

or demand) and considered land-use and land cover (LULC) classes. The key element of this participatory scoring process is a matrix, which can be provided to the participants either empty or with pre-populated scores. In this matrix, the columns describe selected ES, and the rows LULC classes. The participants are then asked to fill in their scores for ES supply or demand in the different LULC types in an empty matrix or to correct the estimates in the pre-populated in matrix. Additionally, participants can score their confidence in the knowledge of each ES and LULC using the scale 0 - 5 (very uncertain - very certain) (Campagne et al., 2017). Next, the expert estimates can be analysed using simple (or complex) descriptive statistics.

In the context of the ÖSKKIP project (see Subchapter 1.7), the expert estimates for ES supply and demand were collected during two workshops held in 2018: 1) 'Angebot und Bedeutung von Ökosystemleistungen in Stadtregionen' (engl. *Supply and importance of ecosystem services in urban regions*), and 2) 'Ökosystemleistungen in den Stadtregionen: Angebot, Nachfrage und Planungsrelevanz' (eng. *Ecosystem services in urban regions: supply, demand and it's planning relevance*). Both workshops took place in the selected case study areas Rostock and Munich (for the description of the case study areas, see Chapters 1.6 and 4). Figure 9 shows photographs from two of those events. For detailed descriptions of the workshops, see Barkmann et al. (2019) and Barkmann et al. (2020).

Figure 9. Left: Workshop in the urban region of Munich. Photo: ifuplan. Right: Workshop in the urban region of Rostock. Photo: Hafencity Universität Hamburg

1.5.4. Simple GIS mapping

ES have been mapped with GIS software and available proxy indicators and data (such as literature, statistical, or LULC data) (see Chapter 4). The advantage of this method is that results can be generated relatively quickly without using complex methods and when data, time and money are scarce (Burkhard and Maes, 2017; Harrison et al., 2017). Furthermore, many proxy indicators are well-known and easy to communicate and to understand (Burkhard and Maes, 2017; Campagne et al., 2020; Jacobs et al., 2017; Roche and Campagne, 2019).

1.5.5. Models

ES can be assessed, mapped and quantified with computer models. Models can provide a deeper understanding of interactions and interdependencies between biophysical, ecological, and/or socio-economic characteristics and provide the opportunity to explore alternative scenarios by changing parameters within models (Dunford et al., 2017). A variety of models for mapping individual ES exist. For this thesis, **InVEST[3] models** and the **hydrological model LEAFlood[4]** have been used.

Several individual ES can be mapped using the InVEST model suite (The Natural Capital Project, 2021b). The InVEST models are provided in a desktop application and relatively easy to run, as only basic to intermediate GIS skills are required. The results are site-explicit, allowing the opportunity to explore the impact of ecosystem structures and functions on ES supply (The Natural Capital Project, 2021b). For this thesis, following InVEST models were tested:

- Food (from cultivated terrestrial plants): Crop Production (NatCap, 2022);
- Pollination: Pollinator Abundance: Crop Pollination (NatCap, 2022);
- Local climate regulation: Urban Cooling (The Natural Capital Project, 2019);
- Coastal protection: Coastal Vulnerability (The Natural Capital Project, 2021a).

However, due to data availability reasons, only results from the InVEST models *Pollinator Abundance: Crop Pollination* and *Urban Cooling* could be computed. For more details, see the Supplementary information for Chapter 4.

The hydrological model LEAFlood (Chapter 6, Wübbelmann and Förster, 2022) is based on the functions of the open source Python packages 'Catchment Modelling Framework' (Kraft et al., 2011). Several hydrological processes are considered in LEAFlood: canopy interception, canopy evaporation, throughfall, soil infiltration, and surface runoff. The model is driven by meteorological data (precipitation, temperature, wind speed, relative humidity, and solar radiation), Digital Elevation Model (DEM), LULC data, tree data, and soil data (Wübbelmann et al., submitted). The model calculates and estimates the amount of surface water storage, canopy storage, soil water storage (all water depth in mm), and the outflow at outlets (in m^3/time). For a detailed model description, see Wübbelmann and Förster (2022).

1.5.6. Data acquisition

Chapters 2 and 3 used literature data. See supplementary information for Chapter 2 and 3 for the lists of the considered peer-reviewed articles.

Chapter 4 used a bundle of datasets. The experts' estimates for ES supply were collected with the expert-based ES matrix approach during the aforementioned topical workshops in Rostock and Munich. For the simple GIS mapping with proxy indicator and data and for computing the InVEST models *Pollinator Abundance: Crop Pollination* and *Urban Cooling,* LULC, literature and statistical data from various data sources were used. For detailed descriptions of the datasets used, see the Supplementary information for Chapter 4.

Chapter 5 used a) the opinion and experiences of 17 scientists, and, b) the perspectives from 14 practitioners, which were collected through semi-structured interviews. See Supplementary information for Chapter 5 for further information.

For computing the hydrological model LEAFlood in Chapter 6, meteorological data (precipitation, temperature, wind speed, relative humidity, and solar radiation), LULC data, tree data, soil data, and Digital Elevation Model (DEM) has been used. For assessing ES demand, spatial data about population

[3] InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs
[4] LEAFlood - Landscape vegetation and flood model

density, infrastructure, land reference value, and cultural buildings was required. A detailed overview of the datasets used is provided in the Supplementary information for Chapter 6.

1.6. Case study areas

Chapters 4 – 6 are focussing on case study areas, which are described in the following paragraphs. Chapter 4 focused on the urban regions of Rostock and Munich (see Figure 10). The case study regions include a core city (Rostock and Munich) and adjacent surrounding areas including small and medium sized cities. These case study areas represent two different urban regions with significant differences in the number of inhabitants, population density, size, geographical location and infrastructure. However, both case study areas face population growth, urban sprawl and urbanisation processes. The climate in both urban regions is characterised by a warm, temperate climate with humid periods, warm summers and cold winters (Köppen-Geiger climate class Cfa) (Kottek et al., 2006).

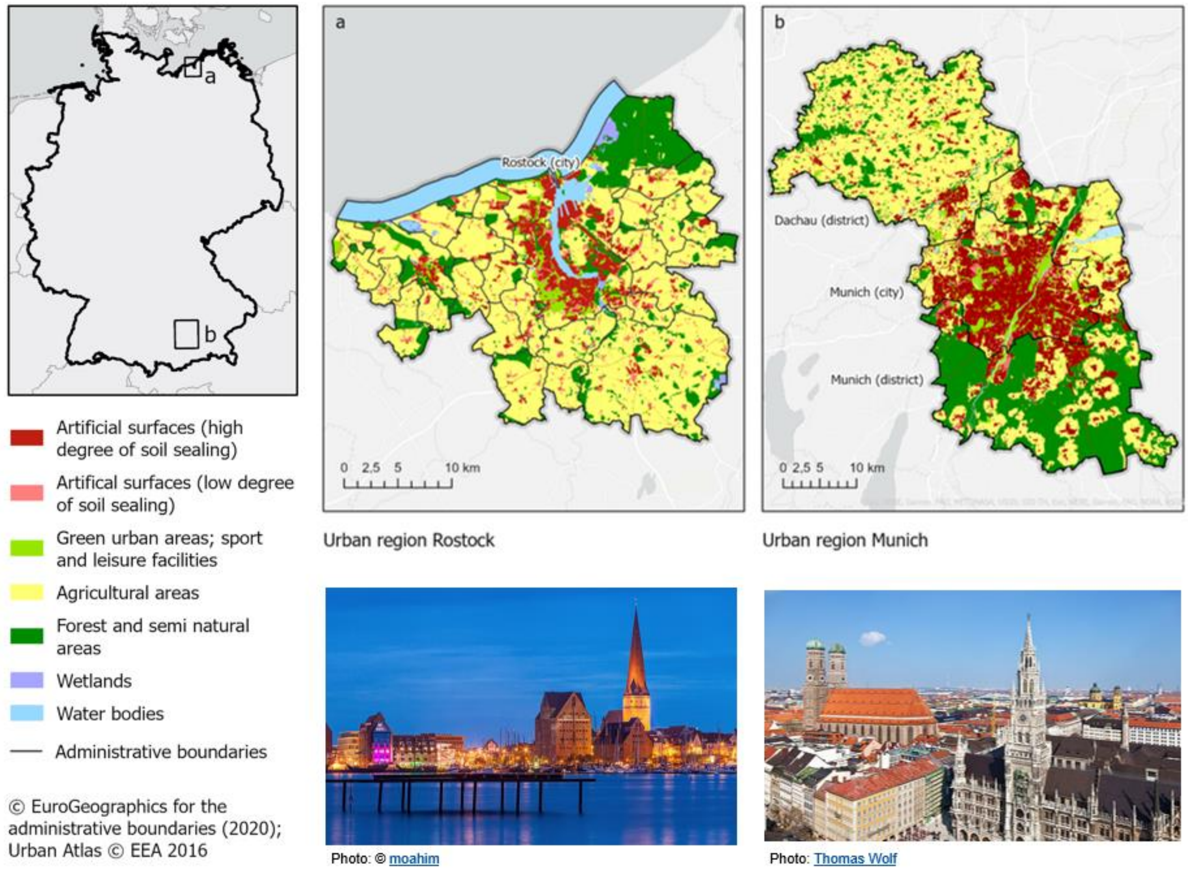

Figure 10. Urban regions Rostock and Munich.

The urban region of Munich is located in the southern part of Germany. The boundaries of the case study region are delimited towards the NUTS3[5] level. This study area encompasses the two districts (Landkreise) Dachau and Munich as well as the city of Munich, which is the capital of Bavaria. This study area covers approximately 1,550 km² and has almost two million inhabitants (Statistisches Bundesamt, 2019). The dominant land-use type of the whole study area is agriculture (44 %), followed by forest areas (27 %). The city of Munich, however, is primarily characterised by artificial surfaces.

[5] NUTS - Nomenclature des unités territoriales statistiques (*engl.* Nomenclature of territorial units for statistics). This nomenclature provides a comprehensive classification of territorial units, which allows cross-border statistical comparisons. NUT3 level represents regions (in Germany: Kreise, kreisfreie Städte) (Eurostat, 2021).

Despite being a densely-built city, Munich has several parks, such as the Englisher Garden, which is frequently visited by urban citizens and visitors.

As an economically attractive location, Munich is one of the fastest-growing cities in Germany (Bundesinstitut für Bau-, Stadt-, und Raumforschung, 2020). The district of Dachau is located in the north-western part of the urban region. This district has a hilly and agricultural-dominated countryside. However, the urban sprawl extending from Munich is advancing into the district's territory. The district of Munich is located in the east and south of the urban region. The city's growth is also strongly noticeable in this district too, especially close to the city's boundaries (Bayerisches Landesamt für Umwelt, 2021). The highest elevation of the case study area (approximately 700 m) can be found in this district, with the foothills of the Alps.

The urban region of Rostock is located on the Baltic coast in the Northeast of Germany in Mecklenburg-Western Pomerania and is part of the district (Landkreis) Rostock. The study area encompasses 21 municipalities, including the Hanseatic city of Rostock. The study area covers approximately 670 km² and has a population of over 270,000 inhabitants (Statistisches Bundesamt, 2019). The dominant land-use type is agriculture (63 %). From an orographic perspective, the city region of Rostock is located in a bulky to hilly moraine landscape. Several fens can be found along the Warnow river (Bundesamt für Naturschutz, 2009). The urban region of Rostock is an attractive place to live and work. The city itself and also some smaller towns in the vicinity of the city are experiencing strong population growth (Bundesinstitut für Bau-, Stadt-, und Raumforschung, 2020). The maritime character of the region attracts tourists and day visitors (Statista, 2022). The Rostock Heath (a coastal forest and heathland region) in the east of the study area is another popular tourist attraction and important nature conservation area.

Chapter 6 is focused on a local study area within the urban region of Rostock. The study area covers 4.5 km² and includes several city districts of Rostock. A heterogeneous mix of land-use types (such as urban green spaces, forests, built-up areas, and infrastructure) is located in this area. This study area has observed several floods through heavy rainfall in the past (Wübbelmann et al., submitted). More information is provided in Chapter 6.

Chapter 5 is focused on ten urban case studies across Europe: Istanbul (Turkey), Lisbon (Portugal), Munich (Germany), Łódź (Poland), Dresden (Germany), Geneva (Sitzerland), Rostock (Germany), Liberec (Czech Republic), Rescaldina (Italy), Ragalna (Italy). These case study areas cover a wide range of spatial scales, geographic and climatic conditions, and population densities. Two of the case study areas are the aforementioned urban regions Rostock and Munich. More information about the case study areas are provided in the Supplementary information for Chapter 5.

1.7. ÖSKKIP research project

This thesis partially results from work carried out within the ÖSKKIP[6] research project which tested the integration capacity of the ES concept into urban and regional planning in Germany. The Federal German Ministry of Education and Research (BMBF) funded this interdisciplinary research project within the framework of the strategy 'Research for Sustainability' (FONA – Forschung für Nachhaltige Entwicklung) from March 2017 to December 2021. ÖSKKIP was subdivided into several sub-projects.

[6] ÖSKKIP - Ökosystemleistungen von Stadtregionen – Kartieren, Kommunizieren und Integrieren in die Planung zum Schutz der biologischen Vielfalt im Klimawandel (engl: Ecosystem Services of Urban Regions – Mapping, Communicating, and Integrating into Planning to conserve biodiversity during a changing climate). www.öskkip.de

Within the sub-project 1 'ES in urban regions', selected ES in the urban regions of Rostock and Munich were assessed and mapped. The results were needed and used for communication and discussions with local stakeholders (Barkmann et al., 2020; Barkmann et al., 2019). ÖSKKIP revealed that there are changes for an implementation of the ES concept in different formal and informal planning instruments in Germany. However, comprehensive integration into spatial planning processes is still hampered by, among other things, the need for legal adjustments and better availability of data and indicators (Deppisch et al., 2021a; Deppisch et al., 2021b).

The research project involved the partners HafenCity University Hamburg, Leibniz University Hannover, and ifuplan (Institute for Environmental Planning and Spatial Development) Munich as an implementation partner. The two urban regions of Rostock and Munich were represented as ÖSKKIP case study areas. Local stakeholders from the two urban regions were invited to several workshops (in which the expert-based ES matrix methods were used) and online discussions.

1.8. Structure of this thesis

As presented in **Chapter 1.1**, the overall objective of this dissertation is to improve the conceptual and methodological understanding of mapping ES on urban and regional scales and to answer three research questions. Table 1 shows which research questions are answered from the original articles.

Table 1. Connection of the Chapters 2-6 to the research questions.

Research questions	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
What are the trends in mapping and assessing ecosystem services in urban areas?	x			x	
What are the conceptual challenges in mapping ecosystem service supply and demand in urban regions?		x	x	x	
What application obstacles do commonly applied ecosystem service mapping approaches face and how can these best be overcome?	x	x	x	x	x

Chapter 2 focuses on ES in urban ecosystems. It is based on the original article *"Urbane Ökosystemleistungen erfassen und bewerten. Stand der Forschung, Indikatoren und zukünftige Perspektiven" (*Assessing and evaluating urban ecosystem services - an overview of research status, indicators, and future perspectives), which was published in 2020 in Naturschutz und Landschaftsplanung 52 (04). This article followed the systematic review statement PRIMSA and focused on three research questions: *Which urban ES are being assessed in current research in Europe? Is there any particular research concentrating on assessing and mapping urban ES? Which indicators and methods have been used?* A systematic literature review was conducted to answer the research questions. Since it became apparent during the review process that a large number of indicators and methods were used for a variety of ES, only the indicators for the ES *local climate regulation* were analysed in more detail.

Chapter 3 deals with the persisting conceptual challenges within the ES concept, especially with ES demand. In the article *"Conceptualising the demand for ecosystem services – an adapted spatial-*

structural approach" (Dworczyk and Burkhard, 2020), the focus was on the following questions: *How to define ecosystem service demand? Where and from whom does the demand for ecosystem services come from? Where to map the demand for ES?* This chapter used existing literature on ES demand to answer the research questions. To answer the last two questions more precisely, the authors have created schematic illustrations to explain and visualise the spatial relationships and connections between areas that provide, benefit from or demand ES. In existing spatial-structural approaches, ES demand is rarely considered or equated with areas where people can use the benefits (Fisher et al., 2009; Syrbe and Grunewald, 2017; Walz et al., 2017). This Chapter introduced and illustrated the 'Service Demanding Area' (SDA).

Chapter 4 presents the original article *"Challenges entailed in applying ecosystem services supply and demand mapping approaches: a practice report"* (Dworczyk and Burkhard, 2023), which has been submitted in the journal *land* and is currently under review. This publication focused on the research questions: *1) How useful are commonly used ES mapping approaches in regional urban contexts, and which major obstacles to their application did we encounter? 2) How can [the] experiences [from the ÖSKKIP research project] help inform future research and comparable application perspectives in ES mapping?* In this article, the authors used different easy-to-apply mapping methods (expert-based ES matrix method, simple GIS mapping with proxy indicator and data, and InVEST models) to map the supply and demand of selected ES. The authors summarised experiences from the ÖSKKIP research project and provided recommendations for future research on mapping ES supply and demand in urban regions.

Chapter 5 highlights a summary of lessons learned from implementing the ES concept into urban planning practice from ten European urban case study areas. This study compared the views from scientific experts, who are focusing on urban ES, with the views from practitioners, who are responsible for spatial planning and decision-making in urban contexts. The position of the ES concept in urban planning and decision-making practices has been assessed via discussions, questionnaires, and semi-structured interviews. Scientists and practitioners generally agree on both the opportunities of the ES concept to improve urban planning and the barriers and operational limitations that still exist. The article summarised the opinions and needs from both perspectives and provided recommendations for an improved implementation of the ES concept in future urban case studies (Grunewald et al., 2021).

Chapter 6 presents a study on one ecosystem service, namely ***flood regulation*** (also mentioned as flood regulating ES), in a district of the city of Rostock. The frequency and intensity of heavy rainfall events are projected to increase with climate change. This increase is expected to result in higher flood risks and damages. The ES *flood regulation* describes how ecosystems provide flood protection through the capacity of vegetation and soils to retain water. People benefit from this ES because it helps to manage, mitigate, or prevent potential damages to human health, cultural heritage, economic activity, and infrastructure (Haines-Young and Potschin, 2018). This study modelled with a hydrological model (LEAFlood) the actual and potential supply of and demand for flood regulation under a) current and future climate conditions, and, b) different nature-based solution measures. This publication has been submitted to *Frontiers* and is currently under review (Wübbelmann et al., submitted).

Chapter 7 synthesises the answers of the aforementioned research questions of this study and presents the main conclusions as well as prospects for future research.

Chapter 2

Urbane Ökosystemleistungen erfassen und bewerten. Stand der Forschung, Indikatoren und zukünftige Perspektiven

Dworczyk, C., Burkhard, B.
Naturschutz und Landschaftsplanung (2020), 52, 176–183

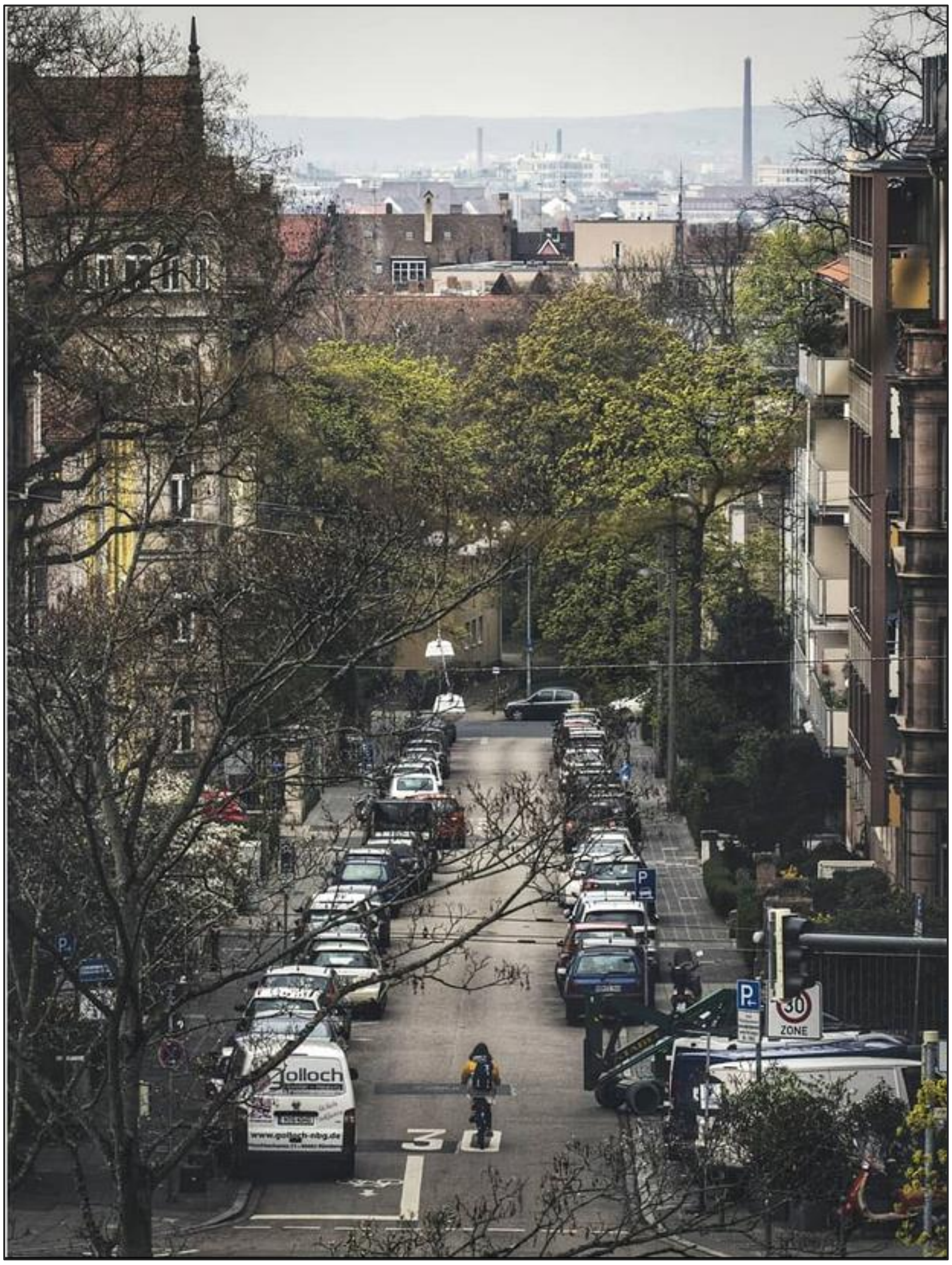

Figure 11. Street trees improve the air quality. Photo: Jolanta Dworczyk.

Originalarbeit

Urbane Ökosystemleistungen erfassen und bewerten

Stand der Forschung, Indikatoren und zukünftige Perspektiven

Von Claudia Dworczyk und Benjamin Burkhard

Eingereicht am 30.07. 2019, angenommen am 18.02.2020

Abstracts

Die fortschreitende Verstädterung und Urbanisierung in der Welt führen zu tiefgreifenden Veränderungen von Ökosystemen. Diese Veränderungen werden zusätzlich durch den Klimawandel und den Verlust von Biodiversität verstärkt. Für die Gesundheit und das menschliche Wohlbefinden der wachsenden städtischen Bevölkerung sind urbane Ökosysteme, die multiple Ökosystemleistungen (ÖSL) bereitstellen können, besonders wichtig. Vor Ort spielen insbesondere regulierende und kulturelle ÖSL eine wichtige Rolle, die zum Beispiel das lokale Klima oder die Luftqualität regulieren und Erholungsmöglichkeiten im urbanen Raum bereitstellen. Vor allem in Europa trifft das Konzept der urbanen ÖSL daher auf ein steigendes wissenschaftliches und politisches Interesse. Über die urbanen ÖSL werden verstärkt neue Informationen durch verschiedene Indikatoren generiert, deren Aussagekraft jedoch von unterschiedlicher Qualität ist. Im Rahmen einer systematischen Literaturuntersuchung werden Hintergründe, das internationale ÖSL-Klassifizierungssystem CICES 5.1 und aktuelle Forschungsaktivitäten zum Thema urbaner ÖSL thematisiert.

Recording and evaluating urban ecosystem services – an overview of research status, indicators, and future perspectives

Many cities are witnessing ongoing urban densification and urbanisation processes that are leading to far-reaching changes in ecosystems. These ecosystem changes are further compounded by climate change and the loss of biodiversity. However, urban ecosystems that can provide multiple ecosystem services (ES) are of essential importance for the health and social well-being of the growing urban population. Therefore, the concept of urban ES is creating increasing scientific and political interest, especially in Europe. Numerous indicators are used to generate new information about urban ES, but their informative value is of varying quality. In the course of a systematic analysis of articles, this review surveys the context of these articles, looks at current research activities in the field of urban ES, and introduces the Common International Classification of Ecosystem Services, CICES 5.1.

1 Theoretischer Hintergrund: Urbane Ökosysteme und deren Leistungen

Im jüngsten Bericht des Weltbiodiversitätsrates IPBES (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services) wird deutlich aufgezeigt, dass sich der Zustand der Biodiversität, der Ökosysteme und der von ihnen bereitgestellten Ökosystemleistungen (ÖSL) verschlechtert (IPBES 2019, Definitionen siehe Tab. 1). Die weltweiten Verstädterungs- und Urbanisierungsprozesse werden hierbei als die menschlichen Aktivitäten identifiziert, die Wasser- und Nährstoffkreisläufe, das Klima und die biologische Vielfalt weltweit am stärksten verändern (WBGU 2016).

Angesichts des wachsenden Anteils der städtischen Bevölkerung müssen Stadt- und Regionalplaner sowie politische Entscheidungsträger festlegen, wie Flächen und natürliche Ressourcen im urbanen Raum nachhaltig verwaltet werden sollen. Dies ist keine leichte Aufgabe, da die Bevölkerung, die Wirtschaft und der Naturschutz konkurrierende Anforderungen an die Gestaltung der urbanen Räume stellen (WBGU 2016). Das Konzept der ÖSL kann hierbei einen Lösungsansatz für die Entscheidungsfindung bieten, da es Zusammenhänge zwischen ökonomischen, sozialen und ökologischen Themen anspricht und systematische Analysen ermöglicht (Müller et al. 2010).

Das ÖSL-Konzept erreichte bereits in den letzten Jahren eine zunehmende politische Relevanz, die durch internationale Abkommen und Beschlüsse weiter erhöht wird. So ist das ÖSL-Konzept beispielsweise in der europäischen Biodiversitätsstrategie 2020 (BMUB 2007, EU 2011) verankert. Gemäß Ziel 2, Maßnahme 5 werden alle EU-Mitgliedsstaaten aufgefordert, ihre Ökosysteme und deren Leistungen bis zum Jahr 2020 zu erfassen, räumlich darzustellen und den Zustand von mindestens 15 % der geschädigten Ökosysteme durch die Einrichtung Grüner Infrastruktur (GI) zu verbessern (EK 2013, EU 2011). Diese Aufforderung schließt Städte und somit die urbanen Ökosysteme mit ein (Maes et al. 2013).

Mit dem Begriff „urbane Ökosysteme" werden Ökosysteme bezeichnet, die von einer hohen Bevölkerungsdichte sowie einem hohem Bebauungsgrad geprägt sind (Elmqvist et al. 2013) und in denen komplexe Interaktionen und Abhängigkeiten zwischen den Menschen und ihrer Umwelt stattfinden (Young et al. 2006). Diese sozio-ökologischen und in höchstem Maße anthropogen modifizierten Systeme sind in jeder Stadt einzigartig und würden ohne menschlichen Einfluss nicht existieren.

Von einer konzeptionellen Ebene betrachtet, ist ein urbanes Ökosystem ein offenes System, das nicht klar von anderen Ökosystemen abgegrenzt werden kann und andere Ökosystemtypen erheblich beeinflusst (Kohsaka 2010). Viele Ökosystemfunktionen und ÖSL finden über die Stadtgrenzen hinaus statt (Elmqvist et al. 2013). Diese Stadtgrenzen können in Abhängigkeit von verschiedenen Betrachtungsmerkmalen (zum Beispiel nach administrativen, politisch gesetzten Grenzen,

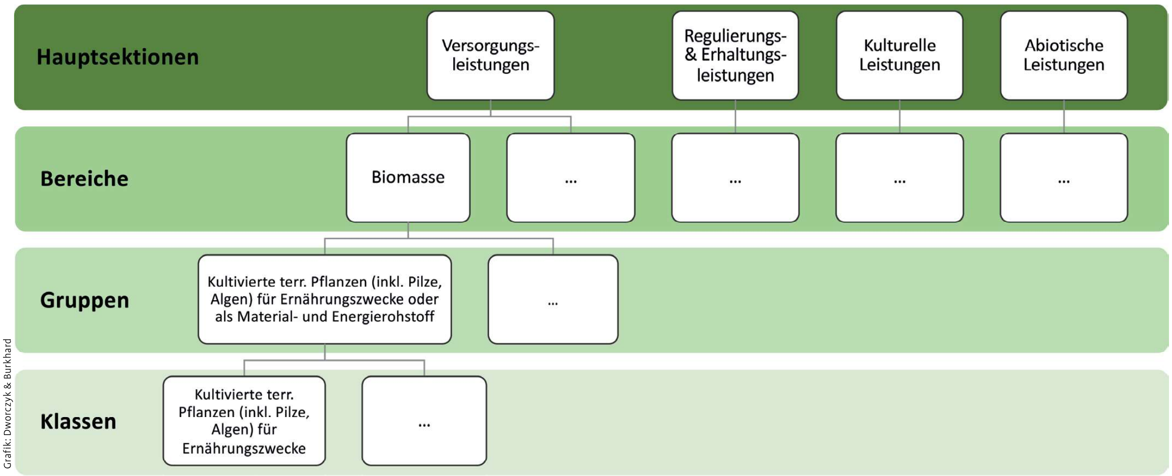

Abb. 1: Die hierarchische Struktur von CICES 5.1, adaptiert nach Haines-Young & Potschin (2018: 9).

Bevölkerungsdichten oder Landnutzungen) gezogen werden, die eindeutige Unterscheidungen zwischen urbanen und nicht-urbanen Ökosystemen zusätzlich erschweren (Maes et al. 2016, Seto et al. 2013).

In urbanen Ökosystemen werden die ÖSL in erster Linie durch die Stadtnatur und die GI bereitgestellt. Der Begriff Stadtnatur beschreibt die „*Gesamtheit der in urbanen Gebieten vorkommenden Naturelemente einschließlich ihrer funktionalen Beziehungen*" (Kowarik et al. 2016: 294). Stadtnatur ist auf allen städtischen Flächennutzungstypen zu finden und umfasst alle Arten von Tieren und Pflanzen – von Pflanzen auf Balkonen bis hin zu Bäumen in Stadtwäldern (ebd.). Unter GI wird hingegen ein „*strategisch geplantes Netzwerk natürlicher und naturnaher Flächen mit unterschiedlichen Umweltmerkmalen, das mit Blick auf die Bereitstellung eines breiten Spektrums an Ökosystemleistungen angelegt und bewirtschaftet wird*" (EK 2013:3), verstanden. Der Begriff GI wird für verschiedene Skalenebenen verwendet und beschreibt zum Beispiel nationale beziehungsweise regionale ökologische Netzwerke oder die multifunktionalen Grünraumnetzwerke in urbanen Räumen (Hansen & Pauleit 2014).

In Städten basiert die Bereitstellung von urbanen ÖSL nicht nur auf natürlichen, sondern auch auf anthropogenen Strukturen und Einträgen, was auch als ÖSL-Koproduktion bezeichnet wird (Fischer & Eastwood 2016). Einerseits beeinträchtigen Verschmutzungen sowie hohe Versiegelungs- und Bebauungsgrade die natürlichen Ökosystemfunktionen (wie Evapotranspiration) und damit ÖSL (wie Temperaturregulierung) (Alavipanah et al. 2017, Dronova 2017). Andererseits können gezielte Maßnahmen, wie der Ausbau der städtischen GI, die urbanen Ökosysteme aufwerten und stärken, sodass sie ein höheres Potenzial für die Bereitstellung mehrerer ÖSL besitzen (Fischer & Eastwood 2016).

2 Erfassung urbaner Ökosystemleistungen

Zahlreiche wissenschaftliche Forschungsaktivitäten und europäische Arbeitsgruppen wie MAES (Mapping and Assessment of Ecosystems and their Services) oder TEEB (The Economics of Ecosystems and Biodiversity) erfassen und bewerten ausgewählte urbane ÖSL. Welche ÖSL als am relevantesten eingestuft werden, hängt hierbei von den gegebenen ökologischen und sozio-ökonomischen Merkmalen und vom Forschungsfokus ab (Gómez-Baggethun & Barton 2013, Luederitz et al. 2015).

ÖSL können anhand des europäischen Klassifizierungssystems CICES 5.1 (Common International Classification of Ecosystem Services) beschrieben und klassifiziert werden (Maes et al. 2016). In CICES 5.1 werden die ÖSL in den drei Hauptsektionen (1) Versorgungsleistungen, (2) Regulierungs- und Erhaltungsleistungen und (3) kulturelle Leistungen aufgelistet. Eine vierte Sektion der abiotischen Leistungen erweitert die Liste zusätzlich. CICES 5.1 ist ein hierarchisches System, das über mehrere Ebenen strukturiert aufgebaut ist (Bereiche, Gruppen, Klassen). Dadurch werden die ÖSL in immer detaillierter werdende Betrachtungseinheiten aufgeteilt. Die Bildung von zusätzlichen Ebenen, die die (Teil-)Aspekte der ÖSL-Klassen hervorheben, ist möglich (vgl. Abb. 1; Haines-Young & Potschin 2018).

In der Forschung zu urbanen ÖSL stehen bislang vor allem regulierende sowie kulturelle ÖSL im Fokus (Haase et al. 2014, La Rosa et al. 2016). Versorgende ÖSL werden hingegen vergleichsweise selten angesprochen (Russo et al. 2017). Ein wichtiger und naheliegender Grund dafür ist, dass in urbanen Räumen in der Regel nur wenige Wald- und landwirtschaftliche Nutzflächen zu finden sind. Auch sind die Ernteerträge auf gärtnerisch genutzten Flächen gering (ebd.). Die meisten Güter und Produkte aus dieser ÖSL-Sektion werden zudem auf dem globalen Markt gehandelt und lassen sich vergleichsweise einfach transportieren. Dadurch ist die Verbindung zu den notwendigen Ökosystemen und Landnutzungsflächen räumlich und zeitlich entkoppelt (Kremer et al. 2016). Gärtnerisch genutzte Flächen dürfen jedoch nicht ausschließlich auf ihre Fähigkeit, pflanzliche Nahrungsmittel oder Rohstoffe bereitzustellen, reduziert werden. Vielmehr muss die Gesamtheit der ÖSL betrachtet werden: Klein- oder Gemeinschaftsgärten sind beispielsweise für die Stadtbevölkerung wichtige Naherholungs- und soziale Begegnungsstätten, haben regulierenden Einfluss auf das lokale Klima und die Luftqualität, mindern Starkregenereignisse und bieten Lebensräume für Pflanzen und Tiere (Camps-Calvet et al. 2016, Russo et al. 2017).

Um das ÖSL-Konzept in stadt- und regionalplanerischen Entscheidungen integrieren zu können, ist es hilfreich, wenn die ÖSL mit belastbaren Indikatoren erfasst werden können. Indikatoren sind messbare, quantifizierbare Metriken oder Ersatzgrößen, die auf überprüfbaren Daten

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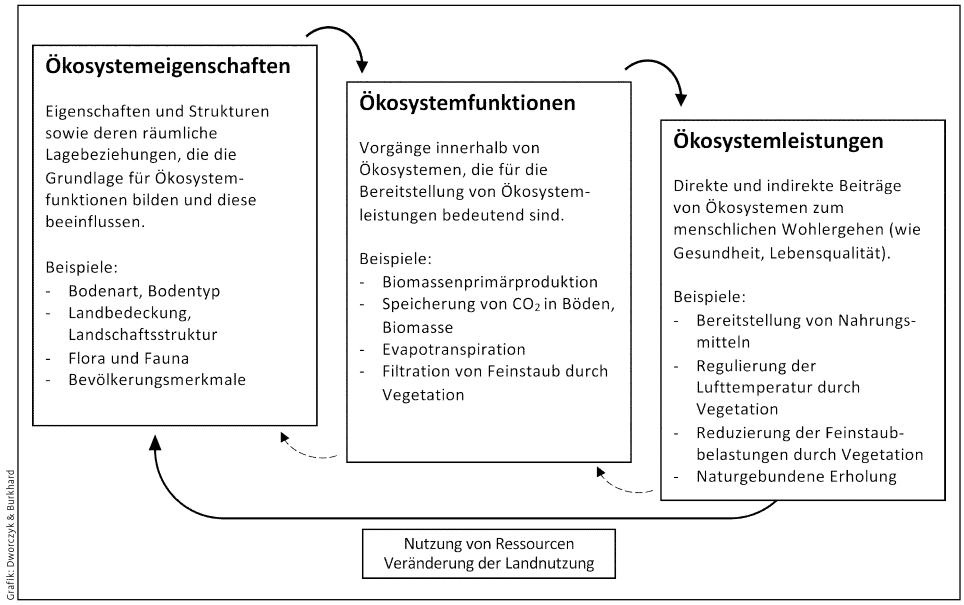

Abb. 2: Vereinfachte ÖSL-Kaskade nach HAINES-YOUNG & POTSCHIN (2010) und VAN OUDENHOUVEN et al. (2012) mit schematischer Darstellung von Abhängigkeiten. Durchgezogene Pfeillinien symbolisieren die direkten Einflüsse, gestrichelte Pfeillinien indirekte Wechselbeziehungen.

und Informationen basieren und die Informationen aus einem abzubildenden Themenbereich widerspiegeln, zusammenfassen und synthetisieren (BARKMANN 2004, HAASE et al. 2014, HEINK & KOWARIK 2010).

Für die ÖSL-Indikatoren werden diverse formale und inhaltliche Anforderungen gestellt, die je nach Forschungsfokus sehr spezifisch sein können. Zusammengefasst sollen die Indikatoren quantifizierbar, skalierbar, zeitlich und räumlich explizit sein und sich für die urbane Maßstabsebene eignen (GRUNEWALD et al. 2016b, VAN OUDENHOVEN et al. 2012). Im Idealfall sollen diese Indikatoren auf verständliche Art und Weise die individuellen städtischen Landbedeckungskombinationen, die ökosystemaren Eigenschaften und Funktionen vor Ort sowie die sozio-demografischen, kulturellen, wirtschaftlichen und politischen Aspekte einbeziehen (HAASE et al. 2014, MAES et al. 2016). Zudem sollten sie aussagekräftige Informationen über die gewählten ÖSL-Perspektiven (zum Beispiel ÖSL-Angebot, ÖSL-Nachfrage) liefern und dynamische Landnutzungsveränderungen erkennen können (EGOH et al. 2012, HAASE et al. 2014).

Bislang verhindert die Komplexität urbaner Ökosysteme die Berücksichtigung aller Einflussfaktoren, die zur Erfassung und Quantifizierung einer urbanen ÖSL notwendig wären. Häufig werden aus Vereinfachungs- oder Kommunikationsgründen sogenannte Proxy-Indikatoren verwendet, die Eigenschaften oder Funktionen eines Ökosystems abbilden (VAN OUDENHOVEN et al. 2012). Diese Indikatoren beschreiben stellvertretend ÖSL, bilden jedoch keine Informationen über die eigentliche Leistung oder gar den Nutzen für den Menschen ab. Die Unterschiede zwischen Ökosystemeigenschaften, Ökosystemfunktion und ÖSL sowie deren Wechselbeziehungen werden im weit verbreiteten *ÖSL-Kaskadensystem-Modell* von HAINES-YOUNG & POTSCHIN (2010) deutlich (Abb. 2).

Für diesen Beitrag wurde eine systematische Literaturüberprüfung durchgeführt, die aufzeigt, welche urbanen ÖSL in Europa in der aktuellen Forschung untersucht werden. Aus den häufig genannten ÖSL lassen sich Forschungsschwerpunkte erkennen, die mit Beispielen untersetzt dargestellt werden. Aus Platzgründen werden exemplarisch die Indikatoren der ÖSL *Regulierung von Temperatur und Luftfeuchtigkeit, inklusive Luftaustausch und Verdunstung* (= lokale Klimaregulation, CICES Code 2.2.6.2) bezüglich ihrer Aussagekraft näher betrachtet. Aus den Ergebnissen der Literaturüberprüfung werden Empfehlungen für zukünftige urbane ÖSL-Forschungsaktivitäten zusammengefasst.

3 Methodisches Vorgehen

Die systematische Literaturrecherche erfolgte nach dem PRISMA-Statement (MOHER et al. 2009), das in adaptierter Form bereits in der ÖSL-Forschung getestet wurde (GARCIA RODRIGUES et al. 2017, SIEBER et al. 2018). Mithilfe der wissenschaftlichen Literaturdatenbank Scopus wurden be-gutachtete, englischsprachige Artikel gesucht, deren Veröffentlichungsjahr zwischen Januar 2010 und Februar 2019 liegt und die sich mit dem Thema urbane ÖSL in Europa auseinandersetzen. Die Artikel wurden anhand von Schlüsselwörtern ([„Ecosystem service" OR „Natural benefit" OR „Environmental good"] AND [„Urban" OR „City"] AND [„Mapping" OR „Spatial" OR „valuation" OR „Indicator"]) ermittelt. Weitere 46 Artikel wurden auf Empfehlung von Fachkollegen und Fachkolleginnen in die Ergebnisdatenbank integriert. Dadurch wurden 1047 wissenschaftliche Artikel identifiziert, die in einem weiteren Schritt überprüft und nach folgenden festgelegten Ein- und Ausschlusskriterien auf 177 Artikel reduziert wurden (siehe Tab. A1 unter Webcode NuL2231):

(i) Das ÖSL-Konzept ist integraler Bestandteil des Artikels,

(ii) der urbane Raum steht im Fokus und

(iii) der Artikel beschreibt eine Fallstudienregion in Europa.

Die in den Artikeln beschriebenen ÖSL wurden nach CICES 5.1 auf ÖSL-Klassen-Ebene sortiert. In CICES 5.1 sind Zuweisungen zu äquivalenten ÖSL-Bezeichnungen aus CICES 4.3 sowie aus dem Millennium Ecosystem Assessment (MA) (2005) und TEEB (2010) vorhanden, die in der Recherche genutzt wurden. Die Indikatoren wurden nach der Vorgehensweise von OUDENHOVEN et al. (2012) in das ÖSL-Kaskadensystem-Modell eingeordnet. So kann untersucht werden, ob die Indikatoren Ökosystemeigenschaften, Ökosystemfunktionen oder ÖSL beschreiben.

Auf der CICES-Sektionen-Ebene werden Regulierungs- und Erhaltungsleistungen in

Abb. 3: Anzahl der ÖSL-Nennungen (nach ÖSL-Klassen) im urbanen Kontext.

Grafik: Dworczyk & Burkhard

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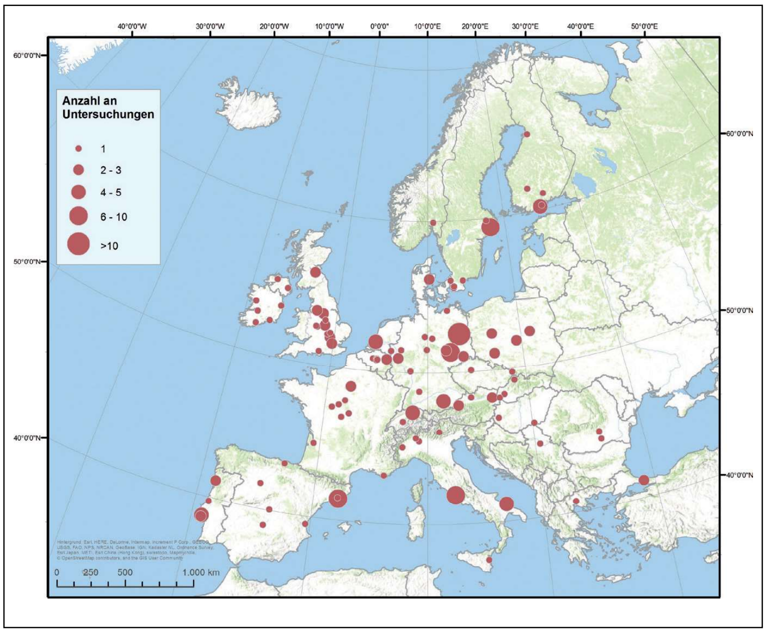

Grafik: Dworczyk & Burkhard

Abb. 4: Räumliche Verteilung der Fallstudiengebiete in den analysierten Publikationen (n = 177).

91 Artikeln, Versorgungsleistungen in 50 Artikeln, kulturelle Leistungen in 81 Artikeln sowie abiotische Leistungen in 29 Artikeln genannt. Dabei betrachten 112 Artikel mehrere ÖSL aus verschiedenen ÖSL-Sektionen. Eine Häufigkeitsverteilung ist in Abb. 3 dargestellt. Nur etwa die Hälfte der 177 ausgewählten Artikel verwenden Indikatoren in ihren Untersuchungen. Diese 90 Artikel beschreiben zusammengefasst 453 unterschiedliche Indikatoren. Die ÖSL „lokale Klimaregulation" wird in 24 Artikeln mithilfe von insgesamt 33 unterschiedlichen Indikatoren untersucht (siehe Tab. A2 bis Tab. A4 unter Webcode NuL2231).

4 Analyse vorhandener Forschungsaktivitäten

Die urbanen ÖSL werden in Europa in verschiedenen Untersuchungsgebieten erfasst und bewertet. Insgesamt werden in den Artikeln 118 verschiedene Fallstudiengebiete (Städte, Stadtregionen) genannt, die in 23 europäischen Ländern liegen (Abb. 4). Berlin ist das am häufigsten untersuchte Gebiet (14 Artikel), gefolgt von Barcelona (10) und Leipzig (9). Die Länderauswertung zeigt, dass bislang vergleichsweise wenige veröffentlichte Forschungsergebnisse aus Südosteuropa vorliegen. Durch eine gezielte Suche nach wissenschaftlichen Artikeln können zwar entsprechende Publikationen aus zum Beispiel Bulgarien (Koulov et al. 2017, Nedkov et al. 2017) identifiziert werden – intensive Forschungsaktivitäten wie in Deutschland oder Großbritannien finden sich jedoch noch nicht.

Wie bereits in anderen Übersichtsstudien (zum Beispiel Hansen & Pauleit 2014, Pulighe et al. 2016) beschrieben, werden im urbanen Kontext vor allem ÖSL betrachtet, die

- in einem klimabezogenen Kontext stehen,
- Umweltverschmutzungen und deren, zum Beispiel, gesundheitliche Folgen abschwächen,
- eng mit der Bewertung der urbanen Biodiversität verbunden sind und
- sich nicht transportieren oder durch technische Maßnahmen ersetzen lassen.

Zu diesen Themenbereichen werden im Folgenden wichtige ÖSL exemplarisch dargestellt.

4.1 Klimabezogener Kontext

Höhere Lufttemperaturen und Starkregenereignisse führen in Städten zunehmend zu gesundheitlichen und wirtschaftlichen Problemen (EEA 2017). Besonders Hitzewellen, die durch städtische Wärmeinseleffekte verstärkt werden, beeinträchtigen die Gesundheit der Stadtbevölkerung (Depietri et al. 2013). Die ÖSL „lokale Klimaregulation" (CICES 2.2.6.2) rückt angesichts dieser Problematiken immer stärker in den Forschungsfokus. Vegetationsreiche Grünflächen beeinflussen die lokalen klimatischen Bedingungen und spenden Schatten, wodurch sich die Lebensqualität der Stadtbevölkerung erhöhen kann (Bastian et al. 2013). Die Erfassung dieser ÖSL ist jedoch nicht einfach, da das lokale Klima durch die komplexen klimatischen Vorgänge und standörtlichen Faktoren und Besonderheiten einer Stadt geprägt wird.

In den untersuchten Artikeln wird die ÖSL mit zum Teil sehr unterschiedlichen Indikatoren erfasst und kommuniziert. Fast die Hälfte der identifizierten Indikatoren beschreiben Eigenschaften des untersuchten urbanen Ökosystems: Die ÖSL wird zum Beispiel anhand von Temperaturmustern (Kremer et al. 2018) oder durch Vegetationsmerkmale (Neuenschwander et al. 2014) abgeleitet. Es werden gehäuft zwei Indikatoren verwendet, die stellvertretend Ökosystemfunktionen beschreiben: 1) Oberflächen-Emissivitäts-Index als Proxy für städtische Wärmebelastungen, 2) f-Evapotranspiration-Index zu standardisierten Verdunstungsraten für (urbane) Landnutzungstypen und damit verbundene Kühlungseffekte bodennaher Luftschichten (vergleiche Schwarz et al. 2011, Szumacher & Pabjanek 2017). Diese Indikatoren liefern noch keine Informationen über die eigentliche ÖSL oder den Nutzen für den Menschen. Eine Quantifizierung der ÖSL kann beispielsweise mittels der durch Vegetation entstandenen Temperaturabnahmen ausgedrückt werden (Kain et al. 2016). Zu den ÖSL-Indikatoren zählen auch solche, die Informationen über den Bedarf oder die Nachfrage nach lokaler Klimaregulation liefern. In den Artikeln wird hierfür beispielsweise das Ausmaß der Vulnerabilität der Stadtbevölkerung bei Hitze ermittelt (Depietri et al. 2013). Eine Bewertung der ÖSL beruht bislang nur selten auf den Ergebnissen einer physikalisch basierten Modellierung, die wie bei Moss et al. (2019) die Einflüsse der Vegetation und Stadtstrukturen auf das lokale Klima berücksichtigt.

Mit dem Klimawandel und der damit verbundenen Zunahme an extremen Wetterereignissen rückt auch die globale Klimaregulation (ÖSL-Klasse „Regulierung der chemischen Zusammensetzung von Atmosphäre und Ozeanen", CICES 2.2.6.1) in den urbanen ÖSL-Forschungsfokus. Diese ÖSL umfasst insbesondere die Regulierung, Speicherung und Sequestrierung von Treibhausgasemissionen (vor allem CO_2) (EK 2016). Kohlenstoffsequestrierung und -speicherung finden in der lebenden ober- und unterirdischen Biomasse und der organischen Bodensubstanz, einschließlich urbaner Vegetation und Böden, statt (Davies et al. 2011, Mexia et al. 2018, Nikodinoska et al. 2018). Diese Ökosystemfunktionen werden intensiv beleuchtet und mit entsprechenden Indikatoren bewertet (Baró et al. 2014, 2017, Holt et al. 2015). Eine Bewertung der ÖSL, welche zum Beispiel durch die jährliche Veränderungen von atmosphärischen Emissionskonzentrationen ausgedrückt werden kann (van Oudenhoven et al. 2012), findet in den untersuchten Artikeln nicht statt.

Die ÖSL „Erhalt des Wasserhaushalts und des Abflussregimes (inkl. Hochwasser-, Küstenschutz)" (CICES 2.2.1.3) wird bei der Vermeidung von Überschwemmungsereignissen in Städten thematisiert. Diese ÖSL kann durch eine Verlangsamung des oberirdischen Wasserabflusses oder durch Wasserrückhalt ausgedrückt werden (TEEB DE 2016). Es werden gehäuft Indikatoren verwendet, die Informationen über den Nutzen für den Menschen vermitteln, zum Beispiel solche Indikatoren, welche Aussagen zur Regulierung des Wasserdurchflusses und der Abflussminderung (Holt et al. 2015, Liquete et al. 2016), zur Reduzierung der Wassermengen in die städtischen Entwässerungssysteme (Aevermann & Schmude 2015) sowie zum Hochwasserschutz durch unversiegelte, naturnahe Böden und vegetationsreiche Bodenbedeckung (Morel et al. 2015) ermöglichen.

4.2 Abschwächung von Umweltverschmutzungen und deren Folgen

Städtische Ökosysteme können Umweltverschmutzungen und deren Folgen reduzieren, wenn ausreichend Grünflächen zur Regulierung und Erhaltung der Luft-, Boden- und Wasserqualität vorhanden sind. Besonders ausführlich wird der Fokus auf die Regulierung der urbanen Luftqualität („Filtration/Festlegung/Speicherung/Akkumulation durch lebende Systeme", CICES 2.1.1.1) gerichtet. Diese ÖSL wird primär durch drei Arten von Informationen ausgedrückt, die sich gut in das Schema von ÖSL-Angebot, ÖSL-Nachfrage und ÖSL-Fluss einteilen lassen (Burkhard & Maes 2017): Die trockene Depositionsgeschwindigkeit von Schadstoffen ist eine Maßzahl, die als Proxy-Indikator für die Ermittlung des ÖSL-Angebots verwendet wird (Baró et al. 2014, 2016, 2017, Maes et al. 2016). Anhand der Exposition der Bevölkerung gegenüber Schadstoffkonzentrationen, die über den in geltenden Rechtsvorschriften festgelegten Grenzwerten liegen, werden Informationen über die ÖSL-Nachfrage ermittelt (Baró et al. 2016). Die Menge der durch die Vegetation entfernten Luftschadstoffe, die als Produkt der trockenen Depositionsgeschwindigkeit durch die Vegetation und die Schadstoffkonzentration geschätzt wird, bilden den ÖSL-Fluss ab (Depietri et al. 2016).

4.3 Erhaltung der Biodiversität

Die ÖSL „Erhaltung von Aufzuchtpopulationen und -habitaten (inkl. Genpoolschutz)" (CICES 2.2.2.3) ist eng mit der Erhaltung der Biodiversität verbunden. Unter CICES 5.1 wird die ÖSL durch das Vorhandensein ökologischer Bedingungen (normalerweise Lebensräume), die zur Erhaltung der Populationen wildwachsender Pflanzen und wildlebender Tiere erforderlich sind, thematisiert. Diese Pflanzen und Tiere, die in diesen Habitaten einen Lebensraum finden, können wiederum für den Menschen nützlich sein und stellen die eigentliche ÖSL dar (Haines-Young & Potschin 2018). Viele Städte weisen dann eine relativ hohe Biodiversität auf, wenn durch eine heterogene Stadtstruktur unterschiedliche Lebensräume für Pflanzen und Tiere angeboten werden (Gómez-Baggethun & Barton 2013). Umgekehrt verfügen stark verdichtete Städte mit wenigen qualitativ hochwertigen Frei- und Grünflächen in der Regel nur über eine kleine Anzahl an geeigneten Habitaten (Neuenschwander et al. 2014). Inwiefern die Zusammensetzung und die räumliche Verteilung von städtischen Grünflächen das Vorkommen von Arten beeinflussen, ist Gegenstand in einigen der untersuchten Artikel (Breuste et al. 2013, Hou et al. 2015). Für die Bewertung dieser ÖSL werden insbesondere Proxy-Indikatoren verwendet, welche die Eigenschaften des Ökosystems beschreiben und beispielsweise Informationen zur Fragmentierung liefern (Holt et al. 2015, Stürck & Verburg 2017).

4.4 Transportierbarkeit und Ersetzbarkeit

Die oben angesprochenen regulierenden und erhaltenden ÖSL (beispielsweise „lokale Klimaregulation") lassen sich nur in einem sehr kleinen Maße durch technische Maßnahmen (zum Beispiel Klimaanlagen) ersetzen oder gar über größere Entfernungen transportieren. Die Notwendigkeit, dass diese ÖSL in situ im urbanen Ökosystem bereitgestellt werden müssen, um hier die Nachfrage durch die Bevölkerung zu decken, ist vermutlich ein Grund für die verstärkte Betrachtung dieser ÖSL (Burkhard et al. 2014).

Auch kulturelle ÖSL lassen sich nur schwer ersetzen oder transportierten. Hierzu zählen die am häufigsten erforschten kulturellen ÖSL „Merkmale lebender Systeme, die Aktivitäten ermöglichen, die durch aktive, passive oder alle Sinne erfassende Interaktionen Gesundheit, Erholung oder Genuss fördern" (CICES 3.1.1.2, 3.1.1.1). Auch hier ist die Bereitstellung der ÖSL eng mit der GI verbunden, die die Stadtbevölkerung für aktive oder passive naturgebundene Freizeit- und Erholungsaktivitäten nutzen können. Die untersuchten Artikel beschäftigten sich zusammengefasst mit der Beziehung zwischen den strukturellen Merkmalen von Grünflächen und den Anforderungen und präferierten Aktivitäten der Stadtbewohnerinnen und -bewohner sowie Besucherinnen und -besucher. Gehäuft werden hierfür die individuellen Wahrnehmungen und Präferenzen von befragten Personen abgefragt (La Rosa et al. 2018, Riechers et al. 2018, 2019). Die ÖSL wird oft durch die Quantifizierung von Ökosystemeigenschaften abgeleitet. Die Indikatoren beschreiben beispielsweise die Größe oder Verteilung der urbanen Grünflächen (Massoni et al. 2018, Quatrini et al. 2019). Verstärkt wird hierbei die Erreichbarkeit von städtischen Grünflächen analysiert (Grunewald et al. 2017, Kolcsár & Szilassi 2018).

5 Empfehlungen für zukünftige Forschungsaktivitäten

Urbane Ökosysteme stellen verschiedene ÖSL bereit, die für die Gesundheit und Lebensqualität der Stadtbevölkerung von Bedeutung sind. Die Erfassung, Bewertung und räumliche Darstellung der ÖSL im urbanen Raum nimmt eine wichtige Rolle ein, die die Multifunktionalität von GI aufzeigt (Artmann et al. 2017).

Die einzigartigen ökologischen, wirtschaftlichen und sozialen Merkmale einer Stadt erschweren die Übertragbarkeit von Ergebnissen aus bisherigen urbanen ÖSL-Studien. Unterschiedliche Herangehensweisen, Maßstabsebenen und unzureichend beschriebene Indikatoren limitieren die Vergleichbarkeit zwischen den Forschungsergebnissen zusätzlich. Unter den untersuchten Artikeln befinden sich nur 35 Artikel, die Vergleiche durch die Untersuchung mehrerer Fallstudienregionen durchführen. Kremer et al. (2016) betonen, dass bei der urbanen ÖSL-Forschung Vergleiche zwischen Städten jedoch besonders notwendig sind, um

- die zentralen Triebkräfte von urbanen Ökosystemfunktionen und ÖSL erkennen zu können,
- die Auswirkungen verschiedener städtischer Landbedeckungskombinationen

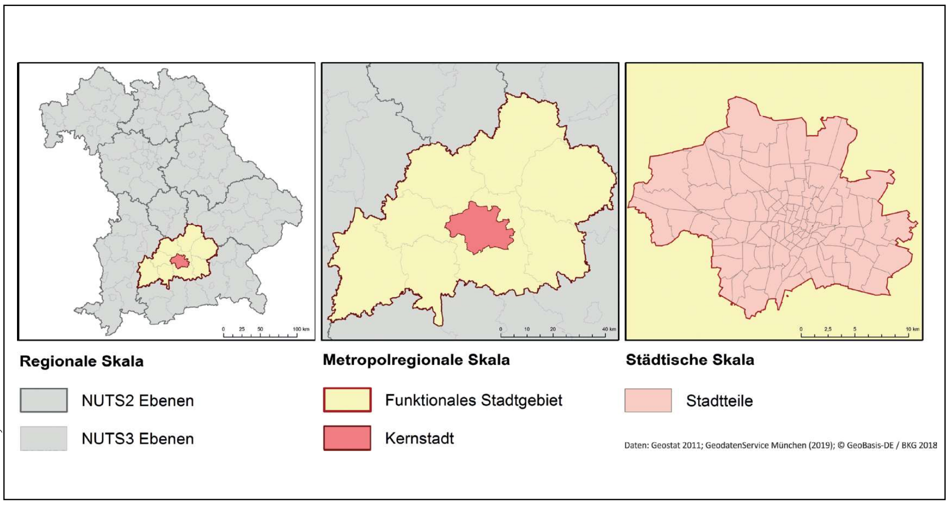

Abb. 5: Die Abbildung zeigt bespielhaft die drei urbanen Skalenebenen für München. Links: München liegt in Oberbayern (NUTS2-Ebene), das in 23 Landkreise beziehungsweise kreisfreie Städte (NUTS3-Ebene) unterteilt ist. Mitte: Das funktionale Stadtgebiet (FUA) deckt gleichzeitig die Metropolregion ab. München ist die Kernstadt. Rechts: Die städtische Skale besteht aus der Kernstadt und kann auf zum Beispiel Stadtteilebene weiter skaliert werden (eigene Darstellung, angelehnt an Maes et al. 2016: 64).

auf die Bereitstellung urbaner ÖSL verstehen zu können,
- das Wissen über städtische ÖSL-Nachfrage, die sich durch veränderte soziale Anforderungen, Bedürfnisse oder kulturelle Hintergründe ändert, fördern zu können und
- um geeignete nationale und internationale Bewertungsmaßstäbe für städtische ÖSL festlegen zu können.

Die Arbeitsgruppe MAES schlägt für einheitliche, nachvollziehbare und übertragbare urbane ÖSL-Forschungen standardisierte Herangehensweisen vor. Diese Vorschläge wurden im EU-Projekt EnRoute (Enhancing Resilience of urban ecosystems through green infrastructure) auf ihre Umsetzbarkeit getestet (Maes et al. 2019, Zulian et al. 2018). Aus den Empfehlungen von MAES, den Verbesserungsvorschlägen von EnRoute sowie aus den Ergebnissen der Literaturstudie lassen sich folgende Empfehlungen für zukünftige Forschungsaktivitäten zusammenfassen:
1) Verwendung einheitlicher urbaner räumlicher Skalenebenen,
2) Identifikation der urbanen Grünen Infrastruktur,
3) klare Beschreibungen der eingesetzten Indikatoren.

5.1 Verwendung einheitlicher urbaner räumlicher Skalenebenen

Zur Klassifikation der urbanen ÖSL empfehlen Maes et al. (2016) die Berücksichtigung der urbanen Skalenebenen aus dem EUROSTAT-Handbuch „Methodological manual on territorial typologies" (EUROSTAT 2019). Mit diesen definierten Skalenebenen steht ein EU-weites System für die Beschreibung urbaner Räume zur Verfügung, das eine konsistente Bewertung der urbanen Ökosysteme ermöglicht. Zudem werden diese Skalenebenen bereits für eine kohärente Datensammlung innerhalb der EU genutzt. Mindestens drei urbane Skalenebenen können nach administrativen Grenzen und auf Basis eines Bevölkerungsdichte-Rasters (1 km × 1 km) gezogen werden (Abb. 5):

Regionale Skala: Gebildet nach der europäischen Systematik der Gebietseinheiten für die Statistik (NUTS).

Metropolregionale Skala: Funktionales Stadtgebiet (functional urban area – FUA), das eine Stadt mit ihrer Pendlerzone abdeckt. Bei dieser Skalenebene ist ein städtisches Zentrum (räumliches Konzept, das auf Rasterzellen mit hoher Bevölkerungsdichte basiert) Voraussetzung.

Städtische Skala: Dicht besiedeltes Gebiet und Kerngebiet der FUA (mindestens 50 % der Bevölkerung leben in einem oder mehreren städtischen Zentren).

Zu erwähnen ist, dass weitere Unterteilungen (zum Beispiel nach Stadtteilen)

Abb. 6: Moderne Grüne Infrastruktur, hier auf dem Campus der Wirtschaftsuniversität in Wien, bietet vielfältige pflanzliche und bauliche Elemente.

Originalarbeit

Fazit für die Praxis

- Urbane Ökosysteme stellen verschiedene Ökosystemleistungen bereit, die für die Gesundheit und Lebensqualität der städtischen Bevölkerung wichtig sind.
- Ökosystemleistungen werden in Städten sowohl durch natürliche als auch durch anthropogene Strukturen und Einträge bereitgestellt und können durch gezielte Maßnahmen gefördert werden.
- Die urbane Grüne Infrastruktur bietet im besonderen Maße Ökosystemleistungen an und spielt für die städtische Biodiversität eine wichtige Rolle. Eine Identifikation der urbanen Grünen Infrastruktur ist bei der Quantifizierung der Ökosystemleistungen hilfreich.
- Die Beschreibung der räumlichen (urbanen) Skalenebene ist bei der Übertragung von Ergebnissen auf andere Untersuchungsgebiete notwendig.
- Für vergleichende Bewertungen, Erfassungen und räumliche Darstellungen von Ökosystemleistungen sind robuste, nachvollziehbare und übertragbare Indikatoren unablässig.
- Ausführliche Beschreibungen über die eingesetzten Indikatoren helfen der Wissenschaft und den Entscheidungsträgern bei der Interpretation der Ergebnisse.

denkbar sind und je nach Möglichkeit betrachtet werden sollen. Aufgrund der individuellen Stadtstrukturen kann sich die Bereitstellung der ÖSL über sehr kurze Distanzen hinweg stark ändern und sich auch über die Grenzen der Skalenebenen erstrecken. Die Verwendung von entsprechend detaillierten Daten wird daher empfohlen (Zulian et al. 2018).

5.2 Identifikation der Grünen Infrastruktur

In einer Stadt wird mit der GI das multifunktionale Grünraumnetzwerk hervorgehoben, das im besonderen Maße ÖSL bereitstellt und für die städtische Biodiversität von zentraler Bedeutung ist. Die Verbesserung und der Ausbau der GI kann für eine Stadt die Schlüsselstrategie für ein nachhaltigeres, gesünderes und lebenswerteres Lebensumfeld darstellen (EK 2013). Die Erfassung der GI liefert ein umfassendes Bild über die Verteilung der heterogenen Grünräume und stellt für Entscheidungsträger bereits eine wichtige Informationsquelle dar (Maes et al. 2019). Je nach vorhandener Datenlage ist jedoch eine strukturierte und nachvollziehbare Bestimmung der GI mit Umsetzungsproblemen verbunden (Zulian et al. 2018).

Die Arbeitsgruppe MAES beschreibt als Lösung Klassifizierungsansätze, die zur Bestimmung genutzt werden können. Es kann sowohl eine strukturelle Klassifizierung (zum Beispiel nach Landbedeckungsarten oder Vegetationsmerkmalen) und/ oder eine funktionale Klassifizierung (zum Beispiel nach Landnutzungstypen, räumlichen Strukturen) erfolgen (Maes et al. 2016). Hierfür können bekannte Datensätze (zum Beispiel CORINE Land Cover, ATKIS Basis DLM) oder Informationen aus Fernerkundungsdaten herangezogen werden (Maes et al. 2019).

5.3 Klare Beschreibungen der eingesetzten Indikatoren

Bei der Untersuchung der Indikatoren der ÖSL „lokale Klimaregulation" wird deutlich, dass die Aussagekraft der eingesetzten Indikatoren von unterschiedlicher Qualität ist. Bei näherer Betrachtung zeigt sich außerdem, dass die meisten Indikatoren die ÖSL stellvertretend beschreiben und quantifizieren (Proxy-Indikatoren). Die Ergebnisse lassen darauf schließen, dass die Erfassung und räumliche Darstellung der ÖSL „lokale Klimaregulation" in urbanen Ökosystemen noch wenig erforscht ist. Ähnliche Ergebnisse werden auch in einer Literaturstudie über die kulturellen ÖSL von La Rosa et al. (2016) erörtert.

Die zunehmende Verstädterung und Urbanisierung erfordert dringend die Weiterentwicklung von Indikatoren, die die Rolle des urbanen Ökosystems für die Stadtbevölkerung hervorheben und Entscheidungsträger überzeugen können. Damit die Ergebnisse dauerhafte Wirkung erzielen, sollte der gewählte Indikator auf die wissenschaftliche Qualität und Aussagekraft geprüft und hinterfragt werden. Zukünftige Forschungsaktivitäten können bei der Nutzung und Weiterentwicklung von Indikatoren wichtige Beiträge leisten, indem sie nicht nur ausführliche Beschreibungen, sondern auch Angaben über die verwendeten räumlichen Skalenebenen, Bewertungsmaßstäbe und Ergebnisinterpretationen bereitstellen. Für die strukturierten Beschreibungen ist die Verwendung bereits existierender Vorlagen für Indikatorenkennblätter (Grunewald et al. 2016a, La Notte et al. 2017, Podschun et al. 2018), „Blueprints" (Crossman et al. 2013, Seppelt et al. 2012) oder ÖSL-Steckbriefe aus den diversen MAES-Berichten hilfreich.

6 Fazit

Urbane Ökosysteme stellen oft auf vergleichsweise kleinen Flächen eine Vielzahl von ÖSL bereit, die aufgrund der hohen Bevölkerungsdichten in urbanen Räumen in der Regel einer extrem hohen Nachfrage unterliegen. Für die langfristige Erhaltung und den Schutz dieser ÖSL müssen entsprechende Erfassungen und Bewertungen verständlich und nachvollziehbar dargestellt werden.

Dank

Die vorliegende Arbeit wurde im Rahmen des Forschungsprojektes ÖSKKIP (Ökosystemleistungen von Stadtregionen – Kartieren, Kommunizieren und Integrieren in die Planung zum Schutz der biologischen Vielfalt im Klimawandel) durchgeführt, das mit Mitteln des Bundesministeriums für Forschung und Bildung (BMBF) gefördert wird (Förderkennzeichen: FKZ 01LC1604B).

Literatur

Aus Umfangsgründen steht das ausführliche Literaturverzeichnis unter Webcode NuL2231 zur Verfügung.

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Chapter 3

Conceptualising the demand for ecosystem services – an adapted spatial-structural approach

Dworczyk, C., Burkhard, B.
One Ecosystem (2021) 6, e65966. https://doi.org/10.3897/oneeco.6.e65966

Figure 12. How to identify areas where more nature is urgently needed in urban areas?
Photo: Jolanta Dworczyk.

One Ecosystem 6: e65966
doi: 10.3897/oneeco.6.e65966

OPEN ACCESS

Review Article

Conceptualising the demand for ecosystem services - an adapted spatial-structural approach

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Academic editor: Alessandra La Notte

Received: 15 Mar 2021 | Accepted: 30 Oct 2021 | Published: 07 Dec 2021

Citation: Dworczyk C, Burkhard B (2021) Conceptualising the demand for ecosystem services – an adapted spatial-structural approach. One Ecosystem 6: e65966. https://doi.org/10.3897/oneeco.6.e65966

Abstract

People require multiple ecosystem services (ES) to meet their basic needs and improve or maintain their quality of life. In order to meet these needs, natural resources are exploited, threatening biodiversity and increasing the pressure on the Earth's ecosystems.

Spatial-structural approaches are used to explain and visualise the spatial relationships and connections between areas that provide and benefit from ES. However, areas where the demand for these ES occurs are rarely considered in existing spatial approaches or equated with areas where people can use the benefits.

In order to highlight the differences between these two areas, we would like to introduce the 'Service Demanding Area' (SDA) in an adapted spatial-structural approach.

This approach relates SDA to already familiar ES provision and use units, namely Service Providing Areas (SPA), Service Connecting Areas (SCA) and Service Benefitting Areas (SBA) and can be used to schematically illustrate, understand and analyse the different forms of demand that can emerge.

A literature review was conducted to provide an overview of the spatial mapping of ES demand. Three issues arose that should be addressed to improve the assessment of ES demand: 1) The term ES demand is not used consistently. To avoid confusion, it is important to clarify how ES demand is understood and how it differs from the other components of the ES concept (e.g. ES supply, ES potential, ES flow); 2) It is important to consider that ES demand is multi-faceted and is generated on different geographical scales, including the full range of stakeholders' perceptions, needs and desires which broadens the picture of societal demand for ES; 3) Meaningful interpretations between ES supply and demand need to be available to inform decision-makers about interventions for reducing ES trade-offs and mismatches.

Keywords

service providing area; service benefitting area; service demanding area; service connecting area

1 Introduction

Biodiversity and healthy ecosystems are essential to support and sustain human well-being (IPBES 2019). People require multiple ecosystem services (ES) to meet their basic needs and to improve or to maintain their quality of life. To meet these needs, ecosystems are exploited to satisfy the increasing demand for drinking water, food, materials, energy and other wishes (Millennium Ecosystem Assessment 2005, Maes et al. 2020, Vysna et al. 2021).

The concept of ES describes the various contributions of ecosystem to human well-being (Maes et al. 2018). It is an anthropocentric concept, as the benefits people obtain from ecosystems are the main focus (Millennium Ecosystem Assessment 2005). These benefits can include any "positive change in well-being through the fulfilment of needs and wants" (Potschin-Young et al. 2018) which refers, not only to products and goods, but also to health improvements, experiences or positive effects that may result from ES.

ES research is becoming increasingly important as the consequences of overuse of resources, climate change, biodiversity loss and other environmental changes become more tangible (IPBES 2019). The ES concept has already achieved policy relevance in recent years and has the potential to become an important tool for decision-makers in (environmental) policy, spatial planning and economy, as it can address linkages between environmental, social and economic issues (Maes et al. 2018, Maes et al. 2020). It provides a holistic framework for examining: 1) the extent to which people need or demand ES to meet their basic needs and to improve their quality of life and 2) the extent to which nature can meet those in a sustainable way (Burkhard and Maes 2017, Wolff et al. 2017).

The ES concept is embedded in national ecosystem assessments, which are driven by the Convention on Biological Diversity (CBD) (European Union 2011, Secretariat of the Convention on Biological Diversity 2020), assessments of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (IPBES 2019) or natural capital accounting (The Economics of Ecosystems and Biodiversity (TEEB) 2010, United Nations 2021). Recently, the UN System of Environmental-Economic Accounting (SEEA) presented a "statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity" (United Nations 2021). This framework is consistent with the national accounting standards (United Nations 2021).

Even though the ES concept has gained increasing importance in scientific research, research gaps continue to reduce its practical application (Heckwolf et al. 2020, Czúcz et al. 2020, Grunewald et al. 2021). There are a number of open conceptual and methodological questions that remain to be addressed, in particular, on the subject of ES demand (Wolff et al. 2015, Geijzendorffer and Roche 2014, Geijzendorffer et al. 2015). For example, ES literature often emphasises that ES demand is very multifaceted, as it is driven by various factors, including, for example, access to ES, socio-economic conditions, demographic changes, technological influences and marketing (*Villamagna et al. 2013, Wolff et al. 2017, Schröter et al. 2018*). However, this diversity makes it difficult to understand and to map ES demand (Wolff et al. 2015, Czúcz et al. 2020). Using schematic illustrations and examples, this article presents the different ways in which demand for ES can be spatially allocated. It aims to show how spatial distribution of ES supply and demand is ES-dependent and how the spatial dynamics of ES flows play a crucial role in understanding the actual fulfilment of ES demand and the spatial allocation of benefits. For this purpose, we have developed the concept of a Service Demanding Area (SDA), which we have integrated into the existing spatial-structural approaches.

Before discussing the SDA in detail, we will summarise our understanding of key ES terms and provide a brief overview of existing concepts used to describe the application of ES components in spatial-structural contexts. We will then look at the literature on ES demand, focusing on those papers which deal with the development of an adapted spatial-structural approach, before introducing the SDA. Above all, the following discussion will seek to synthesise key findings on assessing and mapping ES demand in a spatial-structural context, while also proposing, in the form of the SDA, a new element with which to further develop the ES approach.

1.1 Definitions of ES key terms with specific focus on ES demand

The inter- and transdisciplinary nature of the ES concept has led to the development of different understandings of the ES terminologies (Bastian et al. 2012, Honey-Rosés and Pendleton 2013).

In the European Union, the initiative Mapping and Assessment of Ecosystems and their Services (MAES) synthesises knowledge about ES and aims to improve the evidence base for sustainable policy developments in the context of the EU Biodiversity Strategies 2020 and 2030 (European Union 2011). MAES brings together research results from many scientific fields, making a common understanding of the ES concept essential. Therefore, a comprehensive MAES glossary was created, bringing together the various existing definitions. The glossary was also expanded with terms that reflect, not only ES-research, but also specific topics (Potschin-Young et al. 2018). It should be noted that these harmonised definitions have an explicit focus towards the research topic of mapping and assessing ES. In developing the spatial-structural approach, we mainly followed the MAES understanding (Potschin-Young et al. 2018) of the key terms of ES supply, ES potential, ES flow and ES demand, which are listed in Table 1 and explained in more detail below.

The distribution of ES tends to be spatially heterogeneous and can change over time. ES are generated by ecological processes and functions, which, in turn, are influenced by biodiversity, local climates, topography, land cover, human activities and land-use decisions (Wei et al. 2017, Schirpke et al. 2019b). This provision of ES by specific ecosystems, irrespective of their actual use, has commonly been referred to as *ES supply* (Burkhard et al. 2012, Potschin-Young et al. 2018, Vallecillo et al. 2019, González-García et al. 2020).

In the ES concept, the consideration of *ES potential* is important. Here, the potential (or hypothetical) quantities or qualities of ES that can be provided or used in a certain region are examined in light of current land use and ecosystem conditions and properties (Burkhard and Maes 2017, Maes et al. 2020). ES potential can be used to show: (a) the extent to which an ecosystem can potentially provide services and (b) what limitations there are likely to be on the sustainable and/or permanent use of these services (Potschin-Young et al. 2018).

ES flow describes "the amount of an ecosystem service that is actually mobilised in a specific area and time” (Potschin-Young et al. 2018, p. 23). Matter, energy and/or information can be exchanged between ecosystems in ways from which people can benefit (Kleemann et al. 2020). This exchange can, depending on the nature of the specific ES, take place within a localised surrounding or over long distances, for example, through trade, transport, political decisions or ecological phenomena, such as global climate regulation (Schröter et al. 2018). Here, the focus is on ES which are delivered or accessed either passively, via biophysical processes (e.g. airflow) or actively, as a result of human involvement (i.e. via water pipelines, through food transport etc.) (Ala-Hulkko et al. 2019). Individual actors can also play an important role in the ES flow dynamics by enabling or restricting the transport and access of ES in the first place (La Notte and Dalmazzone 2018). This has implications for where and which people can actually benefit from the respective ES.

ES demand can be described as "the need for specific ecosystem services by society, particular stakeholder groups or individuals. It depends on several factors such as culturally-dependent desires and needs, availability of alternatives, or means to fulfil these needs. It also covers preferences for specific attributes of an ecosystem service and relates to risk awareness" (Potschin-Young et al. 2018, p. 20). The needs or wishes for ES vary from people to people as well as from situation to situation. The needs depend on many factors, for example, the availability of natural resources, socio-cultural backgrounds and the (financial) ability to meet these needs (Maslow 1954). Since the underlying reasons are manifold, they can also be expressed in different ways. Wolff et al. (2015) suggested to use different types of demand rationale. ES demand can be expressed and assessed as: (1) an expression of wishes, values and norms; (2) derived from the different forms of use and/or (3) consumption of ES and (4) or as the need for risk reduction/ prevention and increased security (Wolff et al. 2015). The form of expression, therefore, depends on what the assessor wants to emphasise, be it dependence on functioning (local) ecosystems, the benefits acquired from these or the different preferences and patterns of use within a society (Wolff et al. 2017). The location of demand for some ES produces additional challenges. This is particularly the case for ES that pursue environmental goals on a global scale (e.g. global climate regulation or the conservation of natural habitats) and whose benefits are reaped worldwide or are strongly shaped by inherent moral (or intrinsic) values (Burkhard et al. 2012, Jax et al. 2013, Baró et al. 2015, Sauter et al. 2019).

Table 1.

Table 1 shows how important key terms are defined or explained: a) in the Oxford Dictionary (Oxford University Press (OUP) 2020); b) in the core glossary of ecosystem services mapping and assessment terminology (Potschin-Young et al. 2018) and c) defintions or explanations in official reports on ecosystem accounting from the United Nations (United Nations 2019, United Nations 2021).

	Main meaning (with relation to the ES concept) in the Oxford Dictionary (Oxford University Press (OUP) 2020)	**Definitions in the core glossary of ecosystem services mapping and assessment terminology** (Potschin-Young et al. 2018)	**Definitions or explanations in official reports on ecosystem accounting from the United Nations** (United Nations 2019, United Nations 2021) .
Capacity	1) The maximum amount that something can contain. 2) The amount that something can produce.	Capacity (for an ecosystem service): "The ability of a given ecosystem to generate a specific ecosystem service in a sustainable way" (p. 12).	"Ecosystem capacity is the ability of an ecosystem to generate an ecosystem service under current ecosystem condition, management and uses, at the highest yield or use level that does not negatively affect the future supply of the same or other ecosystem services from that ecosystem" (p. 335) (United Nations 2021).
Demand	1) An insistent and peremptory request, made as of right. 1. a) Pressing requirements (usually demands). 1. b) The desire of consumers, clients, employers etc. for a particular commodity, service or other item.	Demand (for an ecosystem service): "The need for specific ecosystem services by society, particular stakeholder groups or individuals. It depends on several factors, such as culturally-dependent desires and needs, availability of alternatives, or means to fulfil these needs. It also covers preferences for specific attributes of an ecosystem service and relates to risk awareness" (p. 20).	No definition.

	Main meaning (with relation to the ES concept) in the Oxford Dictionary (Oxford University Press (OUP) 2020)	**Definitions in the core glossary of ecosystem services mapping and assessment terminology** (Potschin-Young et al. 2018)	**Definitions or explanations in official reports on ecosystem accounting from the United Nations** (United Nations 2019, United Nations 2021) .
Flow	1) The action or fact of moving along in a steady, continuous stream. 1.a) The rate or speed at which something flows. 1.b) The rise of a tide or a river. 2) A steady, continuous stream or supply of something.	Flow (of an ecosystem service): "The amount of an ecosystem service that is actually mobilised in a specific area and time" (p. 23).	Explanations for actual flow: "The ecosystem services supply and use account records the actual flows of ecosystem services supplied by ecosystem types and used by economic units during an accounting period" (p. 77). (United Nations 2019). "Following standard accounting treatments, the measure of the supply and use are equivalent and will be equal to the actual flow between the ecosystem asset and people" (p. 117) (United Nations 2021).
Potential	1) Latent qualities or abilities that may be developed and lead to future success or usefulness. 1.a) The possibility of something happening or of someone doing something in the future (often **potential for/to do something).** As an adjective: 2) Having or showing the capacity to develop into something in the future.	Ecosystem service potential: "The natural contributions to ecosystem service generation. It measures the amount of ecosystem service that can be provided or used in a sustainable way in a certain region. This potential should be assessed over a sufficiently long period of time" (p. 21).	The potential supply of ES "indicating the potential sustainable flow of services, assuming that there is no limitations in the demand for the service" (p. 21) (United Nations 2019).
Supply	1) A stock or amount of something supplied or available for use. 1.a) The action of providing what is needed or wanted. 1.b) The amount of goods or service offered for sale (in economics).	Ecosystem service supply: "The provision of a service by a particular ecosystem, irrespective of its actual use. It can be determined for a specified period of time (such as a year) in the present, past or future" (p. 21).	"Supply of ecosystem services is equal to the use of those services during an accounting period, [...], supply is not recorded if there is no corresponding use" (p. 77) (United Nations 2019).

Unfortunately, all presented terms are not understood or used consistently and there are also further different definitions for the term ES demand (see Table 2 and Suppl. material 1).

Table 2.

Examples of existing definitions of ES demand used in ES literature. Further definitions, see Suppl. material 1.

Author	Definition
Burkhard et al. (2012), p. 18	"The sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period not considering where ecosystem services actually are provided."
Villamagna et al. (2013), p. 116	"The amount of a service required or desired by society."
Schröter et al. (2014), p. 541	"ES demand is the expression ofthe individual agents' preferences for specific attributes of the service, such as biophysical characteristics, location and timing of availability and associated opportunity costs of use".
Geijzendorffer et al. (2015), p. 322	"Demand was defined as the actual expression of the willingness of stakeholders to obtain a service (for instance, in money, time investments or travel distances)".

For example, the terms ES supply and ES potential are often used synonymously (Wei et al. 2017, Maes et al. 2020) or are equated with the terms *potential ES supply* (Goldenberg et al. 2017, Rioux et al. 2019, United Nations 2019) or *ES capacity* (Burkhard et al. 2009, Geijzendorffer and Roche 2014, González-García et al. 2020).

A few examples underline some of the existing ambiguities between ES flow and ES demand: for example, the definition of Geijzendorffer et al. (2015) is close to the economic understanding of demand. In economics, demand is traditionally understood as the intention and willingness of economic units (e.g. businesses, governments or households) to buy goods, products or services (Bryan et al. 2018).

In SEEA EA, supply and use tables are commonly applied to record the actual flow of ES between ecosystem assets and economic units (United Nations 2019). The SEEA EA follows standard accounting principles, according to which "the measure of the supply and use are equivalent and will be equal to the actual flow between the ecosystem asset and people" (United Nations 2021, p. 117). This means that the actual flow represents the actual use and transaction that takes place between ecosystem types and economic sectors and households (La Notte et al. 2019). However, the actual use of ES does not necessarily consider important spatial aspects. Furthermore, it usually does not take into account broader costs and benefits that may result from increased or decreased consumption of ES that affect other aspects, for example, health. Thus, "ecosystem accounting does not consider the relationship between people and the environment from an economic or social welfare perspective" (United Nations 2019, p. 77). However, current considerations examine experimentally whether the potential flow, as the total flow that the respective ecosystem types can generate for each ES, can also be integrated into the SEEA EA (La Notte and Dalmazzone 2018, La Notte and Marques 2019, La Notte et al. 2019). With this consideration, it would also be possible to examine whether the ecosystems and their services are used in a sustainable way or not (La Notte et al. 2019).

Demand for ES is often directly associated with the beneficiaries, those (individuals, households or economic units) who perceive the final benefit of the ES. Some studies emphasise that, without the demand for and use of an ES, there is no ES flow (Burkhard and Maes 2017, Czúcz et al. 2020). Therefore, the actual use of ES is often used synonymously as ES flow in the ES mapping literature (e.g. Burkhard et al. 2012, Villamagna et al. 2013, Burkhard et al. 2014, Baró et al. 2015, Zhao and Sander 2015, Baró et al. 2016).

Other ES demand definitions take into account, not only the amount of ES used or consumed, but also the expressed needs, wishes or preferences (Villamagna et al. 2013, Schröter et al. 2014, Potschin-Young et al. 2018). This is an important distinction as expressed needs, desires and preferences for ES may differ from the actual ES received. In this article, we followed this understanding where the demand for ES describes the extent to which society, interest groups or individuals need or desire ES to meet their basic needs and to improve their quality of life.

1.2 Spatial-structural approaches

ES mapping approaches have proven to be an essential tool to assess ES and to communicate the complex spatial information of ES (Burkhard and Maes 2017). For comprehensible communication, abstract concepts are often clarified and visualised in an extremely simplified way, not only using maps, but also pictures or illustrations.

In order to be able to describe the differences between the areas where ES are provided and where benefits arise, Fisher et al. (2009) highlighted the spatial relationships between Service Providing Areas (SPA) and Service Benefitting Areas (SBA) in a schematic figure. Syrbe and Walz (2012) extended the scheme to include the Service Connecting Areas (SCA), which give greater consideration to the space between SPA and SBA. As these areas do not necessarily overlap, the location of the SCA can be used to show ES 'flow'. An extended version of these illustrations can be found in Walz et al. (2017).

The spatial dynamics of ES flows can be very diverse. Natural or anthropogenic barriers, sinks or depletions regions have an influence on the distribution and accessibility of ES (Burkhard et al. 2014, Wei et al. 2017). Therefore, ES flows has been the focus in various schematic illustrations that explain, in simple drawings, the spatial dynamics of respective ES (e.g. Serna-Chavez et al. 2014, Rioux et al. 2019). Here, illustrations were on the one side used to explain models. For example, Bagstad et al. (2013) used schematic illustrations to explain the multi-agent simulation system (SPANS) model that focuses on detailed mapping of ES flow. Ala-Hulkko et al. (2019) presented a scheme to explain the calculations in a spatial accessibility analysis, which aims to assess the spatial flows and balance between ES supply and demand. On the other hand, these representations also contribute to increasing the empirical understanding of the spatial dynamics of ES. For example, Syrbe and Grunewald (2017) classified the spatial dynamics of SCA in more detail and described six cases, where they included the different scales and various access possibilities:

1. *Local*: ES are provided and demanded in the same area (*in situ*). Since the ES do not have to "flow" or be transported as a result, the benefits of these ES can also be located in the same area.
2. *Proximity*: Natural processes and ecological laws determine the close transfer of ES.
3. *Process*: Natural processes take place over further distances.
4. *Access*: People actively access areas to benefit from provided ES.
5. *Transport of goods*: ES products and goods (wood, food etc.) are transported to people who demand these things.
6. *Global*: The benefits of some ES are global and cannot be spatially constrained.

The conceptual diagram by Schröter et al. (2018) aims to improve the understanding of inter-regional telecouplings in socio-ecological systems by explaining the spatial dynamics and effects of four different types of inter-regional flows and transport mechanisms between a sending and a receiving system. The authors explained that biophysical ES flows can: a) be transported through human-made carriers (e.g. for food, raw materials); b) take place through species migration and dispersal (e.g. bird migration) and c) arise passively through diverse ecosystem processes and functions (e.g. flood protection). A special point here is that, in the case of cultural ES, the exchange of data, information or media can also represent a form of ES flow. Although the framework focuses on inter-regional ES flows, the considerations could be applied at any scale (Schröter et al. 2018).

In SEEA EA, tables showing supply and use are applied to record the actual flows of ES between ecosystem assets and economic units (United Nations 2019). There is also an interest in mapping this supply and use information. However, the exchange between ecosystem and economic units takes place from an accounting perspective, which may limit the mapping ambitions. In accounting terms, the ecosystem-economic unit exchange, for example, for provisioning services (food, raw materials) takes place at the point of harvest. This means that ES are treated as provided and used in the same area (*in situ*). The transport of harvested materials to the regions where it is actually consumed is the subject of standard economic accounting. Therefore, this aspect has no role in ecosystem accounting and is, therefore, not mapped (United Nations 2021).

In these presented approaches, the Service Benefitting Areas equal the areas where people demand ES. This situation, however, is rarely simple. In highly anthropogenically-modified landscapes, such as cities, some areas have a high demand for ES, such as air quality or local climate regulation, which most cities cannot meet by the few existing remnants of nature (Baró et al. 2015,Grunewald et al. 2021).

This aspect is crucial for detecting ES mismatches, in which the quantity of ES demand exceeds the amount or quality of ES supply (Baró et al. 2015, Geijzendorffer et al. 2015, Syrbe and Grunewald 2017). As ES mismatches can indicate unsustainable use and inequitable distribution, there is an interest in illustrating how, when and where they can arise (Villamagna et al. 2013). Looking at two selected ES, Goldenberg et al. (2017), for example, used a schematic illustration to depict the main differences between potential and realised ES supply and demand, emphasising that demand can also remain unmet. We want to further develop these considerations within a spatial context with the integration of the SDA.

2 Methods

Based on an examination of available material, existing concepts were summarised and streamlined in order to develop an adapted spatial-structural approach which includes SDA.

2.1 Literature review

For the development of our adapted approach, existing reviews and theoretical articles about supply and demand of/for ES were highly relevant (see Fisher et al. 2009, Burkhard et al. 2012, Syrbe and Walz 2012, Villamagna et al. 2013, Geijzendorffer and Roche 2014, Geijzendorffer et al. 2015, Wolff et al. 2015, Hegetschweiler et al. 2017, Stosch et al. 2017, Syrbe and Grunewald 2017, Wei et al. 2017, Walz et al. 2017, Schröter et al. 2018, La Notte et al. 2019). This literature was expanded with further articles by conducting a search in the scientific literature databases, ISI Web of Knowledge (https://webofknowledge.com) and Scopus (http://scopus.com). The search keyword combinations are documented in Table 3. Due to the extensive amount of literature, articles were limited to studies that explicitly stated that the demand for ecosystem services was assessed and spatially mapped. In this way, it was possible to examine articles that might describe spatial relationships and patterns between SPA and SDA.

Table 3.

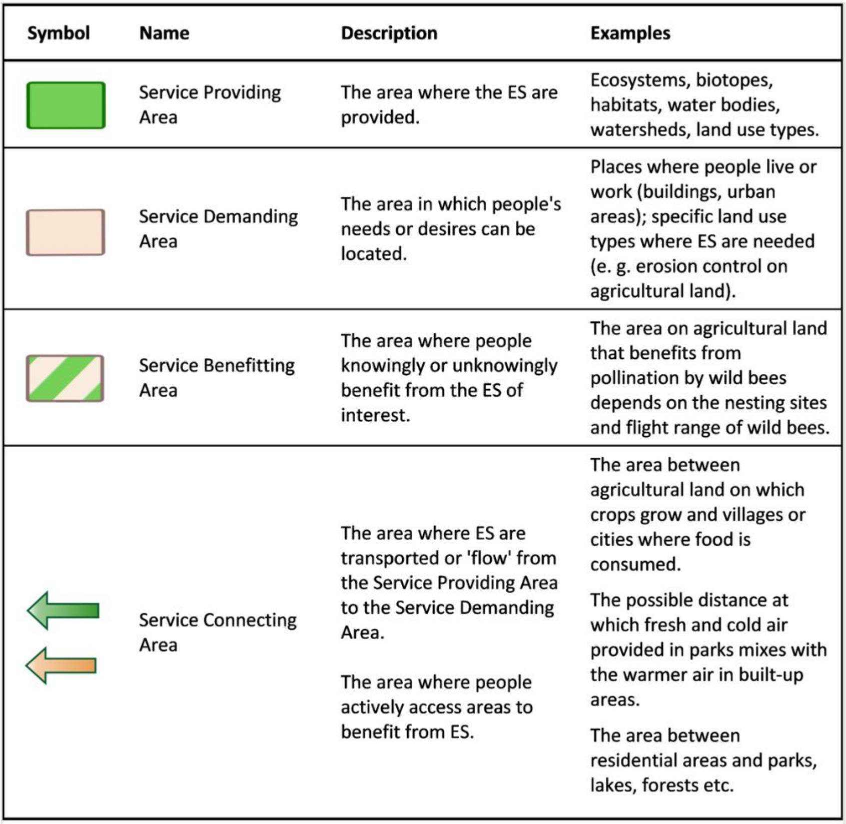
Examined keyword combination. The highlighted keywords were used for further analysis as they address the mapping of ES.

Keywords	**Occurrence**	
	Scopus	**ISI Web of Knowledge**
Ecosystem Service + Demand	402	716
Ecosystem Service + Demand + Supply	145	218
Ecosystem Service + Demand + Mapping	**44**	**97**

As Wolff et al. (2015) published a comprehensive review on mapping ES demand and was especially considered in this article, the search was limited to articles from 2015 to 2020. From this search, the relevant literature was selected by reading abstracts and examining the texts. A record was made of which definition of demand was used, who demands ES, whether mismatches were considered, which ES were investigated, which spatial representation of the demand for ES was chosen and which methods were used.

2.2 Development and structure of the adapted spatial-structural approach

The illustrations and descriptions of the adapted spatial-structural approach were compiled, based on already-existing graphical representations, terms and explanations. These have been redesigned and reformulated to include the SDA. An overview of the central components is shown in Fig. 1. The components can be explained as follows:



Symbol	Name	Description	Examples
	Service Providing Area	The area where the ES are provided.	Ecosystems, biotopes, habitats, water bodies, watersheds, land use types.
	Service Demanding Area	The area in which people's needs or desires can be located.	Places where people live or work (buildings, urban areas); specific land use types where ES are needed (e. g. erosion control on agricultural land).
	Service Benefitting Area	The area where people knowingly or unknowingly benefit from the ES of interest.	The area on agricultural land that benefits from pollination by wild bees depends on the nesting sites and flight range of wild bees.
	Service Connecting Area	The area where ES are transported or 'flow' from the Service Providing Area to the Service Demanding Area. The area where people actively access areas to benefit from ES.	The area between agricultural land on which crops grow and villages or cities where food is consumed. The possible distance at which fresh and cold air provided in parks mixes with the warmer air in built-up areas. The area between residential areas and parks, lakes, forests etc.

Figure 1.

Overview and explanations of the central components.

Service Providing Areas (SPA) locate areas where ES supply/potential emerge. These areas contain natural elements and may include parts or even whole ecosystems that represent complex, functional units of plant, animal and microorganism communities and their non-living environment (Potschin-Young et al. 2018). The most appropriate spatial units are those that are closely related to the ES concerned. These can be, for instance, biotopes, habitats, water bodies, watersheds, land-use types or the areas of impact of related ecosystem functions or processes (such as floodplains). As ecosystem condition, conservation, as well as land management measures are important factors influencing ES supply, these areas can consist of natural and anthropogenic elements and characteristics

(Syrbe and Walz 2012, van Oudenhoven et al. 2012, Walz et al. 2017). La Notte et al. (2019) described how ecosystems (or, in this case, the SPAs) can play different roles in providing ES potential. They can: 1) increase the productivity of an ES (e.g. food production or raw materials); 2) influence the suitability of ecosystems for providing, for example, pollination services or suitable habitats; 3) act as a sink (when ES absorb matter or energy, such as in air filtration); 4) buffer matter or energy which flows through the SPA (e.g. flood regulation); or 5) form the area where intangibles, such as information or cultural identities, are generated (La Notte et al. 2019).

We propose that people's needs or desires can be spatially located and are an indication of **Service Demanding Areas (SDA)**. When characterising the SDA, it should be kept in mind that the spatial location can vary with the selected ES demand type as well as with the group of people from whose perspective the expressed demand is to be presented. SDA often correspond to the usual location of people (urban areas, buildings), but can also be located with the help of closely related land-use types, on which the benefits of ES are intended to be received.

Service Connecting Areas (SCA) visualise the different forms of ES flows and transport mechanisms. As already mentioned above, the representation of the SCA is strongly scale-dependent. Depending on the ES considered, the SCA can be represented by natural or anthropogenic elements (such as streams, rivers or human-made infrastructures). The spatial distance of impact and possible access restrictions or barriers should be taken into account in the presentation of the SCA as these are crucial in determining whether people can reach or benefit from ES. Often SCA can only be detected by conducting specific analyses, as is particularly the case with inter-regional ES flows (Schröter et al. 2018, Kleemann et al. 2020).

Service Benefitting Areas (SBA) represent the areas where people knowingly or unknowingly benefit from the ES of interest.

The various spatial relationships that can occur were ordered into three main categories:

1) *In-situ*: ES are provided and demanded in the same area (*in situ*). Since the ES do not have to "flow" or be transported, the benefits of these ES can also be located in the same area.

2) Directional connections: ES are not provided and demanded in the same area, but these areas are near each other, directional connections exist. The provided ES can "flow" through natural processes or people who demand these ES, actively access the SPA in order to benefit from provided ES.

3) Non-directional connections: ES are provided and demanded in areas with non-directional connections. The provided ES "flow" through natural processes over long distances, ES products and goods (wood, food etc.) are transported to people who demand these things or people who demand these ES actively access the SPA to benefit from provided ES.

3 Results

In the following sections, we will present the outcomes of the literature review and present the newly-introduced component of service demanding areas in the adapted spatial-structural approach in more detail and with examples.

3.1 Literature review

Altogether 33 articles were identified which addressed demand for ES. A detailed overview of the articles analysed and the definitions, ES, methods and scale of analysis used can be found in Suppl. materials 1, 2.

The articles looked at different ES at a varying level of detail (see Suppl. material 2). Nine articles focused only on one ES, 24 articles considered two or more ES. The demand for regulating ES was considered most frequently, with a popular focus on specific ES, such as global or local climate regulation, water flow regulation, air quality regulation and pollination. Amongst the cultural ES, the demand for nature-based recreation was most frequently assessed, followed by the demand for intangible services, such as natural heritage and intrinsic values of biodiversity. The demand for provisioning services received the least attention. Here, the demands for food, (drinking) water and raw materials were most often analysed.

The spatial scales of the case study areas varied from local to international, with regional studies being most predominant (*21*). Fifteen articles did not describe from which perspective ES demand had been assessed. In the remaining articles, it can be deduced which perspective was presented. In Quintas-Soriano et al. (2019), the demand for ES was assessed by randomly selected persons. In some papers, key or local stakeholders and/or experts assessed or estimated the demand for ES (Beichler 2015, Palacios-Agundez et al. 2015, Li et al. 2016, Palomo-Campesino et al. 2018, Kokkoris et al. 2019). Others assessed the demand of particular interest groups like vulnerable people (Cortinovis and Geneletti 2018), farmers (Chen et al. 2018), visitors/tourists (Schirpke et al. 2018, Zhao et al. 2019), people dependent on wild medicinal plants or certain consumers groups (Wolff et al. 2017). The demand of different population groups was also examined, identifying them as residents (Schirpke et al. 2018), rural population (Chen et al. 2018) or households (Sahle et al. 2018b, Yuan et al. 2019). Three articles used environmental quality standards (Baró et al. 2015, Baró et al. 2016, Chen et al. 2019), which are set by institutions to assess discrepancies as a proxy threshold to determine expected or required ecosystem conditions from a societal perspective demand.

Statistical/literature data was most commonly used for simple assessments and mapping of ES demand (18) (e.g. Baró et al. 2016). In contrast, only six articles used comprehensive models to calculate the demand for a few selected ES: recreation, pollination, flood regulation and wild medicinal plants (e.g. Wolff et al. 2017). Participatory methods were used in eight articles, including participatory mapping, qualitative participatory scenarios, preference assessments and various types of surveys (e.g. Beichler 2015, Palacios-Agundez et al. 2015, Quintas-Soriano et al. 2019). For example, interviewees expressed their estimation of the extent of a region's ES demand using the ES matrix look-up table method (Li et al. 2016, Chen et al. 2018). Furthermore, results were analysed with different statistical and spatial analysis methods, such as principal component analysis, cluster analysis, multi-criteria analysis or spatial prioritisation (e.g. Verhagen et al. 2017, Schirpke et al. 2019a, Schirpke et al. 2019b). Some articles combined scenario-based analyses with trade-off analyses to consider and determine the effects of, for example, changes in land cover and land-use, land use management or policy and/or climate change (Goldenberg et al. 2017, Cimon-Morin and Poulin 2018, Cortinovis and Geneletti 2018, Sauter et al. 2019, Yuan et al. 2019). In 30 articles, a combination of methods was found. Most articles (29) analysed ES mismatches and trade-offs, by comparing results from ES supply/potential with ES demand assessments.

3.2 Demand for ecosystem services in a spatial-structural approach

Fig. 2 illustrates possible types of spatial relations in the adapted ES spatial-structural approach in a generalised and simplified way.

Based on the spatial relationships presented above (Chapter 2.2), a distinction can be made between the following types of relationships between the SPA and SDA:

1) ***in situ***: ES can be provided and demanded in the same area (*in situ*). The benefit of this ES can be found in the same area, as it does not require the ES to "flow" or be transported. There may still be areas where the ES is demanded, but not provided at this location. This can lead to an unmet demand. It is also possible that there are areas that provide the ES, but these ES are not used by people and, therefore, are not classified as SBA.

Example: Crop yield is influenced by ES which regulate and maintain soil quality. These ES can, however, only provide benefits in their immediate location. The benefits of these ES can be seen directly where soils with good natural soil quality are used, i.e. in the SDA. These ES can also be provided in areas like urban parks, but the benefits seen in urban parks are not related to food production. Gardens or agricultural land where these ES are not provided would display unmet demand.

2) There are several ways in which **directional connections** can occur between SPA and SDA:

2a) **Central directional**: ES are provided in an area surrounding the SDA. The ES provided "flow" through natural processes into the SDA, where the benefits can be used. However, the flow distance of the respective ES can be limited. Outside this range, there would remain unmet ES demand.

Example: City residents can benefit from the supply of fresh and cold air produced in the open spaces in the surrounding area that mixes with the warmer air in the built-up areas. As this distance is limited, people living in centrally located built-up areas may still need local climate regulation.

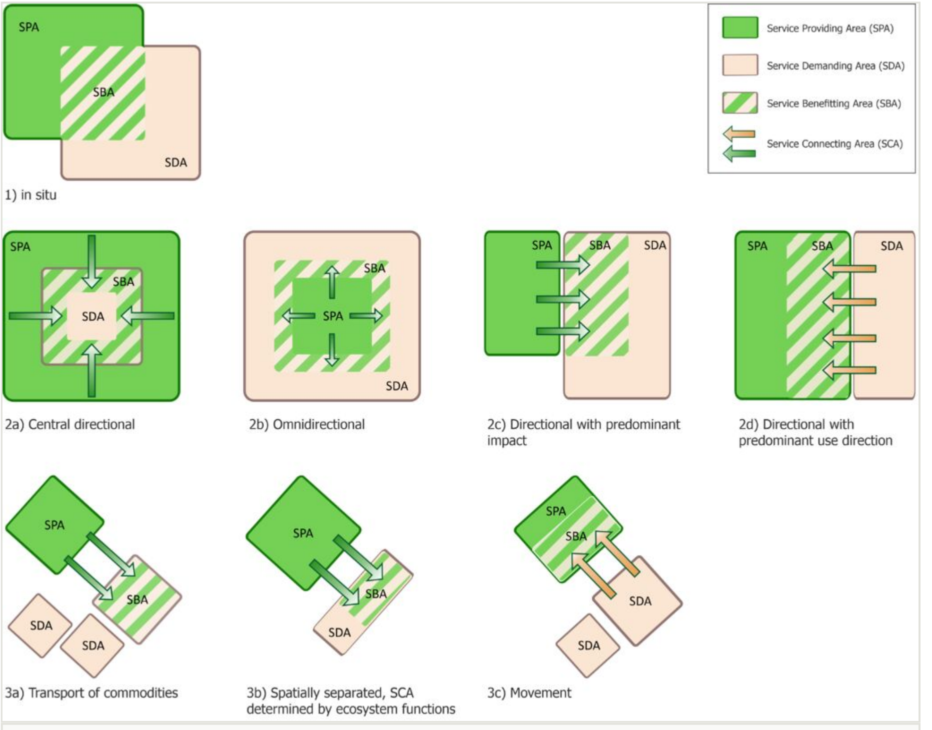


Figure 2.

Spatial-structural approach including Service Demanding Areas (SDA). Types of spatial relations of Service Providing Areas (SPA), Service Benefitting Areas (SBA) and Service Connecting Areas (SCA) (adapted and extended from Fisher et al. (2009), Syrbe and Walz (2012), Syrbe and Grunewald (2017), Walz et al. (2017) and with consideration of the work from Schröter et al. (2018), La Notte et al. (2019)).

2b) **Omnidirectional**: This case is similar to 2a), except that a central SPA provides benefits to a surrounding SDA.

Example: A park within a city provides fresh and cool air that mixes with the warmer air in the built-up areas. As this provision distance is limited, residents in more built-up areas cannot benefit from this ES type.

2c) **Directional with a predominant impact direction**: ES are provided in an area that is close to the SDA. The SCA is determined by ecological functions and processes, with a predominant direction of impact. If the SCA is missing, the SDA behind it cannot benefit from the respective ES.

Example: The residents of a built-up area are protected from storm surges by natural coastal protection through, for instance, dunes, coastal wetlands or seagrass. As not all coastal areas provide this ES type, there may be built-up areas not protected by natural coastal defences. These residents live in areas that are at higher risk of flooding.

2d) **Directional with a predominant use direction**: This case is similar to 2b), except that there is a movement from the SDA to the SPA.

City residents can actively walk to urban parks for sport and recreational reasons. Using the natural environment helps the residents to stay fit. SCA can be used to display the distances that residents travel from their homes. However, some of the suitable urban green spaces may be too far and are, therefore, not used. There may also be urban settlements where the distance to any park or green area is too far. The demand of these people for the ES remains unfulfilled.

3) The SPA and SDA can be **spatially separated** from each other at greater distances, where **non-directional connections** exist. There are several circumstances:

3a) The areas where ES are provided and demanded are spatially separated. However, there is an SCA, determined by ecological functions and processes, which ensures that the benefits of these ES take place where they are in demand. Nevertheless, there may still be areas that do not benefit from the ES, for example, due to barriers influencing the SCA.

Example: A floodplain upstream protects residents in a built-up area against river flood events. As there may also be urban areas that cannot benefit from the ES due to, for instance, geographical reasons, an unmet demand may exist.

3b) **Movement**: This case is similar to 2d, except that people actively access areas at greater distances in order to benefit from the ES provided there.

Example: People can travel around the world to enjoy and benefit from ES provided by aesthetic landscapes. As some places are too far away or inaccessible due to restrictions, these areas do not represent SBA. Similarly, there may be people who cannot travel or for whom the places are too far away, which may result in an unmet demand.

3c) **Transport of commodities**: SDA and SPA are spatially separated; thus, the connection area is determined by the transport of goods and materials or information. Areas, where these things are transported, can benefit from the ES. However, it may also be that these things are not transported into certain areas, which means that the demand is still unsatisfied.

Example: Agricultural land provides crops, fruits and vegetables that can be transported to urban areas worldwide where people live and need food. However, there may be (for various reasons) no food transport to certain urban areas, so residents cannot benefit from this food supply, which, in the worst case, can lead to hunger.

4 Discussion

This article contributes to the conceptual understanding about ES demand and aims to illustrate that not only the areas where the benefits of ES arise and can be used by people should be considered, but also that it is essential to look at the areas where the demand for these ES arise in the first place. By taking this aspect into account, interventions can be explored that could strengthen the role of healthy ecosystems - especially where people are particularly dependent on nature - and where solutions should focus on reducing ES demand to protect the ecosystem (Chaplin-Kramer et al. 2019, Chen et al. 2019).

We hope that with the addition of SDA to existing spatial concepts, the difference between ES demand and benefits can be highlighted. In addition, the schematic illustrations and examples show that similar spatial connections exist that significantly influence the fulfilment of ES demand.

4.1 Ecosystem service demand is multifaceted

Spatially-explicit mapping of ES demand is challenging given that demand is multifaceted and can change over time.

ES are not delivered to society as a single group of beneficiaries; the groups differ in their cultural and demographic characteristics (such as age, gender and ethnicity), have different levels of education, interests, motivations, financial resources or consumption patterns (Pascual et al. 2014, Pascual et al. 2017, Hegetschweiler et al. 2017). Therefore, people demand ES in very different and often contradictory ways, leading to trade-offs between the interests of different stakeholders (Cavender-Bares et al. 2015).

Often, only a few actors (such as farmers, landowners, business enterprises or institutions) have an impact on land-use change and the ES flow mechanism and, thus, play a crucial role in creating, distributing and meeting ES demand (La Notte et al. 2019, Watson et al. 2019). In particular, institutions can strongly influence the demand for specific ES through land-use decisions, guidelines, environmental quality standards or policy objectives (Geijzendorffer and Roche 2014, Baró et al. 2015, Baró et al. 2016, Chen et al. 2019). For example, Schulp et al. (2014) have shown how demand for pollination increased after the European Commission started to promote and subsidise pollinator-dependent crops (oilseed rape, sunflower and other oil crops) with the EU Biofuels Directive (European Commission 2009). Due to the increasingly negative impact of agricultural intensification on ES potential, the authors call for further ecosystem protection at the EU level to help meet demand for pollination. Identifying these 'enabling actors' (La Notte and Dalmazzone 2018) and the geographic and policy scale from which they influence land use helps to better understand who is responsible for land-use change and what policy or management interventions are needed to enhance or maintain ES successfully (Darvill and Lindo 2015, Geijzendorffer et al. 2015).

In general, as with all ES assessments, the spatial scale also plays an essential role in ES demand (Geijzendorffer and Roche 2014). The illustrations and examples of the spatial concept presented here show that the spatial distribution and connection of the SPA and SDA can vary greatly depending on the ES. Therefore, it is advisable to examine possible SPA and SDA for each ES and determine whether specific patterns can be identified in different human-environment systems.

As demand varies from ES to ES, it can also be met in diverse ways. In many cases, ES supply is actively co-produced and increased through human activities and interventions (Bennett et al. 2015, Fischer and Eastwood 2016) or the benefits are imported in the form of products and goods from other regions. For example, food production on agricultural land is enhanced through various agricultural interventions (Wiggering et al. 2016, Bethwell et al. 2021) and the harvest is subsequently transported to beneficiaries (Ala-Hulkko et al. 2019). Strategically planned networks, such as green infrastructure, safeguard or enhance recreational opportunities (Hegetschweiler et al. 2017), multiple ES and support biodiversity (Chen et al. 2019, European Commission 2019, Hersperger et al. 2020).

The high demand for ES and trade-offs between ES can also be reduced without increasing ES supply through intelligent policy-making, for example, by increasing prices, fees or taxes on certain products (Fisher et al. 2009), by restricting access to fragile ecosystems (Schägner et al. 2016), through planning laws that aim, for instance, at social and environmental justice (Jacobs et al. 2016, Cortinovis and Geneletti 2018) or through agreements on climate, ecosystem and biodiversity. This option is often a solution for regulating ES, as the underlying ecosystem processes and functions often take place over longer distances and the benefits cannot be used or consumed directly (Sauter et al. 2019). The demand for global climate regulation, for example, can be expressed as a demand for a global ecosystem state in which CO_2 and other GHG emissions, as major contributors to global climate change, are adequately sequestered and stored at a global scale (Burkhard et al. 2012, Baró et al. 2015, Sahle et al. 2018a, Cimon-Morin and Poulin 2018). However, alternative scales, data and indicators can also indicate ES demand mismatches for these ES (Rioux et al. 2019). For example, it can be shown at the local level whether anthropogenic emissions exceed local CO_2 sequestration and storage capacity (Zhao and Sander 2015, Sahle et al. 2018a, González-García et al. 2020). Such a study is politically relevant as it can show where and why CO_2 emission levels exceed legally binding CO_2 emission targets (Baró et al. 2015, Chen et al. 2019, Sauter et al. 2019).

4.2 Mapping ecosystem service demand

As with all mapping assessments, data availability is a crucial factor for spatial mapping of ES demand. It is noticeable that, in the studied articles, demand for ES mainly was assessed and analysed, based on simple statistical and/or literature data (see Suppl. material 1). The use of statistical and/or literature data, look-up tables or the ES matrix method is well-suited for comparatively quick and large-scale analyses, especially when implementing comprehensive process-based ES models would be too resource-intensive (Sauter et al. 2019, Campagne et al. 2020). In this way, relatively simple, yet realistic, estimates can be generated that show spatial distribution patterns (Goldenberg et al. 2017). However, it should be kept in mind that the complexity of ES demand is then represented in a simplified way, which may have consequences in identifying or not identifying ES mismatches and trade-offs (Li et al. 2016).

Furthermore, ES demand is often derived from a land-use/land-cover perspective. This approach assumes that certain land-use types have a higher demand for the benefits of the corresponding ES. For example, studies have determined the demand for pollination by the size of vegetable gardens in residential or agricultural areas (Schulp et al. 2014, Rioux et al. 2019, Zhao et al. 2019). A higher demand for ES is often attributed to particularly vulnerable land-use types at higher risk during extreme events. For example, high demand for ES for flood regulation has been attributed to those land-use types that are most likely to experience negative impacts for people during flood events (Nedkov and Burkhard 2012). A similar attribution can also be observed in assessing and managing flood risk in the EU (Directive 2007/60/EC). However, further aspects of demand are also considered, namely the potentially negative impacts of floods on human health, infrastructure, nature conservation areas and cultural heritage (European Union 2007).

The frequent use of proxy indicators (e.g. population numbers or building density, air quality and proximity to green spaces) (Baró et al. 2015) only provides information on the potential use of ES and does not take into account the diverse demands of stakeholders. So far, only a few authors have taken up the challenge of considering the demands of different user groups (e.g. residents, farmers and tourists) to represent different interests or concerns (Chen et al. 2018, Schirpke et al. 2018, Chen et al. 2019). However, such an investigation requires a comprehensive data basis and requires a higher methodological effort.

Various participatory methods are available to indicate the ES demand of different stakeholder groups (see, for example, Cavender-Bares et al. 2015, Palacios-Agundez et al. 2015, La Rosa et al. 2016, Harrison et al. 2018, Quintas-Soriano et al. 2019). Although these methods may not provide accurate geographical data, they provide valuable ES information that is otherwise difficult to assess, such as cultural ES (Beichler 2015, Palomo-Campesino et al. 2018). However, additional methods should be included for ES that are rarely known or often hardly perceived as relevant by stakeholders (Kaye-Zwiebel and King 2014, Quintas-Soriano et al. 2019). Since ES demand is multifaceted, using multiple methods and data types from different disciplines can significantly increase the knowledge and applicability of the results (Milcu et al. 2013, Flood et al. 2021).

In the reviewed articles, ES mismatch analyses were mostly conducted through comparatively simple supply-demand comparisons that express the degree of (im)balance between the ES supply and demand (e.g. Li et al. 2016, González-García et al. 2020). The relationship between ES supply and demand can be strongly influenced by site-specific and short-term aspects, such as weather conditions, land-use/land-cover changes and landscape features, which can be included in the analysis and reveal further underlying correlations (Hegetschweiler et al. 2017). Such comprehensive studies have been conducted, for example, by Schirpke et al. (2018) and Schirpke et al. (2019a), where the use of landscape, temporal and socio-ecological variables was able to identify and explain the heterogeneous distribution of ES bundles in the European Alps.

Interestingly, significant differences in the quality of ES supply and demand assessments can be observed in some articles. The difference in quality is also acknowledged as a limitation by the authors themselves and has also been criticised in other studies (e.g. Czúcz et al. 2020, González-García et al. 2020). Comprehensive modelling of ES demand has only been carried out in comparatively few studies (e.g. Wolff et al. 2017). The reasons for this could be that, so far, suitable demand indicators have only been integrated into ready-to-use models for a few ES (see, for example, InVEST (The Natural Capital Project (NatCap) 2021), ESTIMAP (Zulian 2016) or ARIES (Villa et al. 2014)).

4.3 Limitations

This study complements previous spatial structural approaches with SDA, but also has some methodological limitations. First, we are aware that ES research is a very dynamic field and that there may now be other relevant sources that consider and map ES demand. Second, the selection of our keywords had a major impact on identifying relevant articles and narrowing down the results. This problem has been highlighted in other review articles (e.g. La Rosa et al. 2016).

In the process of editing this article, it became more and more apparent that; a) there continues to be a heterogeneous understanding of key terms and b) that, accordingly, specific key terms are also used differently in ES assessment, mapping or accounting literature. In the official reports of the accounting community, "ES demand" is not used as an independent term (see also Table 1 in the Introduction) - instead, the focus here is on "use of ES" or "actual flow" of services. Expanding the keywords in the literature search with, for example, these terms could have identified more sources.

Given the diversity of ES and the different influencing factors that affect and respond to changes in ES demand, a narrow definition is often avoided to reflect this diversity (Wolff et al. 2015). This flexibility is often even desired in the holistic ES approach to facilitate discussions between disciplines (Czúcz et al. 2020, Grunewald et al. 2021). However, in many of the articles reviewed, the demand for ES was not sufficiently described, leading to further confusion. Overall, the different understandings pose a challenge for the transferability and comparability of the methodological approaches and the ability to communicate and apply the results in policy, land-use management or spatial planning. Understanding the diversely interpreted ES terms is particularly challenging for non-native speakers, especially when English terms themselves contain subtle nuances of meaning and there are no direct translations into their native language (Dłużewska 2016). Therefore, it should be communicated how the ES concept terms are understood and what indicators have been used to represent them.

We would like to emphasise that this paper only intends to provide an initial overview of the spatial relationships between the different components of the ES concept and to make a valuable contribution to future considerations in this field. This being the case, various aspects (e.g. temporal changes) that influence the distribution of the ES are not yet included in the figures or examples used in this paper.

5 Conclusions

Healthy ecosystems play a key role in meeting ES demand by providing, for example, food, clean drinking water, security and protection against natural hazards and a wide range of recreational opportunities. The ES approach provides a holistic framework to examine how nature can sustainably fulfil ES demand.

Matching ES supply and demand, based on conservation and sustainable use of ecosystems and their services, can help safeguard human well-being by avoiding unmet demands. Information and data from respective ES assessments (including the comprehensive and robust data provided by ecosystem and natural capital accounting following SEEA) that integrate ecological, social-cultural and economic value domains, provide the evidence base for appropriate public and private decision-making on relevant spatial and temporal scales - from local to global and from short- to long-term (Goldenberg et al. 2017, Ala-Hulkko et al. 2019, González-García et al. 2020, Vysna et al. 2021).

Having analysed the selected scientific articles, three issues have emerged that can be addressed to strengthen the assessment of ES demand and, thus, ES mismatch analyses. Firstly, different studies perceive ES demand differently and it is important to clarify what is meant by ES demand. Overall, a clear distinction between ES supply, potential, flow and demand is mandatory to consider the different components of complex ES delivery from nature to society. ES research requires both a common internal lexicon and the flexibility to adapt the terminology used in external publications/communications regarding the desired field of application in science, policy, business and society. This would help to increase the mutual understanding within the ES concept and improve the chances of its implementation in related fields of applications, such as, for example, urban and regional planning (Scott et al. 2018).

Secondly, it must be kept in mind that there are different ways to express human needs and desires and that demand is thus multifaceted. Including the full range of stakeholders' perceptions, needs and desires broaden the picture of societal demand for ES (Bennett et al. 2015). It is often the case that multiple stakeholders must be brought on board to elaborate on important land-use decisions. Thus, it is crucial to look at these actors and the spatial and temporal dimensions of the mutual inter-relationships between ES supply and demand in order to identify the most effective approaches for achieving ES sustainability (Villamagna et al. 2013, Geijzendorffer et al. 2015).

Thirdly, to inform decision-makers about reducing ES trade-offs and mismatches, meaningful interpretations between ES supply and demand must be available. The adapted spatial-structural approach is a helpful (visual) support for understanding the ES concept’s spatial components for identifying areas of interest. Studies vary widely in terms of ES demand indicators, data and evaluation methods used. This highlights the lack of a systematic methodological framework or the policy triage system to guide ES research, which comprehensively measures comparable units and can link existing information on ES supply, demand and benefits (Honey-Rosés and Pendleton 2013). Existing frameworks, such as the MAES framework, provide a valuable basis, but need to address the ES demand side strongly (Burkhard and Maes 2017, Heckwolf et al. 2020).

Understandably, a precise assessment of the demand for ES is challenging, as both environmental and socio-economic systems are highly complex as well as spatially and temporally variable. Uncertainties about the interaction of ES supply and demand can, for instance, arise from feedback loops (Stosch et al. 2017). For example, significant socio-economic and cultural changes have occurred due to the current COVID-19 pandemic and are changing the perception and use of the ES provided (Rousseau and Deschacht 2020). The current negative developments related to the pandemic, such as travel restrictions, increase the importance, but also the use of nature-based recreational activities in the immediate vicinity (Kleinschroth and Kowarik 2020, Venter et al. 2020). With the integration of the SDA, we hope that the spatial connections of the complex ES delivery will be more strongly emphasised.

Acknowledgements

The authors would like to thank the editor and the reviewers for their useful comments and literature recommendations. Their valuable suggestions helped us to improve the manuscript significantly. Many thanks to Henning Schumacher for his contributions to the literature review and Angie Faust and Matthew Cruickshank for their valuable feedback and English proofreading.

Funding program

This study was part of the research project ÖSKKIP (Ecosystem Services of Urban Regions – Mapping, Communicating and Integrating into Planning to conserve biodiversity during a changing climate) funded by the German Ministry of Education and Research (BMBF) under the funding code FKZ 16LC1604B. The publication of this article was funded by the Open Access Fund of the Leibniz Universität Hannover.

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Conflicts of interest

None.

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Supplementary materials

Suppl. material 1: Reviewed articles. doi

Authors: Dworczyk, Claudia; Benjamin, Burkhard
Data type: Occurrences
Brief description: Detailed overview of the articles analysed and the definitions, methods and scale of analysis used.
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Suppl. material 2: Ecosystem Services doi

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Data type: Occurrences
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Chapter 4

Challenges entailed in applying ecosystem services supply and demand mapping approaches: a practice report

Dworczyk, C., Burkhard, B.
Land (2023) 12, 52. https://doi.org/10.3390/land12010052

Figure 13. Bees and other insects are vital for pollination. Photo: Jolanta Dworczyk.

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Article

Challenges Entailed in Applying Ecosystem Services Supply and Demand Mapping Approaches: A Practice Report

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Abstract: The Ecosystem Services (ES) concept has been acknowledged by scientists, policy-makers and practitioners to have the potential to support sustainable policy- and land-use decision-making. Therefore, a growing number of research activities are investigating the integration potential of the ES concept into real-world policy- and decision-making processes. These research activities are often confronted with conceptual challenges and methodological obstacles when applying different ES mapping approaches. This study is reporting those challenges encountered during a research project in Germany. In this research project, two urban regions, Rostock and Munich, were selected as case-study areas. In both urban regions, dynamic urbanisation processes occur across the urban administrative boundaries and threaten the supply of multiple ES in the periurban landscapes. The research project invited local stakeholders from the two urban regions to workshops and online meetings to discuss ES-related topics. For those events, maps visualising the spatial patterns of multiple ES were needed for communication and awareness-raising of the ES concept. We chose commonly used and relatively easy-to-apply mapping methods such as: (1) expert-based ES matrix approach, (2) simple GIS mapping with proxy indicators and data, and (3) simple ES models such as InVEST. We encountered several challenges during the mapping processes: The expert-based matrix approach provided valuable results for ES supply, but had limitations in assessing expert estimates for ES demand. Alongside other factors, evolving barriers related to the conceptual complexity of ES demand. Data unavailability/inaccessibility resulted in difficulties mapping all selected ES with proxy indicators at the targeted regional scale. So far, only a few individual ES can be modelled with InVEST models. Despite these challenges, the resulting maps were helpful for communication with local stakeholders. The discussions with stakeholders provided valuable insights into the future needs for ES research and identified existing barriers and challenges. We want to summarise and share our experiences and provide recommendations for future research on mapping ES supply and demand in urban regions.

Keywords: stakeholder involvement; ecosystem services matrix approach; simple GIS mapping; InVEST; map comparison

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Citation: Dworczyk, C.; Burkhard, B. Challenges Entailed in Applying Ecosystem Services Supply and Demand Mapping Approaches: A Practice Report. *Land* **2023**, *12*, 52. https://doi.org/10.3390/land12010052

Academic Editor: Marcin Spyra

Received: 4 November 2022
Revised: 13 December 2022
Accepted: 20 December 2022
Published: 24 December 2022

1. Introduction

Ecosystem services (ES) describe ecosystems' direct and indirect contributions to human well-being [1]. These contributions include services and goods provided by nature (such as food, local climate regulation, and nature-based recreational activities) that bring direct or indirect economic, material, and health or psychological benefits to humans [2]. Unfortunately, many ecosystems are heavily degraded through human activities [3]. For example, ongoing urban sprawl impairs the natural ecosystem functions in rural areas, leading to declining ES and biodiversity loss in periurban areas [4–6]. However, the periurban areas are particularly significant for cities as they provide multiple ES [7,8].

In recent years, the ES concept has been acknowledged by scientists, policy-makers and practitioners to have the potential to support sustainable policy and land-use decision-making [9–12]. The concept is useful for communicating society's dependence on functioning ecological systems and developing sustainable and equitable land management strategies [4]. Therefore, it has been integrated into several international initiatives and policies [4,13,14], such as the European Union (EU) Biodiversity Strategies [15,16]. Recently, the UN System of Environmental–Economic Accounting—Ecosystem Accounting (SEEA EA) updated the statistical frameworks and provided a basis for quantifying ecosystem functions and ES into national accounting standards [17].

Despite this integration of the ES concept into important international initiatives and policies and a growing number of ES research, the ES concept still has limited use and impact in real-world policy and decision-making processes (9–12). Barriers can be attributed, alongside others, to the unclearly communicated added value of the ES concept compared to other approaches in spatial planning, lack of legal obligations, conceptual uncertainties, and methodological challenges of ES mapping approaches [9,18,19]. For example, within the decade of the EU Biodiversity Strategy 2010–2020, all EU Member States were committed to mapping and assessing ecosystems and their services by 2014 (EU Biodiversity Strategy 2020; Target 2; Action 5 [15]). In retrospect, however, this objective has only partially been achieved because there have been, for example, ambiguous definitions and criteria, no clear or binding targets, and a lack of standard guidelines for mapping, monitoring, or assessing ES when the Action was launched [16,20].

Numerous research activities are working and exploring possible solutions to address these knowledge and research gaps [9,20]. This study wants to report the challenges and obstacles that entailed during ES mapping approaches, which were conducted for the OESKKIP research project ("Ökosystemleistungen von Stadtregionen—Kartieren, Kommunizieren und Integrieren in die Planung zum Schutz der biologischen Vielfalt im Klimawandel", in English "ecosystem services of urban regions—mapping, communicating, and integrating into planning to conserve biodiversity under a changing climate"). OESKKIP tested the integration capacity of the ES concept into urban and regional planning and governance processes in Germany [18,21]. The research project, among many other activities, invited local stakeholders from two urban regions (Rostock and Munich) to workshops and online meetings to discuss ES-related topics. For those events, maps visualising the spatial pattern of multiple ES were needed for communication and awareness-raising of the innovative ES concept [22,23].

Several methods and models for measuring, assessing, and mapping ES exist. However, selecting the most suitable method for an ES study is challenging [20]. The tiered approach for ES mapping helps researchers and practitioners select adequate ES mapping approaches for their research purpose, knowledge, and data availability [24,25]. Relatively easy-to-apply methods (tier 1) can, for instance, be used for communication and awareness-raising, as they provide quick overviews of spatial ES issues. More specific information can be conducted with more complex methods (tiers 2 or 3), which provide results with, for instance, higher spatial resolution and allow a more profound analysis of underlying interactions among the ES components and/or socioecological processes. A combination of methods can be applied if a study needs to assess a broad range of ES and/or if resources (such as data, time, money, knowledge) are limited [24,25]. Following this tiered approach, we chose well-known and tested tier 1–2 methods, which would also have the assumed additional advantage of the stakeholders and practitioners being able to reproduce the results if needed [10]. We used: (1) the expert-based ES matrix approach, (2) simple GIS mapping with proxy indicators and data, and (3) simple ES models.

The ES matrix approach is based on lookup tables, in which ES values are linked to appropriate geobiophysical spatial units, such as land-use and land-cover (LULC) types [26,27]. This approach can be applied on all temporal and spatial scales and allows (on the lower tier levels) ES mapping in cost-efficient assessments, even in data-scarce areas or for individual ES, for which tested indicators and methods are lacking [27,28]. All ES values assessed and quantified are classified using a relative scale [27]. This classification and normalisation reduce the complexity and allow comparisons between individual ES [27,29]. The ES matrix approach can be used to analyse different components of ES, for example, ES supply or demand [30–33]. It is possible to determine the ES values via expert estimates (which can be collected in participatory scoring processes, also called the *expert-based ES matrix approach*) or from proxy data and comprehensive model results [28,34].

A simple method for mapping ES is using GIS software and available proxy indicators and data (such as literature, statistical, or LULC data) [35]. Thus, quick results and maps can be generated without using complex methods and when data, time, and money are scarce [36]. For example, estimates of ES values per LULC are often published in the literature. Although these results come from other studies and often from a different context, such value transfers can relatively quickly reveal spatial ES patterns in the area of interest [35]. The advantage of using LULC data is that data are very well accessible, at least in EU member states. Many provisioning ES can be uniquely linked to LULC types. Therefore, the indicators are well known and easy to communicate and understand [28,36–38]. For instance, the LULC type agricultural area indicates that the soil is fertile and suitable for growing edible cultivated terrestrial plants [39]. Therefore, the total size or the proportion of agricultural area in a case-study area can give (in this example) an indication of the supply of food. The results provide distinctive spatial patterns that can be used to identify service providing or demanding areas [27].

Comprehensive ES models are available, provided in a desktop application and therefore relatively easy to assess, such as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) models [40]. The results are site-explicit, allowing the opportunity to explore the impacts of ecosystem structures and functions on ES. Depending on the selected model, only basic to intermediate GIS skills are required [40].

As already highlighted, all chosen methods have the advantage that they can provide relatively quick results. However, there are also well-known limitations, addressing, among other things, the over-simplicity of application, geodata used, data accuracy, and temporal or spatial scale [24,35,41]. For example, it is often assumed that qualitative expert estimates are too subjective and, therefore, less reliable and credible than results from quantitative mapping approaches [38]. However, comparative assessments that could prove this assumption are scarce [28,30,42,43]. Therefore, we compared spatial similarity with simple map comparison tools to test whether the expert-based ES matrix approach is already sufficient for mapping ES with the actual purpose of communication and awareness-raising.

The overall aim of this paper is to answer the following research questions:

1. How useful are commonly used ES mapping approaches in regional urban contexts, and what major obstacles to their application did we encounter?
2. How can our experiences help inform future research and comparable application perspectives in ES mapping?

2. Materials and Methods

2.1. Study Areas

Selected ES of the two German urban regions of Rostock and Munich were mapped in this study. In both urban regions, dynamic urbanisation processes threaten the supply of multiple ES in periurban areas and increase the demand for ES in the urban areas. Figure 1 shows their location in Germany and the main LULC thematic classes of the freely available Urban Atlas data [44].

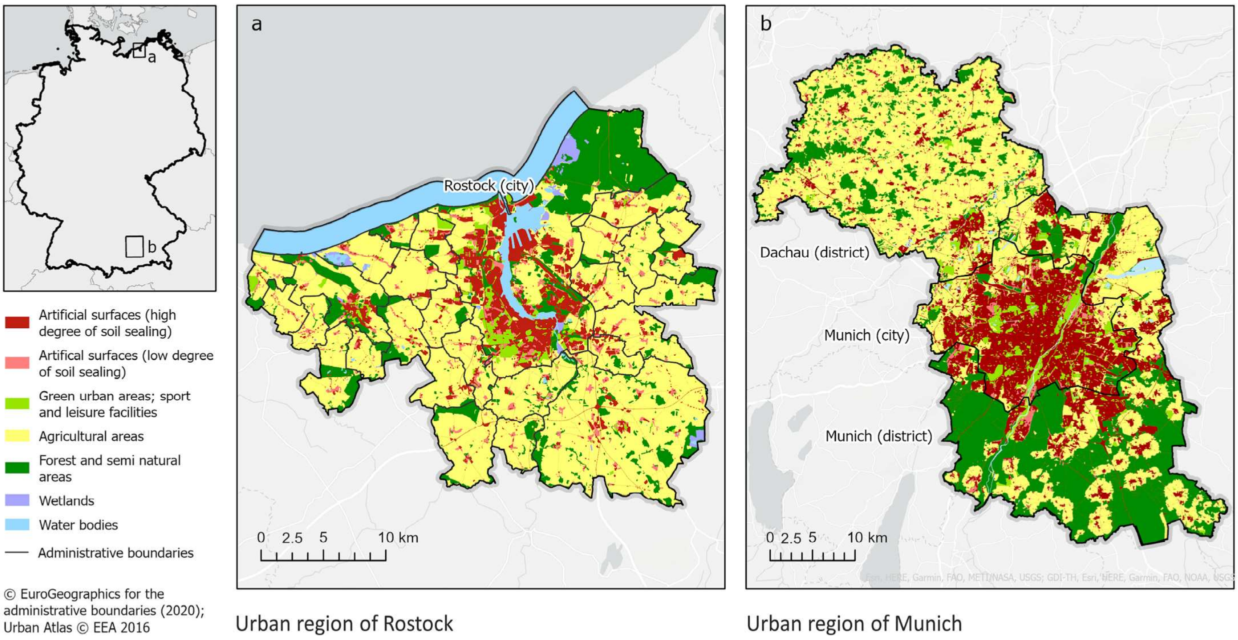

Figure 1. Location of the two urban regions of (**a**) Rostock and (**b**) Munich in Germany. Maps show the main LULC thematic classes of Urban Atlas data [44].

The urban region of Rostock is located in northeastern Germany in Mecklenburg–Western Pomerania. This study area encompasses 21 municipalities, including the city of Rostock. According to the European Nomenclature of Territorial Units for Statistics (NUTS), those municipalities correspond to Local Administrative Units (LAU) [45]. The study area covers approximately 670 km^2 and has a population of more than 270,000 inhabitants [46]. The dominant land-use type is agriculture (63%). The urban region of Rostock is an attractive place to live and work. Some smaller towns in its vicinity are experiencing strong population growth [47]. Owing to its location on the Baltic Sea coast, it is a popular destination for tourists and day visitors [48]. Another popular tourist attraction and important nature conservation area is Rostock Heath (a coastal forest and heathland region) east of Rostock.

The urban region of Munich is located in the southern Germany in Bavaria. The boundaries are delimited towards the regional NUTS3 level. This study area includes two districts, Dachau and Munich, and the city of Munich, which is the capital of Bavaria. This study area covers an area of approximately 1550 km^2 and has over 1.9 million inhabitants [46]. Agriculture (44%) is the dominant land-use type, followed by forest areas (27%). However, the city of Munich is primarily characterised by artificial surfaces and is densely built-up. Munich is an economically attractive location and one of the fastest-growing cities in Germany [47]. Despite being a densely built city, it has several parks, such as the English Garden along the River Isar, which are popular with the inhabitants and visitors. The district of Dachau extends from the northwestern suburbs of Munich. It is a hilly and agricultural-dominated countryside, with many villages and the city of Dachau. The urban sprawl extending from Munich is advancing into the district's territory. The forest-dominated district of Munich is located to the east and south of the city. In the south is the highest elevation of the case-study area (approximately 700 m), announcing the Alpine foothills. The city's growth is also strongly noticeable in this district, especially close to the city's boundaries [49].

According to the Köppen–Geiger climate classification, both study areas are in climate class Cfa, which is characterised by a warm, temperate climate with humid periods, warm summers, and cold winters [50].

2.2. Selected Indicators

This study focused on five ES, which were selected based on their relevance for local stakeholders during workshops in the case-study regions [23]: (1) food (from cultivated terrestrial plants), (2) raw materials (from cultivated terrestrial plants), (3) pollination, (4) local climate regulation, and (5) coastal protection (see Table 1).

Table 1. Classification of selected ES after CICES V5.1 [51].

Code	CICES V5.1, Class Name	Ecosystem Services
1.1.1.1	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	Food (from cultivated terrestrial plants)
1.1.1.2	Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	Raw materials (from cultivated terrestrial plants)
2.2.2.1	Pollination (or "gamete" dispersal in a marine context)	Pollination
2.2.6.2	Regulation of temperature and humidity, including ventilation and transpiration	Local climate regulation
2.2.1.3	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	Coastal protection [1]

[1] Only mapped for the urban region of Rostock.

2.3. Definitions of ES Supply and Demand

We followed the understanding of ES supply and demand from the comprehensive MAES glossary [1]. Here, ES supply is defined as "the provision of a service by a particular ecosystem, irrespective of its actual use" [1]. ES demand can be described as "the need for specific ecosystem services by society, particular stakeholder groups, or individuals. It depends on factors such as culturally dependent desires and needs, availability of alternatives, or means to fulfil these needs. It also covers preferences for specific attributes of ecosystem services and relates to risk awareness" [1].

2.4. Methods

We selected ES mapping approaches following Martínez-Harms and Balvanera (2012) [52], Grêt-Regamey et al. (2015) [24], and the MAES Methods Explorer [53]. We chose (1) the expert-based ES matrix approach, (2) simple GIS mapping with proxy indicators and data, and (3) InVEST models as an example of more complex assessments. The results from simple GIS mapping and InVEST models were classified into the six 0–5 classes to face comparison with the expert estimates from the expert-based ES matrix approach. The classification was done manually and followed the recommendations by Burkhard et al. (2017) [27] and Schumacher et al. (2021) [30] (see Supplementary Materials S1).

If possible, we assessed and mapped ES supply and demand for all selected ES. We used ArcGIS Pro 2.9 for data preparation, mapping, and analysis. Table 2 shows an overview of the methods and indicators used. The following subsection briefly describes the methods used. More detailed descriptions of the data, indicators, methods, and InVEST models used are provided in Supplementary Materials S1.

2.4.1. Method 1: Expert-Based ES Matrix Approach

The experts' estimates for ES supply and demand were collected with an empty matrix during topical workshops in Rostock and Munich [22,23], which followed the methodology for the ES matrix approach based on expert knowledge [54]. The matrix was structured as follows: The columns described selected ES, and the rows the thematic LULC classes of Urban Atlas (see Supplementary Materials S1). Local stakeholders were invited to estimate ES supply and demand using the scale 0–5 (from no relevant ES supply/demand to very high). Additionally, the participants were asked to score their confidence in their knowledge of each ES and LULC class using the scale 0–5 (very uncertain—very certain) [55]. Following Campagne et al. (2017) [55], we analysed the estimates using simple descriptive statistics and weighted the mean values with confidence scores. After that, a joint discussion among workshop participants took place. During these guided discussions, we took notes, clustered main arguments, and used them to interpret the results.

Table 2. Overview of the methods and indicators used to map ES supply and demand.

	Expert-Based ES Matrix Approach		Simple GIS Mapping		InVEST Models	
Ecosystem Services	**Supply**	**Demand**	**Supply**	**Demand**	**Supply**	**Demand**
Food (from cultivated terrestrial plants)	Expert estimates	Expert estimates	Agricultural area (%)	Population density (Inhabitants ha^{-1})	-	-
Raw materials (from cultivated terrestrial plants)	Expert estimates	Expert estimates	Forest area (%)	Population density (Inhabitants ha^{-1})	-	-
Pollination	Expert estimates	Expert estimates	-	Dependence of crops on pollination by insects (%)	Pollinator abundance (Index 0 to 1, dimensionless)	-
Local climate regulation	Expert estimates	Expert estimates	Green and blue areas (%); *f*-evapotranspiration (*f*-ETP) (Index 0 to 1, dimensionless)	Surface emissivity (Index 0 to 1, dimensionless)	Heat mitigation (Index 0 to 1, dimensionless)	Air temperature (Index 0 to 1, dimensionless)
Coastal protection [1]	Expert estimates	Expert estimates	-	Coastal flood risk for the asset: human health, the environment, infrastructure and human economic activities (Index 0 to 5, dimensionless)	-	-

[1] Only mapped for the urban region of Rostock.

2.4.2. Method 2: Simple GIS Mapping

We used proxy indicators that relied only on a single data source: LULC, literature, or statistical data. Unfortunately, no suitable proxy data for assessing the ES supply for pollination or coastal protection could be found. The demand for coastal protection could be mapped with four different proxy indicators, representing the flood risk for the assets of human health, environment, infrastructure, and human economic activities [56].

2.4.3. Method 3: InVEST Models

For the selected ES, the following InVEST models are available:

- Food (from cultivated terrestrial plants): Crop Production [57];
- Pollination: Pollinator Abundance: Crop Pollination [57];
- Locale climate regulation: Urban Cooling [58];
- Coastal protection: Coastal Vulnerability [59].

However, owing to data availability reasons, we could only test the InVEST models Pollinator Abundance: Crop Pollination and Urban Cooling in more detail. More detailed descriptions of the InVEST models used are provided in Supplementary Materials S1. For mapping ES supply of and demand for raw materials, there are no InVEST models yet available [40].

2.4.4. Map Comparisons

The spatial differences between expert estimates and ES values from simple GIS mapping and InVEST models were detected through map comparisons. We compared the maps by calculating a similarity index for each ES. First, we normalised the expert estimates to a scale between 0 and 1 and converted each map into a raster (cell size: 10 ha). The calculation of the similarity index followed three steps [60]:

$$s(map_a, map_b) = map_a - map_b \quad (1)$$

where s represents the similarity values of map_a and map_b [60]. The absolute difference (s2) between map_a and map_b was calculated using:

$$s2(map_a, map_b) = con(s(map_a, map_b) < 0, s(map_a, map_b)^* -1, s(map_a, map_b)) \quad (2)$$

The absolute difference values were switched to similarity values using:

$$\text{Similarity index} = 1 - s2(map_a, map_b) \quad (3)$$

3. Results

Several challenges were encountered with all tested methods in both urban regions during the mapping processes. This resulted in different mapping outcomes of varying quality depending on the ES and the method used (see Table 3). The following subsections describe the results in more detail.

Table 3. Overview of the mapping outcomes. Method 1: Expert-based ES matrix approach, Method 2 = proxy indicators and data, Method 3 = InVEST models; Mapping outcome: yes = ES component could be mapped, yes * = ES component could be mapped, but not for the whole case-study region, no = ES component could not be mapped.

	Expert-Based ES Matrix Approach		**Simple GIS Mapping**		**InVEST Models**	
Ecosystem Services	**Supply**	**Demand**	**Supply**	**Demand**	**Supply**	**Demand**
Food (from cultivated terrestrial plants)	yes	no	yes	yes	no	no
Raw materials (from cultivated terrestrial plants)	yes	no	yes	yes	no	no
Pollination	yes	no	no	yes *	yes	no
Local climate regulation	yes	no	yes	yes	yes	yes *
Coastal protection [1]	yes	no	no	yes *	no	no

[1] Only mapped for the Rostock urban region.

3.1. Method 1: Expert-Based ES Matrix Approach

3.1.1. ES Supply

Fifteen local stakeholders had filled in the ES supply matrix for the urban region of Rostock, and twelve local stakeholders for the urban region of Munich (Supplementary Materials S2). The experts' estimates showed to be similar for the selected provisioning ES. They differed for some LULC types, such as open vegetation areas. Estimates for regulating and maintenance services tended to be less consistent for some LULC types (e.g., flood protection in urban green areas). Participants representing the urban region of Rostock gave divergent estimations for the ES flood and coastal protection, which may indicate a comprehension issue for this ES.

Figure 2 shows the spatial pattern of ES supply. Overall, the maps show an urban–rural pattern, for example, low ES supply in built-up areas and high or very high in less anthropogenically altered areas such as forests or open vegetation areas. Furthermore, the results show that some ES, such as food, are strongly linked with specific LULC types.

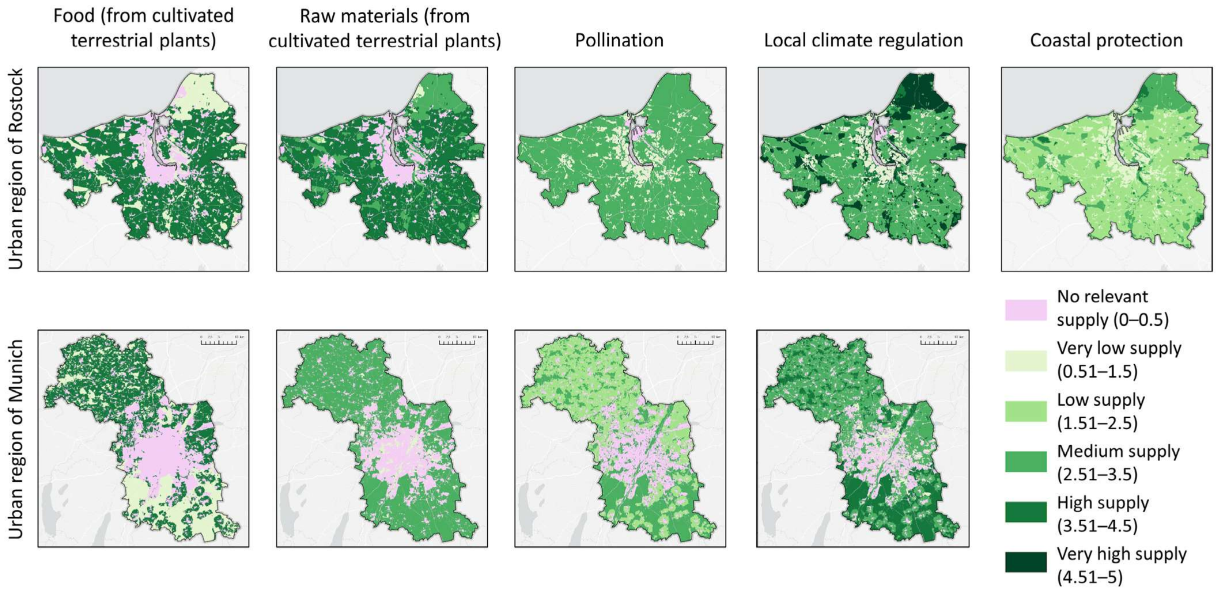

Figure 2. ES supply of food (from cultivated terrestrial plants), raw materials (from cultivated terrestrial plants), pollination, local climate regulation, and coastal protection. The expert estimates ranged from no relevant supply (0) to very high supply (5). The highest ES supply (5) is shown in dark green, and the lowest ES supply (0) is in pink. Based on data from Urban Atlas [44]. Larger maps are provided in Supplementary Materials S2.

Local stakeholders showed interest in the ES matrix approach and gave relevant feedback. For example, the participants suggested using more differentiated LULC data, especially in urban areas. Furthermore, they stated that estimations on a regional scale were difficult, as the urban regions contain rather heterogeneous landscapes. The participants from the urban region of Rostock requested the inclusion of coastal areas and the Baltic Sea and a more decisive distinction between coastal protection and flood protection.

3.1.2. ES Demand

The local stakeholders had difficulties comprehending the term ES demand and preferred not to fill in the blank matrix. As the ES demand matrices were missing, we could not generate maps indicating the spatial distribution of ES demand with this approach. Instead, joint discussions took place on ES demand. The workshop participants mentioned the following points during follow-up discussions as the biggest obstacles that made confident estimates via the expert-based ES matrix approach difficult:

- For non-ES experts, the definition of ES demand was hard to understand.
- The ES demand can be expressed by society, stakeholder groups, or individuals through wishes, values and norms, use or consumption patterns, or the need for risk reduction/prevention and increased security against natural hazards [15,56]. The stakeholders were divided on which perspective and types of demand should be considered.
- Stakeholders found it challenging to estimate ES demand within the selected LULC, as they felt that demand originated from people and markets and not from the specific LULC types.
- It was unclear how to estimate ES demand for provisioning ES, such as food, whose goods and products are transported and used worldwide. In this case, the stakeholders questioned whether a regional assessment of ES supply and demand would be helpful.

- Stakeholders found it challenging to estimate the demand for regulating ES at a regional scale due to the more local scope of many ecosystem processes and functions that are underlying regulating ES.
- The study regions were considered too large and too heterogeneous. The participants from the urban region of Munich especially emphasised this point.

3.2. Method 2: Simple GIS Mapping

ES supply and demand were mapped with proxy indicators and data. The maps visualise distinctive spatial patterns and can potentially reflect service-providing or service-demanding areas. Figure 3 shows exemplary the ES supply of and demand for *food* using the indicators agricultural areas (%) and population density (inhabitants ha^{-1}), respectively.

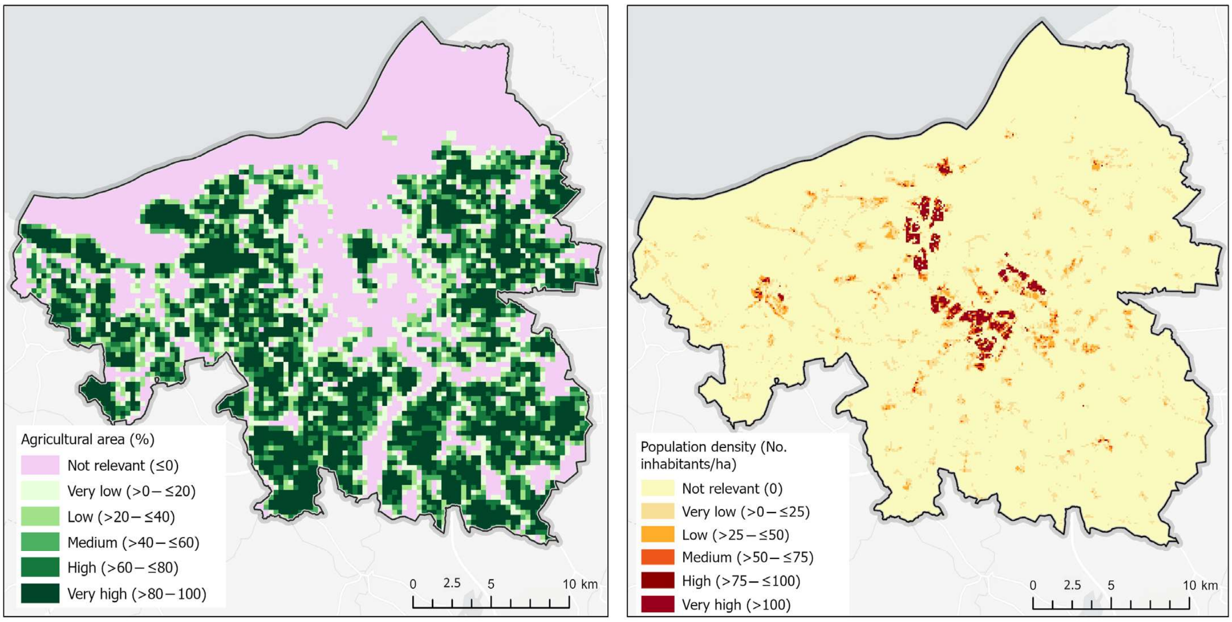

Figure 3. Spatial patterns of ES supply of and demand for food (from cultivated terrestrial plants) in the urban region of Rostock. ES supply and demand have been mapped using the indicators agricultural areas (%) and population density (inhabitants ha^{-1}), respectively.

Several proxy indicators for coastal protection were used (see Figure 4). Those indicators express coastal flood risks for different protected assets (human health, infrastructure, environment, and human economic activities). In addition, the maps show detailed results of the assets at risk of coastal flooding at a local scale. The results highlight that ES demand can be located differently depending on the chosen indicator.

3.3. Method 3: InVEST

Only the InVEST models Pollinator Abundance: Crop Pollination and Urban Cooling could be run. Both models provided site-explicit results. Figure 5 shows exemplary the spatial patterns of potential ES supply for pollination, indicated with the indicator pollinator abundance (index). In both urban regions, only a few areas have medium to high ES supply. These areas are located in the most heterogeneous landscapes of urban regions. The models Crop Production [57] and Coastal Vulnerability [59] could have been suitable for mapping food and coastal protection, respectively. Furthermore, the model Pollinator Abundance: Crop Pollination provides an indicator for mapping ES demand. However, these models or indicators could not be calculated due to data availability reasons.

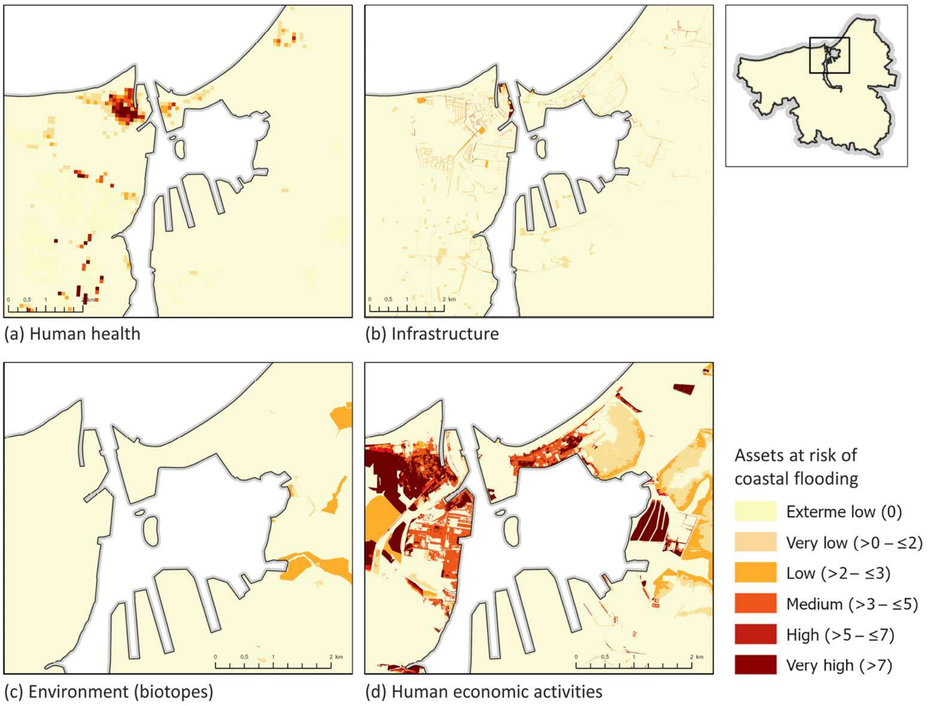

Figure 4. Spatial patterns of ES demand for coastal protection. The proxy indicators express coastal flood risks for different protected assets: (**a**) human health, (**b**) infrastructure, (**c**) environment (biotopes), and (**d**) human economic activities. The maps show the risks of a coastal flood event with a statistical 200-year recurrence interval in the harbour area of the city of Rostock.

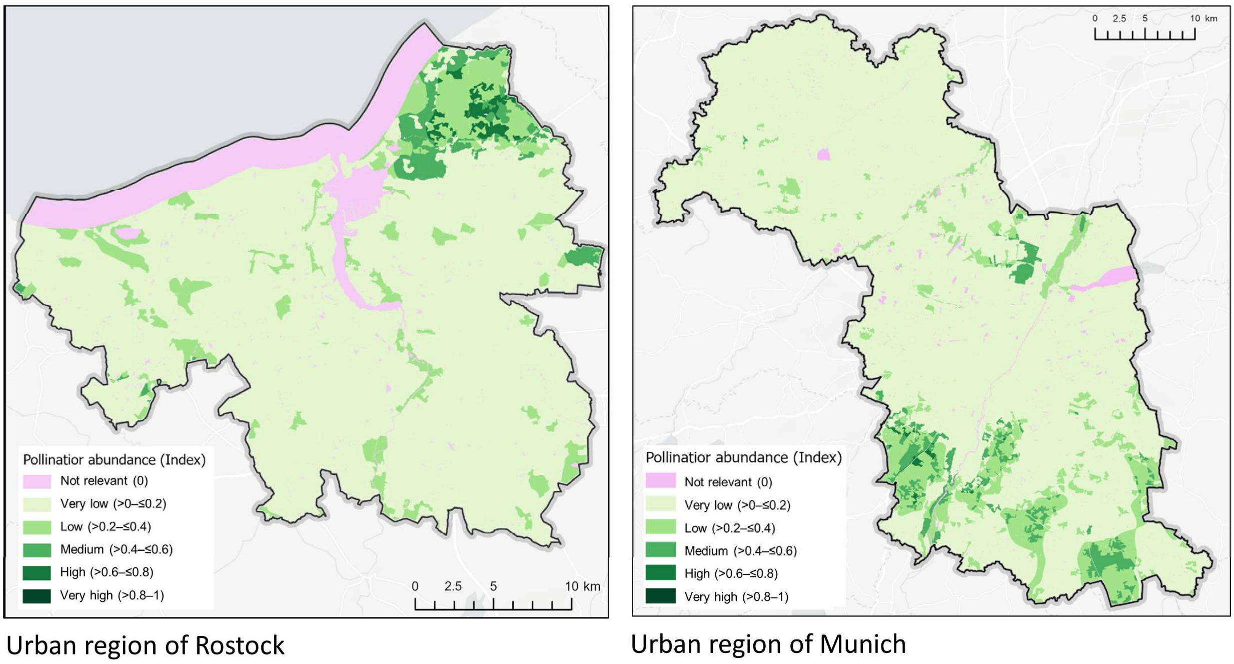

Figure 5. Spatial patterns of pollination supply in the urban regions of Rostock and Munich, modelled with the InVEST model Pollinator Abundance: Crop Pollination.

3.4. Map Comparison (Example: Local Climate Regulation)

We tested the spatial similarity between the expert estimates (results from the expert-based matrix approach), simple GIS mapping using proxy indicators and data, and InVEST models. In this section, we show exemplary results for *local climate regulation* in the urban region of Munich. Overall, the expert estimates differ to varying degrees from the other results (see Table 4 and Figure 6). The comparison between the expert estimates and the indicator green and blue area (%) (mean: 0.63), as well as between the expert estimates and InVEST results, expressed with the indicator heat mitigation index (mean: 0.69), show low spatial similarities. However, in both map comparisons, the spatial dissimilarities are distributed differently: The major dissimilarities are located in the case-study regions' rural areas, whereas anthropogenically influenced areas show higher spatial similarity (see also Supplementary Materials S2).

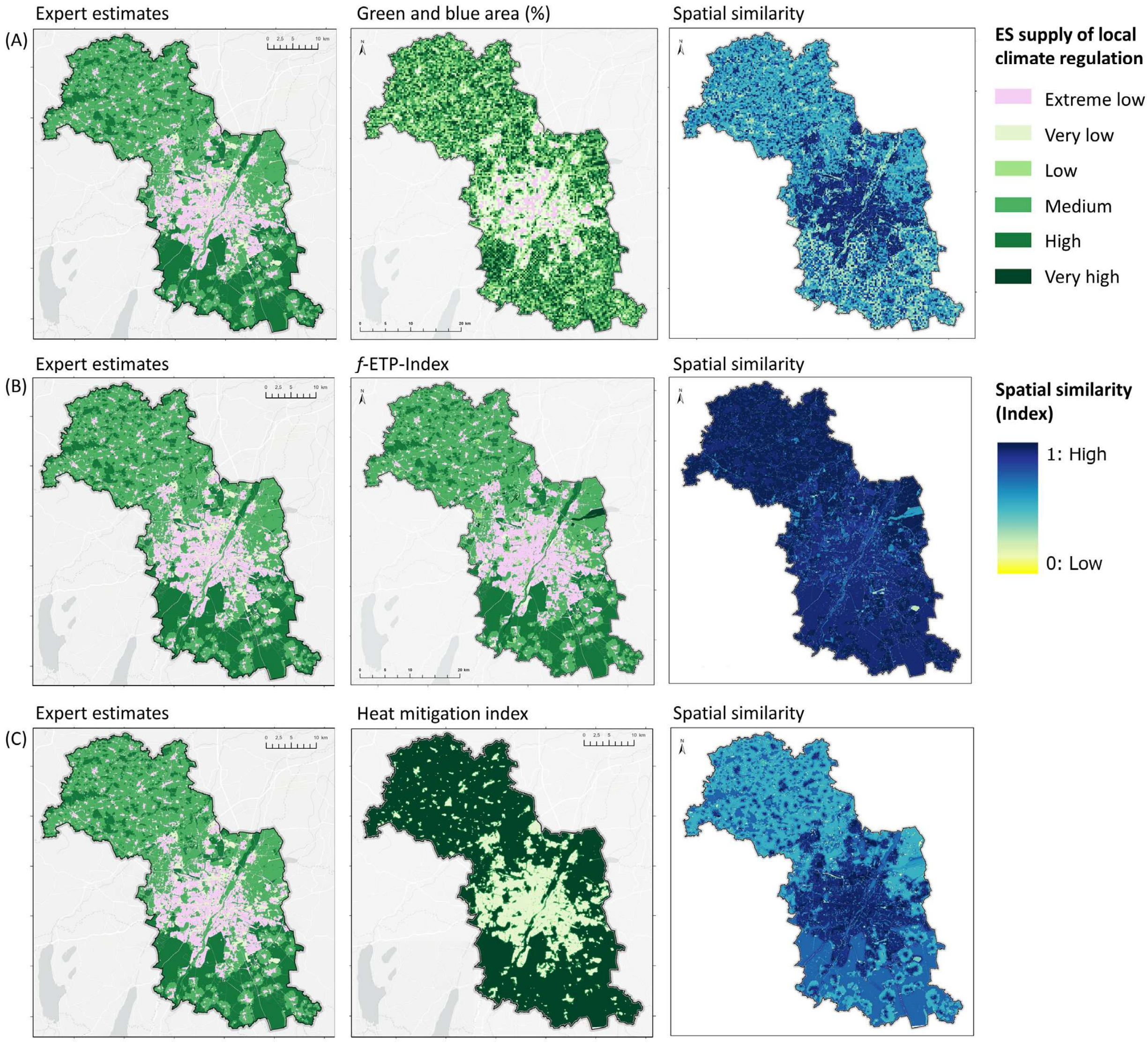

Figure 6. Map comparisons between the expert estimates (expert-based ES matrix approach) and the indicators (**A**) green and blue area (%) (LULC data); (**B**) *f*-ETP-Index (literature data); (**C**) heat mitigation index (InVEST model Urban Cooling). The highest spatial similarity value (1) is shown in dark blue, and the lowest (0) is in yellow.

Table 4. Similarity values of the map comparison between the maps from expert estimates (expert-based ES matrix approach) and the indicators (A) green and blue area (%) (LULC data); (B) *f*-ETP-Index (literature data); (C) heat mitigation index (InVEST model Urban Cooling) in the urban region of Munich. Values: 0 indicates no similarity, and 1 very high similarity between the compared maps.

		A	B	C
Local Climate Regulation Indicator		**Green and Blue Area (%)**	***f*-ETP-Index**	**Heat Mitigation Index**
Similarity index	Mean	0.63	0.91	0.69
	Std. Dev.	0.22	0.12	0.17

High spatial similarity can be identified between expert estimates and indicator *f*-ETP (mean: 0.91). Both the expert estimates and the values of the indicator *f*-ETP were provided for each LULC type. The same data basis can explain the high degree of spatial similarity. However, the result also shows differences, especially in the LULC types water bodies and urban green spaces (see also Supplementary Materials S2).

4. Discussion

We aimed to map ES supply and demand with different ES relevant to the urban regions of Rostock and Munich. The information was needed for communicating and awareness-raising of the ES concept with local stakeholders during workshops and online meetings. We chose several easy-to-apply methods and tested their applicability in two case-study areas. During the ES mapping exercises, we dealt with challenges such as barriers related to understanding problems of the ES concept itself and the impact of data availability on selecting indicators and methods. These challenges, also known as "bottlenecks" [61], are well-known obstacles in ES mapping and have affected the mapping results to varying degrees.

4.1. How Useful Are Commonly Used ES Mapping Approaches in Regional Urban Contexts and What Major Obstacles to Their Application Did We Encounter?

4.1.1. Method 1: Expert-Based ES Matrix Approach

In the last 10–15 years, the ES matrix approach has been tested and updated in many applications [28]. Overall, the expert-based ES matrix approach has been appreciated for its comparably simple and fast technique that provides spatially explicit results on ES supply and demand [27,28,35]. We can only partially agree with this statement, as we could only record expert estimates for ES supply. ES demand can be expressed through different perspectives and demand types [62,63]. Consequently, there are broad possibilities for understanding ES demand [64]. This complexity hindered the local stakeholders' making confident and comparable estimates [22].

Other uncertainties and limitations of the expert-based ES matrix approach are well documented, addressing, alongside other factors, the simplicity of application, experts and panel composition, statistical analyses, geodata used, and size of the case-study area [28,30,65,66]. The latter point was mentioned as a concern in both urban regions, as it reduced the confidence of local stakeholders. Furthermore, Campagne et al. (2017) elaborated that an expert panel size of at least 15 expert estimates is needed to provide reliable expert estimates [55]. Looking at the expert estimates for ES supply, the small number of local stakeholders who participated in Munich (n = 12) and Rostock (n = 15) can be a factor of uncertainty [66,67].

4.1.2. Method 2: Simple GIS Mapping

The simple GIS mapping with proxy indicators and data provided quick results, which show important spatial landscape information of ES supply and demand in the case-study areas. However, we faced obstacles in finding simple, suitable and recommended proxy indicators, and ES-related data for the regional scale.

Several indicators and data sets were of interest in the indicator selection process but could not be used since the needed data were unavailable/inaccessible or unsuitable for regional mapping. For example, the EU-wide working group Mapping and Assessment of Ecosystem and their Services (MAES) recommend well-tested indicators such as crop yield production, wood increment, or timber harvest [20,68], which are also integrated into the SEEA-EA framework [17]. For those indicators, national statistical data are freely available. This data are, however, too coarse to show the spatial patterns of ES supply or demand in the two urban regions [68,69]. Alternatively, we could have used the underlying high-resolution data from the local authorities. These data are, however, expensive or not easily accessible due to data protection reasons [63,70,71]. We could also map the MAES-recommended indicator dependence of crops on pollination by insects [20]. However, the corresponding literature data [72] can only be linked to cultivated crops on agricultural land. Hence, gapless mapping on the urban regional scale was not possible with this indicator.

Since we could not rely on the well-tested and recommended indicators for our selected ES, we used other alternative indicators and data. One of the simplest ways to map ES supply and demand is by using LULC types [36], despite its limited information content [66]. For example, the proportion of agricultural areas (%) can be linked to food supply (see Figure 3). This indicator cannot, however, communicate whether the areas are actually used for food cultivation, nor can the results show whether the land is being used sustainably [73]. Furthermore, using only certain LULC types as predictor variables neglects the capacity of other LULC types to provide ES [29]. Using highly generalised LULC types may not be appropriate for other ES, such as pollination or coastal protection. In these examples, more specific data on habitats, biotopes, or coastal ecosystems would be beneficial for informative ES mapping [30,74].

A transfer of ES values from literature data provides the opportunity to quickly generate cost-effective maps without using complex models. For this option, however, literature data need to be available for the respective ES in the first place. Suitable literature data were—to our knowledge—only available for the proxy indicators *f*-ETP and surface emissivity. The values originate from a study in Leipzig, Germany [75], and have been used in several urban case-study areas in Europe [76]. These two indicators also have the advantage of being available for the same datasets, similar spatial scales, and comparable units. This allows further ES mismatch analyses, which could indicate unsustainable use or inequitable distribution of ES [64,77]. However, for value transfer, the initial detailed modelling results were strongly generalised, which reduces the information content [75]. Furthermore, literature data only assumes that the ES values can be applied to case-study areas, even if the study purposes, temporal or spatial scales, data sources, or context-specific conditions differ [66].

Population density is an often used proxy indicator for visualising potential source–sink patterns [33,62]. We used this indicator for mapping demand for several ES, e.g., food or raw materials. However, ES demand is multifaceted and can cover desires/needs for specific attributes of ES or relates to risk awareness [1,64]. Using the same indicator for assessing and mapping the demand for several ES strongly reduces its inherent complexity. In comparison, the manifold patterns of ES demand for coastal protection had been mapped by considering the specific flood risks for protected assets (see Figure 4). The indicators (see Table 2) have the additional advantage that they are directly linked to the EU Floods Directive (Directive 2007/60/EC) [56,78].

4.1.3. Method 3: InVEST Models

The two tested InVEST models performed well in detecting spatial patterns of the individual ES and provided results with higher spatial resolution. The models can analyse how various parameters influence the supply of the respective ES [65]. For example, the model Pollinator Abundance: Crop Pollination calculates potential habitats and distribution of pollinating insects in a landscape [79]. Our results show that pollinator abundance is high in heterogeneous landscapes and low in homogenous agricultural areas. The results are, therefore, suitable to explain that ES supply can be increased by diversifying landscapes with insect-friendly structural elements.

The InVEST model Urban Cooling includes, in addition to LULC types, climate conditions and the distance to and size of urban green areas, and considers the possible spatial patterns of urban heat islands [58]. The modelled heat mitigation index can inform local stakeholders about the increased cooling capacity of larger urban parks and connected green infrastructure [12]. However, this model does not, for example, integrate the amount and/or the structure of green area quantifiably. Therefore, the results show no heat mitigation differences for forests or agricultural areas in the surroundings of the case-study area and might not be suitable for estimating the supply of local climate regulation on a regional scale.

Both tested models have several methodological uncertainties and limitations, which address the rule-based methodological design and the limited capability for calibration and validation [12,43,79]. As for all model computations, the input data resolution and quality affect the results strongly [65]. As mentioned in the results, we could not run the models Coastal Vulnerability, Crop Production, and the demand component of Pollinator Abundance: Crop Pollination due to data availability reasons.

4.1.4. Map Comparisons

Model results are often interpreted as "more correct" than the results of proxies or expert estimates, even if the accuracy, input data, or reliability of the models used are questionable [80]. However, the map comparisons show that the expert-based ES matrix approach can detect similar spatial patterns of ES supply on the regional scale. Dissimilarities can be explained by the proxy indicator chosen and its informational content, different spatial resolutions of the data sources, and the calculations within the InVEST model Urban Cooling [58]. The model results show no heat mitigation differences on nonurban LULC types, which can explain the greater spatial dissimilarities on those areas.

4.2. How Can Our Experiences Help Inform Future Research and Related Application Perspectives in ES Mapping?

Overall, mapping ES supply and demand at the spatial scale and resolution of urban and periurban areas was challenging for all methodological approaches. We could only map ES supply and demand for some selected ES with simple GIS mapping using proxy indicators and data, or with InVEST model outcomes. Recommended and tested indicators and accessible data were, unfortunately, still missing [64]. Comparably simple ES models such as InVEST provide—if available for the selected ES and spatial scale—more site-specific results. The results show more deeply the interactions between the ES components and/or socioecological processes in the chosen case-study areas. However, running the models demands time and is data intensive, and already requires an in-depth understanding of the respective ES.

The most decisive advantage of the expert-based ES matrix approach is that this approach provides opportunities for communication and discussions with local stakeholders as early as during the collection of the expert estimates. Dialogue between science and policy are important to capture local stakeholders' and decision-makers' interests and needs [9,61,67]. For instance, the local stakeholders questioned the point of mapping ES demand for provisioning ES (such as food), as the demand cannot be reduced easily through, for example, urban or regional planning instruments. Overall, the multifaceted nature of ES demand proved to be a hurdle in participatory ES mapping approaches. For future expert-based ES matrix applications, we recommend alternative methodological designs that use questionnaires and joint discussions instead of a blank matrix. Overall, the discussions on ES demand revealed that this component needs a clarified understanding and further research. Despite the drawbacks on the subject of ES demand, the workshops and discussions were of high relevance (and perhaps equally important than the final maps [67]), as they helped to promote a better understanding of the ES concept amongst the local stakeholders [28,41,81].

It would be advantageous to utilise better the connections to existing legislations or consolidated approaches within the ES concept. Using ES indicators and data [78,82], which are also applied in policies such as the EU Floods Directive (Directive 2007/60/EC), can increase the impact of the ES concept together with the understanding and acceptance of the results amongst local stakeholders [56]. Furthermore, other approaches, such as lifecycle assessments [83–85], ecological footprints [86,87], or the emergy evaluation methodology [88,89], have been developed and broadly applied to highlight the contribution of nature and the origin of the natural resources used or the impacts of human activities on natural resources. In particular, lifecycle assessments and ecological footprints are excellent communication and awareness-raising tools [89]. The methodologies could be used as alternative approaches for assessing the teleconnections between urban and periurban areas [90], ES flows [91,92], and ES demand for provisioning ES and selected regulating and cultural ES [84]. Initial ideas for an integration of the lifecycle assessment or ecological footprints into the ES cascade framework exist, but still need to be developed further [85,93]. For greater impact in spatial planning and governance processes, site-specific results at different spatial scales and the integration of further ES are needed [89,93].

5. Conclusions

This study summarised conceptual and methodological challenges that entailed applying different ES supply and demand mapping approaches during a research project in Germany. The expert-based ES matrix approach provided results on ES supply and detected comparable distinctive spatial ES supply patterns. However, the conceptual complexity of ES demand hampered the participants in making confident estimates on the subject of ES demand. Nevertheless, dialogues with practitioners and local stakeholders were important to capture interests and needs as well as existing barriers that impact the use of the ES concept in real-world decisions.

Simple GIS mapping with proxy indicator and data and the use of InVEST models were accompanied by barriers related to indicator selection, method, and data unavailability/inaccessibility. Recommended and well-tested indicators, which can be applied relatively quickly with simple mapping approaches, are still missing for many ES. These approaches are needed when overviews about ES-related topics are requested for communication and awareness-raising, and when time and/or financial constraints prevent a more in-depth analysis. Future research needs to provide more agreed indicators together with standardised quantification methods to enable both ES supply and demand assessments on comparable spatial scales. With this study and by sharing our experience in mapping selected ES with commonly applied methods, we hope to contribute to fill the gap between scientific state-of-the-art contributions and actual user needs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010052/s1, S1: Table S1. Data used for the ES supply/demand mapping and assessments. Table S2. Overview of the indicators, methods, and categorisation used. If possible, indicators were mapped at a regional scale. Table S3. Overview of the indicators used in the ES modelling. If possible, indicators were mapped at a regional scale. Table S4. Selected LULC classes from CORINE Land Cover (CLC) and Urban Atlas. Table S5. Biophysical table, adapted from Zulian et al. (2013). Marked LULC (*) shows adjusted values for the Urban Atlas dataset. Table S6. Guide table for the InVEST model Pollinator Abundance: Crop Pollination. Table S7. Pollination dependencies (%) of crops that could grow on selected LULC (adapted from Zulian et al. (2013)). Table S8. Biophysical table for the InVEST model Urban Cooling, urban region of Munich. Table S9. Biophysical table for the InVEST model Urban Cooling, urban region of Rostock. Table S10. Classification of flood hazard. Tables S11–S14. Classification of the potential damage for the asset human health, environment, infrastructure, and economic activities. Table S15. Classification of the coastal flood risks into six ES classes. Figure S1. Standardised Kc values for CORINE Land Cover and Urban Atlas, adapted from Nistor (2018 and 2016). S2: Table S16. Expert-based ES matrix approach, ES supply, urban region of Rostock, n = 15. Weighted mean values. Table S17. Expert-based ES matrix approach, ES supply, urban region of Munich, n = 12. Weighted mean values. Tables S18–S20. Similarity values of the map comparison between the maps from expert estimates (expert-based ES matrix approach) and the indicator (A) green and blue area (%) (LULC data), (B) *f*-ETP-Index (literature data), (C) heat mitigation index (InVEST model Urban Cooling) in the urban region of Munich. The value 0 indicates no similarity, and 1 very high similarity between the compared maps. Figures S2–S6. Expert estimates of ES food (from cultivated terrestrial plants), raw materials (from cultivated terrestrial plants), pollination, local climate regulation, and, flood and coastal protection. Urban region of Rostock. Figures S7–S10. Expert estimates of ES food (from cultivated terrestrial plants), raw materials (from cultivated terrestrial plants), pollination, and, local climate regulation. Urban region of Munich. Figure S11. Food (from cultivated terrestrial plants). Indicator: Agricultural area (%). Urban region of Rostock. Figure S12. Food (from cultivated terrestrial plants). Indicator: Population density (Inhabitants ha^{-1}). Urban region of Rostock. Figure S13. Pollination. Indicator: Pollinator Abundance (Index 0 to 1). Urban region of Rostock. Figure S14. Pollination. Indicator: Pollinator Abundance (Index 0 to 1). Urban region of Munich. Figures S15–S18. Coastal protection, mapped with the indicators: Human health at risk of coastal flooding; Infrastructure at risk of coastal flooding; Environment (biotopes) at risk of coastal flooding; Human economic activities at risk of coastal flooding. Urban region of Rostock. Figure S19. Local climate regulation. Indicator: Green and blue area (%). Urban region of Munich. Figure S20. Local climate regulation. Indicator: f-evapotranspiration (f-ETP) (Index 0 to 1). Urban region of Munich. Figure S21. Local climate regulation. Indicator: Heat mitigation (Index 0 to 1). Urban region of Munich. References [94–111] are cited in the supplementary materials.

Author Contributions: Conceptualization, C.D. and B.B.; methodology, C.D.; software, C.D.; formal analysis, C.D.; investigation, C.D.; resources, C.D.; data curation, C.D.; writing—original draft preparation, C.D.; writing—review and editing, C.D. and B.B.; visualization, C.D.; supervision, C.D.; project administration, C.D. and B.B.; funding acquisition, B.B. All authors have read and agreed to the published version of the manuscript.

Funding: The Federal German Ministry of Education and Research (BMBF) funded the OESKKIP research project within the framework of the strategy 'Research for Sustainability' (FONA—Forschung für Nachhaltige Entwicklung) (FKZ 16LC1604B).

Data Availability Statement: Publicly available datasets were analysed in this study. These data can be found here: Eurostat. 2022. Countries. Available online: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries#countries20 (accessed on 2 April 2022). European Environment Agency. 2016. Urban Atlas 2012. Available online: https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012?tab=metadata (accessed on 2 April 2022). European Environment Agency. 2019. Corine Land Cover (CLC) 2012. Available online: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012?tab=metadata (accessed on 2 April 2022). Statistisches Bundesamt. 2015. Ergebnisse des Zensus 2011 zum Download—erweitert. Available online: https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html;jsessionid=6E45AA84910CD1717DDD8A2D100A5DE1.1_cid380?nn=3065474 (accessed on 2 April 2022). Bundesamt für Kartographie und Geodäsie. 2020. Geographische Gitter für Deutschland in Lambert-Projektion (GeoGitter Inspire). Available online: https://gdz.bkg.bund.de/index.php/default/digitale-geodaten.html (accessed on 2 April 2022). European Environment Agency. 2018. Tree Cover Density. Available online: https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density (accessed on 2 April 2022). Climate Data Center. 2020. Datensatzbeschreibung. Monatliche Raster der potenziellen Evapotranspiration über Gras, Version 0.x. Available online: https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/evapo_p/BESCHREIBUNG_gridsgermany_monthly_evapo_p_de.pdf (accessed on 2 April 2022). Climate Data Center. 2019. Berechnete monatliche Werte von charakteristischen Elementen aus dem Boden und dem Pflanzenbestand., Version v19.3. Available online: https://opendata.dwd.de/climate_environment/CDC/derived_germany/soil/monthly/historical/BESCHREIBUNG_derivgermany_soil_monthly_historical_de.pdf (accessed on 2 April 2022). Climate Data Center. 2018. Historische tägliche Stationsbeobachtungen (Temperatur, Druck, Niederschlag, Sonnenscheindauer, etc.) für Deutschland. Available online: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical/ (accessed on 2 April 2022). Yale University. 2019. Global Surface UHI Explorer. Available online: https://yceo.yale.edu/research/

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Acknowledgments: We would like to thank the whole OESKKIP project team and the participating stakeholders for their highly valuable contributions. Many thanks go to Thea Wübbelmann and Nadja Kabisch for helpful discussions and to Ann Cruickshank and Matthew Cruickshank for English proofreading.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Chapter 5

Lessons learned from implementing the ecosystem services concept in urban planning

Grunewald, K., Bastian, O., Louda, J., Arcidiacono, A., Brzoska, P., Bue, M., Cetin, N.I., Dworczyk, C., Dubova, L., Fitch, A., Jones, L., La Rosa, D., Mascarenhas, A., Ronchi, S., Schlaepfer, M.A., Sikorska, D., Tezer, A.

Ecosystem Services (2021) 49, 101273. https://doi.org/10.1016/j.ecoser.2021.101273

Figure 14. Urban water bodies and vegetation help to regulate the local climate in cities during hot summers. Photo: Jolanta Dworczyk.

Ecosystem Services 49 (2021) 101273

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

Lessons learned from implementing the ecosystem services concept in urban planning

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A R T I C L E I N F O

Keywords:
Decision-making
Green-blue infrastructure
Practitioners' perspective
Scientists' perspective
Urban nature

A B S T R A C T

This paper presents a summary of lessons learned from implementing the ecosystem services (ES) approach into urban planning practice in different European urban settings. We summarise a survey co-created with, and presented to, researchers and end-users in city administrations from ten European case study cities. To complement the expert analysis, 14 semi-structured interviews were conducted among stakeholders to assess the use of ES in practice in urban settings. There was strong agreement between scientists and practitioners on both the

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https://doi.org/10.1016/j.ecoser.2021.101273
Received 30 May 2020; Received in revised form 8 March 2021; Accepted 9 March 2021

opportunities and the barriers to uptake the ES concept in urban planning practice. Key agreements were that the ES concept supports decision-making as well as spatial planning, it is most useful as a communication tool, and monetarisation and public pressure can be considered as promoting factors. Barriers are lack of evidence including case studies, standardised methods and criteria to evaluate nature and its benefits, lack of legislations/reform, limited capacity and reluctance to apply ES in planning practice, and limited public involvement. On individual aspects, such as the monetarisation of ES, views differed both among the scientists and the practitioners. Derived from our investigations we summarize in which circumstances the ES concept is most relevant and useful for urban planners and decision-makers.

1. Introduction

Urban nature provides various ecosystem services (ES) that are a basic prerequisite for the quality of life in cities (e.g., Gómez-Baggethun et al., 2013; Kabisch et al., 2015; Artmann et al., 2017; Grunewald and Bastian, 2017; Orta Ortiz and Geneletti, 2018; Scott et al., 2018; Breuste et al., 2020; Palliwoda et al., 2020). Urban nature refers here to urban green and blue spaces (GBS) ranging from the remnants of natural ecosystems, human-designed nature typically found in urban public spaces, such as parks or allotment gardens, and informal green spaces such as wildflower meadows, vacant lots or roadside vegetation (Kowarik, 2005; Sikorska et al., 2020). Blue spaces refer to waters and their surroundings including more or less artificial ones such as channels or ponds. In this context, GBS can be regarded as natural capital – stocks yielding flows of ES, from which people derive benefits (Bateman and Mace, 2020).

ES can be derived by humans both directly and indirectly from GBS, and an increasing number of studies indicate a link between ES provisioning and health and well-being of residents (Bertram and Rehdanz, 2015; Jones et al., 2016; Twohig-Bennett and Jones, 2018). All kinds of GBS and the ES they provide are a common good for society that all citizens should equally benefit from (UN, 2015). In practice, there are winners and losers and the ES generated involve trade-offs according to desired outcomes (Martín-López et al., 2014; Turkelboom et al., 2018). Thus, a key challenge for strategic planning (being it spatial, landscape or urban planning) is to ensure that the urban environment can sustain a stable flow of ES, while promoting equal access to GBS and the goods and services they provide (Scott et al., 2018; Hersperger et al., 2020; Wende et al., 2020).

Urban socio-ecological systems are highly complex and embrace multiple interactions between economic, social and ecological processes (Alberti, 2005; Beichler et al., 2017). Production and consumption, demand and supply of ES interact in the urban environment, where their reciprocal linkages are not only spatiotemporally explicit but also non-linear, determined by the large existence of built and social capital. Such complex interactions make the future of urban areas mostly unpredictable, therefore challenging scientific approaches to anticipate future trends (Xiang, 2013; Kaczorowska et al., 2016; Batty, 2018). In addition, options and challenges for ensuring the flow of ES depend on scales of responsibility and policy actions (Grunewald and Bastian, 2015). A crucial question is how to use the ES concept to improve urban planning, and to steer and manage urban development processes in order to provide favourable living conditions and minimize or avoid negative socio-economic and environmental impacts (Bateman et al., 2013; Paudyal et al., 2016). Another question is whether the ES concept can make a contribution in terms of a comprehensive socio-ecological transformation (Abson et al., 2014; Wolfram et al., 2019; Avelino et al., 2020).

Despite a recent explosion of scientific interest in urban socio-ecological systems (Andersson et al., 2019) and increasing evidence of GBS potential to provide benefits to rising city populations, the range of opportunities, barriers, and needs remains largely unexplored. There is a growing body of literature attempting to integrate ES into landscape and urban planning, management and decision-making (see for example Beaumont et al., 2017; Brzoska and Spāģe, 2020; de Groot et al., 2010; Geneletti et al., 2020; Grêt-Regamey et al., 2017; Haase et al., 2014; Hegetschweiler et al., 2017; Macháč et al., 2020; Scott et al., 2013; Von Haaren et al., 2020). However, few studies (as Scott et al., 2018) contrast the theoretical approach with the degree of implementation from the practitioners' point of view. Although practitioners generally agree on the potential of the ES concept to improve urban planning, they struggle with several complexities and operational limitations inherent to implementing the ES approach. Gaps might exist between practitioners' perceptions and actual implementation (Albert et al., 2014a, 2014b; Mascarenhas et al., 2014; Rall et al., 2015). Also, the empirical data across different urban planning contexts suggests the need to identify common lessons learned from real-world examples and hence support theoretical advancement (e.g., Ruckelshaus et al., 2015).

Against this background, the aim of this article is to assess the practical implementation of the ES concept in current urban planning and decision-making. It aims to answer three main questions:

1. In which cases is the ES concept most relevant or useful to urban planners?
2. To what extent is the ES concept already integrated into urban planning?
3. What are the barriers, opportunities, and needs for uptake of the ES concept?

The assessment combines two components, exploring the perspective of both scientists working on ES in an urban setting, and practitioners responsible for landscape and urban planning and decision-making. We gathered scientific experts' views in a dedicated session at the regional Ecosystem Services Partnership (ESP) Conference in San Sebastian, Spain, in 2018, which we supplemented by follow up discussions and joint work over an extended period; the practitioners' views we gathered through semi-structured interviews in ten cities/city-regions of seven European countries, which acted as case studies for this research.

We then integrated the views from scientific experts with the opinions and needs of practitioners and provided recommendations for an improved implementation of the ES concept in urban planning, structured to cover different categories. We are convinced that sharing experiences and good practices with other cities/city regions can improve the credibility and usability of the ES approach.

2. Methodological approach

To assess the practical implementation of the ES concept in urban planning and decision-making, we developed the methodological approach shown in Fig. 1 and further detailed in the following sections.

2.1. Scientific experts' perspective

We investigated the views of researchers, considered to be the scientific experts in ecosystem services studies during the ESP conference session entitled "Implementation of the ecosystem services concept for urban planning and development". The session was devoted to current state, knowledge, experiences, indicators, and tools but also deficits and challenges in terms of the ES concept and its practical application in urban planning and spatial decision-making. The views from seventeen

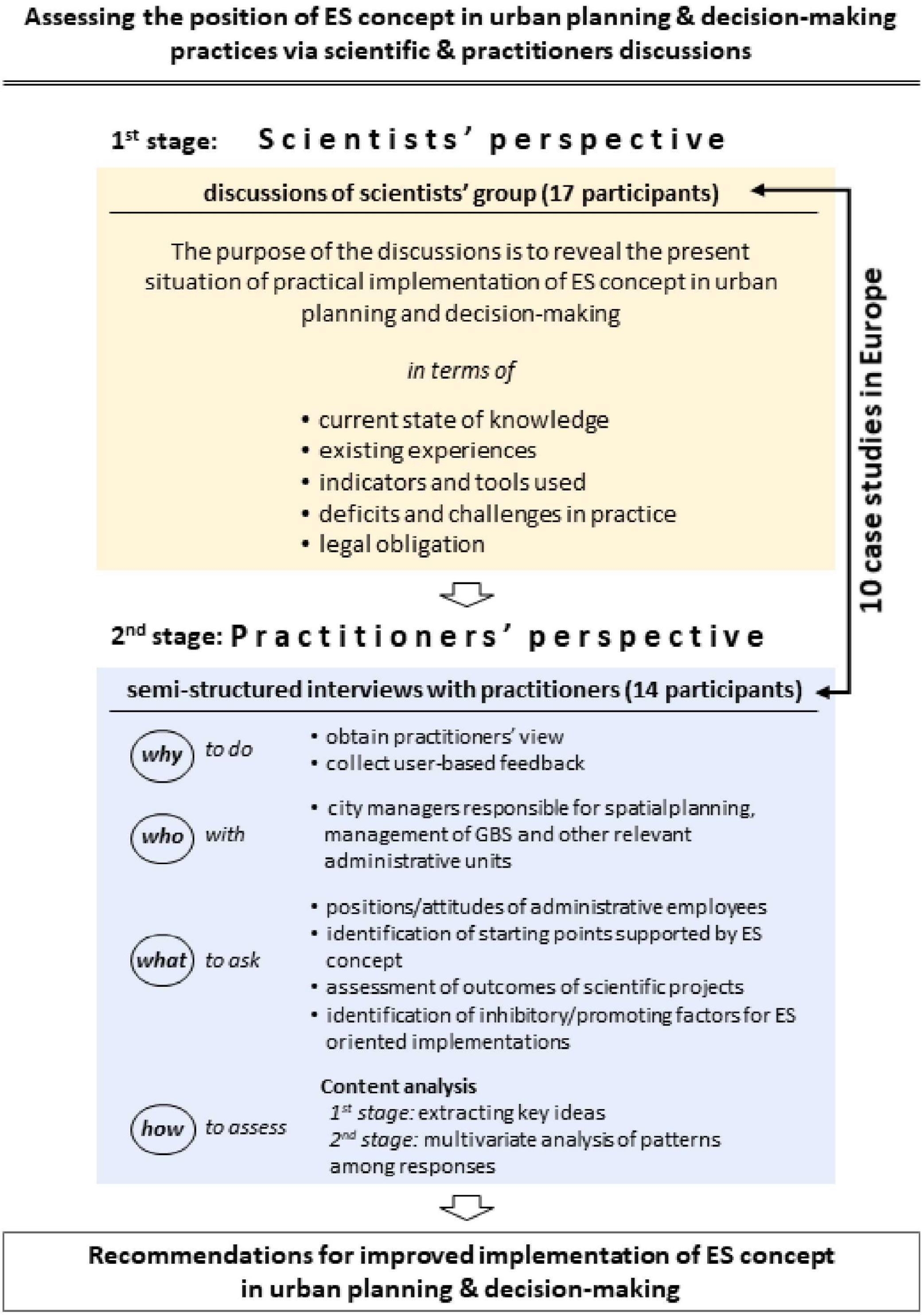

Fig. 1. Research design & methodological approach.

scientific experts, mainly from European countries, were presented. We asked these participants to provide case study examples exploring the degree to which the application of the ES concept had been helpful for specific ecological urban planning issues in cooperation with administrations and decision-makers. The session collated the perspectives of the diverse set of urban scientists on the key questions of the study. From this exercise, key aspects related to the application of the ES concept were bundled (concepts, spatial and temporal approaches, dimensions such as planning, economy, education).

2.2. Case studies

To explore these issues in more detail we selected ten case studies, covering a wide range of spatial scales, size of population, and geographic and climatic conditions across Europe (Table 1, Fig. 2). Contextual information for each local case study supporting this research was systematically collected (Table 2).

Additionally, a brief overview of the state of implementation of the ES concept, including the legally binding character, was prepared for the countries where the case studies and interviews (see next section) were conducted and thus these experiences could be incorporated (Supplementary material B).

2.3. Practitioners' perspective

A survey of practitioners' views was conducted by the case study investigators to obtain the perspective of those likely to be using and implementing ES approaches, which may be a very different perspective from that of the scientists. The survey targeted practitioners working in environmental management and planning authorities, covering different departments and responsibilities. Views on the implementation of the ES concept by practitioners were collected through semi-structured interviews in the case cities. The interview protocol was structured around issues such as ascertaining the level of awareness and knowledge of the integrative ES concept and the perceived level of current integration in urban planning documents or environmental assessments (cf. Mascarenhas et al., 2014). It is important to understand areas with plan led systems as opposed to development led systems, as this significantly affects how the ES concept might be used in decision-making. Plan led systems, such as those in Germany (Wende et al., 2020), means that the ES concept – if embedded – will be a statutory requirement. In development led systems, for instance those in UK, the ES concept is a material consideration only (Scott et al., 2013, 2018).

Table 1
Overview of case study urban areas.

Code	City/City-region (Country)	Spatial scale*	Size of studied area	Population (in 2019)
CS1	Istanbul (Turkey)	Very large metropolitan area	5461 km^2	15.52 million
CS2	Lisbon (Portugal)	Large metropolitan area	3015 km^2	2.8 million**
CS3	Munich (Germany)	Large metropolitan area	1550 km^2	over 1.9 million**
CS4	Łódź (Poland)	Metropolitan area	293 km^2	700,000
CS5	Dresden (Germany)	Metropolitan area	404 km^2	560,000
CS6	Geneva (Switzerland)	Metropolitan area	282 km^2	501,750
CS7	Rostock (Germany)	Medium-sized urban area	670 km^2	275,000
CS8	Liberec (Czech Rep.)	Small-sized urban area	106 km^2	104,000
CS9	Rescaldina (Italy)	Very small urban area	8 km^2	14,200
CS10	Ragalna (Italy)	Very small urban area	40 km^2	9000

*after classification of OECD (https://data.oecd.org/popregion/urban-population-by-city-size.htm).
** Referring to year 2018.

In each case study, we identified and contacted individuals responsible or involved in the urban planning process, the management of green spaces and related aspects, and where an ES approach could be implemented. In most cities it was possible to select decision-makers, managers or other practitioners from different sectors such as Environmental Agencies, Regional Planning Authorities, City Planning Offices, and Offices for Green Space, as well as Mayor/Municipal Environmental Politicians who agreed to participate in the survey. This was useful for providing recommendations on different aspects of urban planning.

The main objectives (O)/questions (Q) used in the survey were as follows:

A) O: Working out of positions/attitudes of administrative employees towards the ES concept (Q1: What do you think about the ES concept in general? Is it necessary or useful for political/administrative actors of the city administration in the implementation or decision-making processes?)
B) O: Identification of starting points/structures of daily work, which can be enriched/supported by the ES concept (Q2: What requirements/requests do you have with regard to ES/biodiversity (nature in the city)? In which concrete instruments do you see possible applications?)
C) O: Assessment of the outcome of scientific case studies/projects (Q3: To what extent are the outcomes/results of ES-assessments relevant (added value) for environmental agencies/authorities and other sectors?)
D) O: Identification of inhibitory/promoting factors for the implementation of the ES concept at municipal administration level (Q4a: Which inhibitory/promoting factors do you see? Q4b: What suggestions do you have regarding fields of application?)

We transcribed the interviews and performed the content analysis (Adams, 2015), following with the extraction and summary of the key points from the interview responses using an unbiased, common language. In order to avoid bias by having a single person conducting the analysis, multiple assessors were involved in the process. The first synthesis of the interviews was conducted by the interviewers themselves who extracted large sections of text around each question, which contained key elements of the interview response. The extraction of key themes from this text was then conducted in parallel by two independent assessors. The two assessors then met together to harmonize their assessments to a common set of phrases. This produced an initial list of 115 phrases across the four questions, with some themes emerging across questions and phrased the same. The list of 115 phrases was then sent back to the original interviewer for a third check on correct interpretation of the interview content. The phrases were subsequently grouped into a maximum of eleven higher-level themes per question, prior to analysis using multivariate approaches to determine commonalities and differences in the responses across the interviews (Supplementary material A, Table A6).

Each of the four questions was analysed separately, with question 4 also split into two parts, each analysed separately. For questions 1–3, each higher-level theme was quantised (process of transforming coded qualitative data into quantitative data, Tashakkori and Teddlie, 1998) by assigning a score of "1" if the participant provided a response that was categorised under that theme with negative views, a score of "2" if the participant had not answered or provided a response with mixed opinions and a score of "3" if the participant provided a response that was categorised under that theme with positive views. For questions 4a and 4b a score of "2" was assigned if the participant provided a response that was categorised under that theme and a score of "1" otherwise.

To derive the key points made by practitioners on the implementation of the ES concept and take into account the discrete nature of the

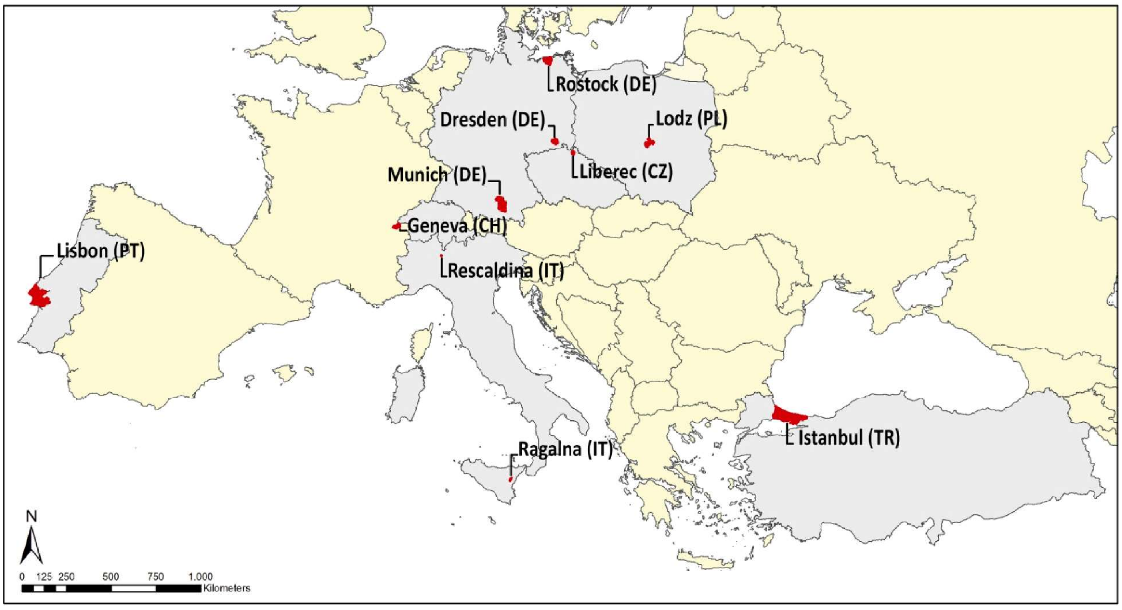

Fig. 2. Locations of the case study areas.

Table 2
Formal code sheet for the description of case studies.

Aspects
City name, country and administrative character (region, administrative city, district)
Responsible person, main contact person (name, e-mail); involved partners, institutions
Focus of the study/application: (a) objective, keywords, (b) ES term/concept explicitly used? (c) investigated ecosystem types and the ES categories/classes, (d) sponsors of the study
Analytical approach: (a) qualitative description and evaluation of ES (non-numeric/ ordinal scaled statements) or/and (b) physical quantitative description and evaluation of ES or/and (c) monetary valuation of ES
Main results, products
Success factors, limitations

data (Kolenikov and Angeles, 2004), a principal component analysis (PCA) based on a polychoric (or tetrachoric if binary data e.g. questions 4a and b) correlation matrix was conducted for each question. Both the eigenvalue-one criterion (Kaiser, 1960) and scree test (Cattell, 1966) were used to determine the number of components selected for PCA interpretation (Supplementary material A). For clarity, only the first two components (PC1 and PC2) were presented and illustrated for each question. Statistical analysis was performed using R 3.5.0 (Team R Core, 2018) and the psych packages (V1.9.12; Revelle, 2019).

3. Results

3.1. Five statements regarding the ES integration in urban planning as a result of the ESP session

Analysis of the statements of the session contributors showed that there was high heterogeneity in the understanding and actual use of the ES concept, which is in line with the literature (e.g., Albert et al., 2014a, 2014b; Mascarenhas et al., 2014; Hansen et al., 2015; Lam and Conway, 2018).

(1) Scientists and practitioners acknowledge ES as an innovative concept to deliver urban planning solutions

ES help to provide arguments for urban planning decisions aimed at environmental conservation (i.e. green space protection and design; limit of soil sealing; biodiversity protection and increase), and better planning/design of new urban areas or rehabilitation of urban ecosystems. A crucial issue to be addressed in contemporary urban contexts is the dichotomy between the pursuit for urban compactness (to limit further urban sprawling) and the demand for new greenery or increased access to it.

These arguments are often based on multiple benefits derived from nature that can be quantified via ES (e)valuation. Improved information on benefits and costs (including opportunity costs – or benefits foregone) can increase the consensus on planning decisions aimed at the protection or increase of the urban ecosystem services. Participatory planning approaches tend to be more successful (i.e. with citizen participation for issues such as identification of preferred equipment/services in parks), and ES can help to communicate the importance of GBS and raise awareness of a wide range of benefits derived by urban ecosystems (see also Mascarenhas et al., 2016).

(2) ES concept and related terminology are still far from reaching a common consensus

Many terms (i.e. ecosystem services, natural capital, green–blue infrastructure, nature-based solutions, well-being, nature's contributions to people, ecological functions and benefits, landscape functions) are often used in an inter-exchangeable and unclear way. This is particularly evident for practitioners or other technical individuals involved in urban decision-making (planners, municipality politicians, officials or technicians), who are not very familiar with the concept of ES, or have never heard of it. Some administrations are characterised by having a lack of experts, inadequate personnel, and a lack of economic resources or appropriate data for the assessment. There is a frequent resistance and inertia in innovating "established" structures and processes, as administrators or technicians might prefer a consolidated approach in urban planning ("continue-as-before"), especially if they are also sceptical towards the added value or novelty of ES (an old idea in new words).

(3) the use of ES in spatial planning and practices at different scales is limited but increasing

The practical use of ES in spatial planning is increasing and involves planning processes at different scales, ranging from urban regions, municipalities of different size to neighborhoods (as residential gardens, street greenery), therefore including different ecosystems or ecological spatial units (e.g. hydrological basins, parks, coastal areas, urban–rural interface, peri-urban landscapes), see also Ronchi (2018), Ronchi et al. (2020) and Tezer et al. (2020).

Previous policy efforts at European, national and regional scales aimed at the promotion of ES in policy-making have increased the use of ES in planning processes (Keenan et al., 2019). However, similar to previous findings by Mascarenhas et al. (2015), a direct and explicit reference to ES in planning processes and related documentation is still rare, and in the majority of the cases ES were a simplistic label to encapsulate or reiterate general environmental/ecological objectives or strategies. Furthermore, the added value of the integration of ES is not always explicitly reported or transparently communicated to all stakeholders involved in the planning processes.

(4) diverse challenges in the ES assessment phases are major factors influencing the degree of ES integration in spatial planning

Quantitative approaches to ES assessment such as monetarisation (especially for regulating and cultural services) depend on so many uncertain factors that it is very complicated if not impossible to evaluate them in a sound and replicable way, or no precise economic relation between the ecosystem and the provided services can be found, or valuation rules are missing. Lack of appropriate and systematic data for ES assessment is also a critical issue, especially when assessment scale decreases and fine resolution data become needed (c.f. Davidson, 2013; La Rosa et al., 2016).

Furthermore, reliability of assessments changes with the single ES considered (see also Hamel and Bryant, 2017). The highest reliability referring to monetary valuation is attributed to provisioning services (as their calculation is based on market products), while the lowest is attributed to cultural ES (especially those which cannot be connected to tourism). Regulating ES also require complex modelling approaches and are heavily dependent on the assumptions made. Differences in results derived from assessments can be a result of the assessment design and application.

Another crucial dimension of uncertainty is the difficult interpretation of the outputs from ES assessments for decision-makers and local politicians, and their translation in a more direct and understandable way. This point is related to the gap between theory (science generated knowledge) and practice (the application of that knowledge) when policies informed by scientific knowledge do not generate collective benefits (c.f. Walker et al., 2001). An important side-effect of the persistency of this gap is the potential loss of trust in the policy-making process by citizens.

(5) binding legal frameworks are essential to ease the ES integration

The overall legal dimension of ES can cover a wide range of laws, regulations, norms, constraints in the use of the land (i.e. protected areas/habitats/elements) but it is not yet a legal approach nor an official instrument. The lack of integration is also strongly due to the relation between urban planning and national/regional planning systems, which shape the scope and content of each spatial plan, as each country/region has its own planning framework and rules for the design of spatial plans. A normative reform can offer a possible path towards the mainstreaming of this concept to local practitioners and planning administrations, embedding ES through new forms of regulations and planning standards, at least in countries with plan led development systems.

3.2. Implementation of ES in urban planning - case studies from Europe

Ten case studies (Table 1) show examples where the application of the ES concept was helpful for specific ecological urban planning issues in cooperation/acceptance of administrations and politicians/decision-makers. The ES term and ES concept were explicitly used in all studies. Most studies had assessed ES qualitatively and quantitatively, while not all had conducted monetary valuations. According to the different objectives and tasks in the case studies, the products to be developed were also different (Table 3).

Even though the concept of ES has been used by scientists for almost two decades, its practical use in urban planning and decision-making process varies from country to country and from city to city. The respective national and local–regional context is important. Amongst others, a clear distinction between existing concepts and the ES approach is desired by practitioners. As a rule, in a planning context of a country or region, it is decisive whether the ES concept is seen as an "add-on" solution or whether ES is already integrated in the planning process.

For the case studies, we tried to interpret possible impacts of current practices depending on the main outcomes (Table 3). Our basic starting point of this interpretation was to answer the questions of "What could the impacts of the outcome of X in the planning scale of Y be and/or how could it be useful for further processes of planning?" This interpretation supports the tangible explanation of current level of ES and urban planning integration at different spatial scales. Thus, it is clear from Table 3 that current ES practices are mostly at the upper-scale planning level such as regional or metropolitan by mainly aiming to steer or guide subscale planning tools like master plans or development plans. This guiding process is basically carried out by determining blue and green infrastructure networks, ES indicators, zoning, critical ES provision areas, etc. that can directly create tangible impacts on planning applications. On the other side, small scale (local/neighborhood level) practices are still in the process of raising awareness of stakeholders, therefore, it is difficult to mention ES based urban planning practices in municipalities of small-sized cities or districts.

There are examples in some cities, particularly in Central and Eastern Europe, where the integration of ES in urban planning has recently started; as reported for cases CS8 (Liberec) and CS4 (Łódź, Tables 3 and 4). Many of these cities have experienced a socio-economic transition from a centrally-planned to a market economy, and a management shift from entirely top-down to participatory (Shkaruba et al., 2017). For emerging economies, the situation is more challenging. Actors of the market economy often have close relationships with policy-makers and central authorities, which can foster urban projects (i.e. spatial development projects) and therefore hamper the use of ES approaches for sustainable planning of cities (CS1, Istanbul).

In several case studies the scientists and practitioners highlighted the interesting discrepancy between the (scientific) criticism of the monetarisation of ES (critical of the reduction of the highly diverse human-nature-relationship into specific or pre-defined economic categories; see for example Schröter et al. (2014) for a synthesis) and the wishes of practitioners and policy makers to rely on monetarisation of ES, as a powerful tool in the discussion with the public on the benefits that some ecosystems can have for people.

The success factors in the implementation of ecosystem services in urban planning listed in Table 4 show that good contacts, trusting cooperation between scientists, practitioners, planners and administration are essential. Limitations concern the data situation but also political and planning related contexts.

The short overview of the implementation of the ES concept in the case study countries (see Supplementary material B) showed that in Portugal and Switzerland, the ES concept is already explicitly implemented in some of the national, regional and/or municipal strategic policy documents and it is integrated in urban planning activities. In most of the studied countries (Turkey, Germany, Italy and Czech

Table 3
Results/output of case study applications and integration of results in urban planning/decision-making.

Case study (CS), City(see Tab. 1)	Addressed/related planning scale	Main results, products, outcomes	Output integrated in planning process/decision-making	Potential direct/indirect impacts of outputs on other planning instruments (spatial plans, policies and actions)
CS1 Istanbul	Greater Municipality Environmental Master Plan	(i) Determination of critical ES potential areas, which will guide spatial land-use and land-management strategies in the environmental master plan.	Yes	- Developing land-use and land management strategies by considering ES - Guiding regulatory tool for subscale (lower level) spatial plans such as masterplans and local level development plans
CS2 Lisbon	Metropolitan area	(i) Qualitative analysis of ES integration.	No	- Not applicable, as the study was on the integration of ES itself.
CS3 Munich CS7* Rostock	Urban and Regional Plan	(i) Analysing formal and informal planning documents as well as participatory processes relating to ES (ii) Determining ES integration potential in planning instruments (iii) Assessing appropriate indicators for urban ES, which can then be used in urban and regional planning (iv) Brochures for planning practitioners, administrators, decision-makers and the public; information event and exhibition (about ES and biodiversity)	Yes	- Identifying connecting points for linking the ES approach to regional and urban planning - Increasing awareness and knowledge of planners, decision-makers/local politicians and public about ES
CS4 Łódź	City of Łódź	(i) Implementing "Blue-Green-Network" concept into city's Integrated Development Strategy (coherent network of urban and metropolitan green areas including sports facilities, public recreation, areas as well as natural areas) (ii) Setting threshold values in the masterplan for Łódź for green areas accessibility standards – minimal distance to green space for each inhabitant and area available (iii) Recreational ES from parks available for the residents in an online map database	Partially, terms "functions and benefits" are used, as ES concept is poorly recognized by the public	- Increasing awareness of public about ES via recreational services of green infrastructure - Developing blue and green infrastructure network in masterplans and monitoring the performances of masterplans via threshold values on urban green space accessibility
CS5 Dresden	Municipal Landscape Plan of Dresden	(i) Brochure for the public, smartphone based guided trail with information of ES for visitors (ii) Recommendations for planners/decision-makers/local politicians	Partly (primarily for the communication process)	- Increasing awareness and knowledge of planners, decision-makers/ local politicians and public about ES
CS6 Geneva	Regional (Canton)	(i) A strategic plan for future tree plantations based on optimizing key ES (ii) Green Infrastructure based on biodiversity, connectivity and ES (iii) Biodiversity Strategy for the Canton of Geneva based explicitly on ES	Yes	- Developing area action plans for tree plantations - Developing action plans for implementation of Biodiversity Strategy - Green infrastructure planning for new projects, policies and zoning laws to ensure the ES based objectives
CS8 Liberec	Municipal Master Plan of Liberec City	(i) Brochure for the public, recommendations for urban planners/decision-makers/local politicians (ii) study on green and blue infrastructure network in the city.	Mainly for communication and raising awareness among decision-makers	- Increasing awareness and knowledge of planners, decision-makers/local politicians and public about ES (blue and green infrastructure) - Developing municipal climate adaptation strategy
CS9 Rescaldina	Municipal Plan	(i) Urban Plan based on ES assessment (The Urban Plan is now approved and in force) (ii) ES were functional for the deployment of a local Green Infrastructure	Yes	- Implementations of ES based spatial decisions via green infrastructure practices
CS10 Ragalna	Municipal Plan	(i) Qualitative evaluation in the report of the plan (ii) Zoning	ES considered (partially) in the final zoning of the Plan	- Increasing awareness of planners, decision-makers/politicians and public about ES in local level - Developing master plans and/or implementing development plans by considering ES potentials

*CS3/CS7 - Munich and Rostock were analyzed together.

Republic) integration of ES in practical planning processes is on a good trajectory but still underdeveloped, the general reason being there is no legal obligation to implement the ES concept into urban planning. In these countries, the ES concept is usually proposed by spatial planners and other stakeholders (on a voluntary basis) as a decision support tool or as an information base for setting strategies (e.g. municipal climate adaptation strategies). In Poland, planners and decision-makers still do not work with the ES concept in a direct way.

3.3. *Synthesis of the interviews with practitioners*

Question 1. "What do you think about the ES concept in general? Is it necessary for political/administrative actors of the city administration?"

Analysis of question 1 is shown in Fig. 3a. The PCA indicated that awareness of ES was closely related to planning and decision-making,

Table 4
Success factors and limitations in the implementation of ES in urban planning within the case studies.

Code/city	Success factors	Limitations
CS1 Istanbul	Scientists and practitioners working together from the beginning. Therefore, practitioners gain experience and knowledge from scientists about new methods and approaches related to ES.	Lack of temporal and site specific ES based quantitative data for different level spatial scales, such as zoning or development scales. Additionally, legal tools of spatial plan making do not have yet an explanatory background for ES integration into spatial plans explicitly.
CS2 Lisbon	Existing contacts with regional planning authority.	Lack of some documented information; Lack of human resources in the administration with deep knowledge/understanding of ES.
CS3 Munich CS7* Rostock	Inter- and transdisciplinary communication and cooperation: bridging the gap between science and practice by integrating actors and experts operating in local and regional planning practice (science-praxis dialogue); Identifying connecting points for linking the ES approach to regional and urban planning by analysing formal and informal planning documents analysing participatory planning processes; Enhanced consciousness on relevance and importance of ES in planning.	Since the ES concept is not yet a legal approach or an official planning input, broad involvement of regional (planning) actors is limited; ES is not recognized as a concept in the administrative process; Lack of data for appropriate and comparable quantification of supply and demand of all selected ES in both study areas.
CS4 Łódź	Cooperation of scientists, local policy makers and other practitioners. Currently a general willingness from administration to integrate ES into spatial planning (translated into some national-level planning policies). Support from the research community sought by municipal institutions.	Often changing political representation in the city which has different priorities (urban greenery is not always the main priority), lack of data (in comparison to other countries), most of the practitioners are not familiar with the ES concept and it has no support in the legal documents.
CS5 Dresden	Scientists and practitioners working together from the beginning.	Lack of data for some approaches; ES not yet a legal approach, not an official instrument; no recognised concept in the administrative process.
CS6 Geneva	Scientists and practitioners working together from the beginning. Technical positions (e.g., GIS analysts) shared between state and research institutions. Cohesive informal group creates safe space for experimentation and exchanges.	Lack of data for key ecosystem services (e.g., pollination) and lack of familiarity with concepts by partners.
CS8 Liberec	Constant engagement of the scientists in the planning process and support by the research community (trainings, workshops, sharing data and knowledge), general willingness to integrate ES into planning	Poor recognition of the term by the public, despite the policy-makers are well familiar with the concept, lack of knowledge in the private sector
CS9 Rescaldina	The support of the local administration in the ES implementation for the decision-making process.	Time-consuming process (5 years), most of the decisions depended on the political stability of the administration.
CS10 Ragalna	Protection of ecosystems, which provide regulating ES, is higher.	No spatial explicit assessment; not all categories of ES included (no specific focus on cultural ES); no focus on large forest ecosystems although present in the municipality.

*CS3/CS7 - Munich and Rostock were analyzed together.

for example, "*some politicians, administration officers but also residents are aware of ES*"(Participant 11), "*you have useful indicators that are valid and can be used in the planning process*" (Participant 5). In general, practitioners who were aware of the ES concept agreed that the ES concept supported decision-making as well as spatial planning: "*I can see how the ES concept can potentially help arbitrate broader societal question that relate to natural resources, especially in urban centres*" (Participant 6). Some practitioners were convinced by the benefit of using the ES concept in planning, for instance, the ES concept can be "*the key to address a series of concerns at the level of regional and municipal planning, but also national level*" (Participant 9), "*it is very useful concept for cities*" (Participant 11). Others already used the ES approach as part of upper-level planning studies (Participant 10).

It was also suggested that the ES concept was useful for decision-making and in some cases "*is already in the language of the local decision-makers*" (Participant 9). The evaluation of benefits provided by the ES concept appeared to be an important aspect for decision-making as it can " *[…] help in argumentation at all levels (officers, politics, public)*" (participant 11).

Some practitioners felt the ES concept could be useful as a communication tool to promote the benefits of nature: "*I see it as a kind of communication concept*" (Participant 1), "[the ES concept could be] *very beneficial for the city's administration, especially in communicating to the citizens how we can use nature for reducing costs of city's functioning*" (Participant 7). However, the analysis separated interviewees who thought it was useful for decision-making and planning, from those who thought it was most useful as a communication tool. As such, some practitioners saw the potential of the ES approach to "*promote activities based on nature*" (Participant 7), while others believed ES could be "*a good way to communicate some of the planning choices*" but not vital for planning processes: "*We have relied for decades on planning processes without ES*" (Participant 14). Some practitioners also referred to the ES concept as "*an idea*" but the lack of legislation in urban planning meant that the ES concept was not applied in practice (Participant 8).

Practitioners who stated the valuation of nature through monetarisation often found the public could play an important role in ES implementation (e.g. public pressure), but found the ES concept difficult to implement and appeared less likely to adopt it (e.g. willingness). For instance, "*It would be very beneficial if the benefits provided by urban nature would be systematically quantified on the city level […] ES assessment and valuation is very complex and needs effort from wide range of experts (multidisciplinary approaches are not very common in public administration)*" (Participant 11). Only two practitioners were sceptical about monetarisation because it "*[…] is not effective in politics*" (Participant 4) and there is no "*meaningful benefit for the administration*" (Participant 1) to value nature through monetarisation.

There was no clear relationship between the opinion of practitioners towards the ES concept and the size of the city they belong to, or in relation to their associated role (Fig. 3a).

Question 2. "What requirements/requests do you have with regard to ES/biodiversity (nature in the city)? In which concrete instruments do you see possible applications?)"

Fig. 3b shows the groupings for question 2. As for question 1, practitioners who stated a system of monetarisation for the valuation of nature often found the ES concept challenging to implement, due for instance to the limited capacity: "*One has already noticed that the many different systems, that the enormous amount of effort required in administration, in mediation, also with the decision-makers, and even more so with the public […]. If that would succeed in bringing the ecological flank into the process via monetarisation, then that would certainly be helpful*" (Participant 5), and requires more funding: "*the […] sector should be adequately funded to meet the growing demands*" (Participant 3). Similar to question 1, there was a divergence among those who thought the concept helped with implementation and decision-making versus those who thought it most useful as a communication tool. Practitioners who were less willing to apply the ES concept often suggested the need for more evidence, such

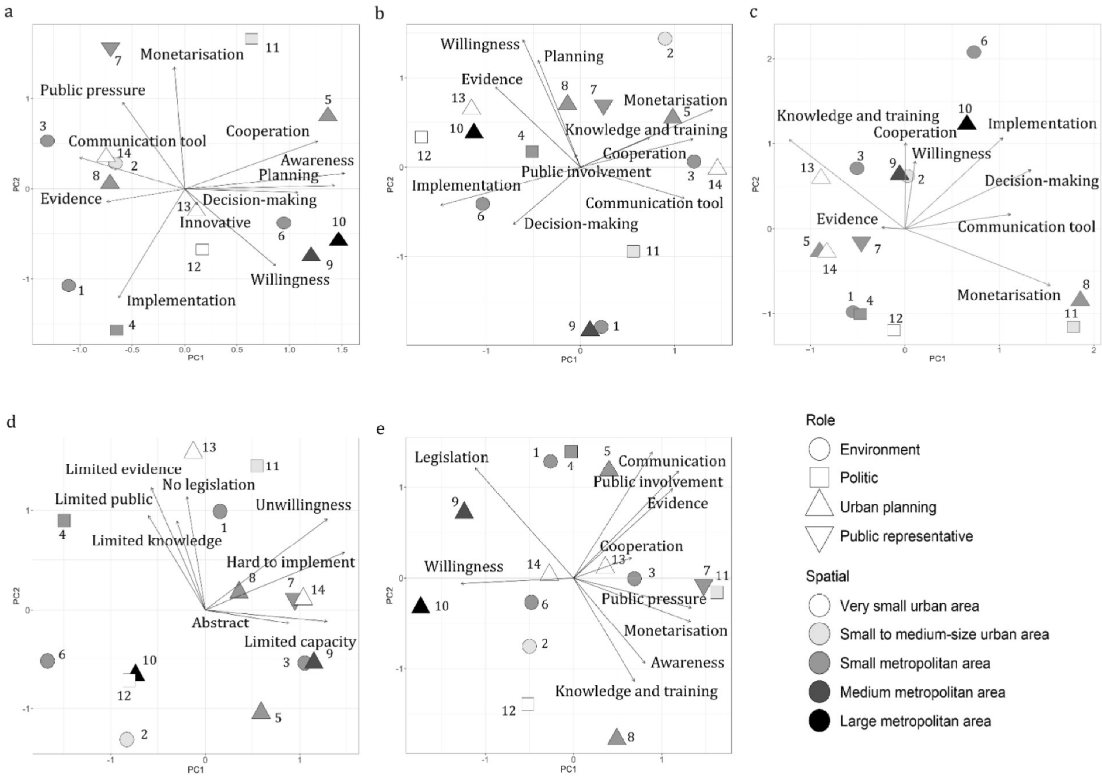

Fig. 3. PCA analysis (only the first two components PC1 and PC2 are presented, see also Supplementary material A) of responses to: a) Question 1 - perceptions of the ES concept, b) Question 2 - the role of ES and biodiversity in urban planning, c) Question 3 - to what extent the outcomes/results of ES-assessments are relevant for different stakeholders, d) Question 4a - the inhibiting and e) Question 4b - the promoting factors from application of the ES concept. Role of the interviewees is indicated by symbols. Shade of grey indicates the spatial scale from small urban area to large metropolitan area (light to dark). Each category (arrow) points in the direction of the positive concept associated with it (a-c) or inhibiting/promoting factors ES application (d-e). Numbers refer to each participant.

as stronger scientific arguments, standardised methods and criteria to value nature, and more case-study examples. No clear pattern was observed between the size of the city or the role of the participant and the requirement with regards to ES (Fig. 3b).

Question 3. "To what extent are the outcomes/results of ES-assessments relevant (added value) for environmental agencies/authorities and other sectors?"

Analysis of responses to question 3 are shown in Fig. 3c. ES assessment appeared to be valuable for decision-making as mentioned by some practitioners: "*This helps decision-makers take such ecosystem services into consideration*" (Participant 6), "*The outcomes of scientific studies provide a directive knowledge for decision-makers like us*" (Participant 10).

Monetarisation was again an important theme with some practitioners believing that ES assessment was "*important in relating benefits from nature with monetary value*" and this exercise could help in negotiations with the public (Participant 8).

As a communication tool, some practitioners indicated having difficulties in translating scientific reports into the language of their own field as illustrated in these following statements: "*Expanding your knowledge base is always useful. There is always a problem when the scientific results are to be incorporated into concrete urban planning work. You have to give it extra thought*" (Participant 5), "*Unfortunately usability of scientific outputs very much depends on erudition of employees [...] for most departments the outputs are often too much scientific*" (Participant 11), "*The ES-based approach requires a change in the traditional planning procedure with results and outputs different from the most common ones and, therefore, it is not always easy to understand the benefits in the use of ES*" (Participant 12).

Knowledge of and training on the ES concept was an important driver of differences between areas of expertise. As such, practitioners from political authorities often highlighted the need for comprehensive knowledge and training of the ES concept as well as case study examples (evidence) in order to understand ES assessments: "*It would help, if the scientific outputs would be developed in close collaboration with city officers (of course if they are willing to collaborate)*" (Participant 11), "*The presence of other experiences concerning the use of ES for planning purposes could be very important for the local administrators to have practical evidence of the opportunities*" (Participant 12).

For this question, there was a clear differentiation in responses according to the role of interviewees (Fig. 3c). Practitioners from environmental agencies and urban planning were mostly located in the top part of the biplot, while politicians such as mayors were positioned closer to the bottom part of the biplot. This pattern may suggest that ES assessment is more favourably received by environmental and urban planning employees than political authorities, and may raise an issue of knowledge transfer between different areas of expertise. Since we researched the relevance of ES assessment for practical urban planning and environmental management, from our point of view it did not make sense to include scientists view. Scientists who are dealing with ES assessment are convinced the assessment outputs are relevant and useful for environmental and urban planning authorities (see Section 3.1). There was no clear relationship between size of the city and the relevance of ES-assessments.

Question 4.

A. Which inhibitory factors do you see? What suggestions do you have regarding fields of application?

Three broad groups of categories could be distinguished from the biplot (Fig. 3d). The first group included limited evidence and methods, limited knowledge and training, no legislation and limited public involvement (high on Axis 2). The second and third groups represented categories related to the implementation of ES, with difficulties to implement and unwillingness to apply ES concept belonging to the second group (independent of the two first axes), and limited capacity and abstract concept for the third group (high on Axis 1).

Participants who highlighted the difficulties in implementation often listed the limited capacity and reluctance to apply ES concept. For instance, a practitioner with public expertise stated: "*I can say that the concept seldom finds support from the administrative bodies. In order to implement it would require extra effort from a given person and broadening their knowledge, which taking into account multiple constraints is little likely*" (Participant 7), and this is further supported by the following statement from a practitioner with urban planning expertise: "*Another possible inhibiting factor is a mismatch between the timing when the plans are developed and the funding opportunities that allow implementing some planning measures on the ground*" (Participant 9).

Most participants stated that the concept of ES was too abstract, challenging to understand the scientific output, and often highlighted the existence of a language barrier. For example, "*In terms of some topics/sub-topics, I hope the representation of ES can do some good*" (Participant 1), "*In our case study, the lack of other experiences has made the process more difficult because we did not understand what the results and outputs could be. The ES assessment was a little bit clear, but the planning application was only theoretical*" (Participant 13), "*Also availability of information mostly in English language is also an obstacle*" (Participant 7).

The lack of legislations/reform was highlighted across several practitioners from various areas of expertise, including environmental practitioners, those with a political role and those dealing with the public. For instance, "*Once the consideration of ecosystem services is enshrined in a law or other mandatory tool, architects and consultants will take them into consideration more explicitly and earlier in their thinking*" (Participant 6), "*In order to achieve the effect in a larger scale – legal implementation is necessary*" (Participant 7).

Additionally, the lack of evidence including case studies, standardised methods and criteria to evaluate nature appeared to be another important barrier to ES application as stated by several employees: "*Yes, it is fundamental to have case studies and best practices in Italy (but also in other contexts) to have clear evidence on the opportunities and positive impacts in the adoption of an ES-based approach for planning purposes*" (Participant 13).

Another possible barrier was the limited public involvement, and this was particularly highlighted by interviewees with a political role as shown with the following statement: "*It is very important to find ways how to influence the broad public – not preach to the converted. Scientific outputs are unfortunately not the best way … these outputs should be presented in an attractive way (i.e. short video with some famous actor, article by recognized journalist etc.)*" (Participant 11).

Relationships between size of the city and the potential inhibiting factors of ES implementation were weak (Fig. 3d). However, there was an indication that politicians held stronger views about the lack of evidence, knowledge and the legislation to back this up.

A. Which promoting factors do you see? What suggestions do you have regarding fields of application?

Analysis is shown in Fig. 3e. Monetarisation and public pressure were both cited as promoting factors. For instance by the full range of participant roles: "*Easy to apply measures or cost estimates that we could use would be needed*" (Participant 7), and by political authorities: "*Monetary valuation is a relatively simple way, how to express the benefits using one simple indicator/value […] The monetarisation is a great basis for negotiations*" (Participant 11).

Several participants suggested that ES application could be greatly enhanced by improved communication, which is supported by analysis of previous questions. Knowledge/training was stated by politicians and urban planners as an important promoting factor for ES application. For instance, an employee of urban planning expertise mentioned: "*I believe that it is essential to organise a training course, specifically dedicated to them [ES], to spread the knowledge on environmental protection and to learn the competencies and skills*" (Participant 13), while a local government official stated: "*My suggestion is to invest in constant and continuous training of technicians/employees of municipal offices in order to give them the instruments and knowledge to integrate ES in planning*" (Participant 12).

There was a weak relationship between the size of the city and the promoting factors for ES application stated by employees (Fig. 3e). Several practitioners from all spatial scales, excluding medium and large metropolitan areas, highlighted the importance of the public in promoting the application of ES: "*There is also increasing pressure from citizens to preserve existing greenery. And this is currently on the rise and you can see the feedback from the city administration. This is not a monetary value now, but already the realisation that the city greenery must be given a different status in urban planning*" (Participant 2). No clear pattern was observed among areas of expertise.

4. Discussion

Overall, the results show multiple similarities emerging from the scientific experts' discussions (Section 3.1), the case study applications in the framework of ES projects with practical relevance, i.e. involving actors from the urban administration or other experts in urban planning (Section 3.2), and the semi-structured interviews with practitioners (Section 3.3). Also, we found common emerging themes (Section 3.2, Supplementary material B): mainstreaming of ES, increasing attention to the concept, but hardly anchored explicitly in national legislation.

Although some practitioners, and often local politicians, complain that academics do not always know what is actually necessary and helpful in decision-making practice on the ground, there were hardly any contrasting views on the usefulness of the ES concept. Only a few interview participants stated that the concept of ES would be too abstract, that it was challenging to understand the scientific output, or highlighted the existence of a language barrier. On individual aspects, such as the monetarisation of ES, views differed both among the scientists and the practitioners. In principle, almost everyone sees monetarisation as useful. But the scientists stress that it is difficult or even impossible to make "objective" monetarisation of ES (see 'challenges in the ES assessment' in Section 3.1), which aligns with findings by Spangenberg and Settele (2010).

We have to acknowledge the complementarity of terms/concepts (ES, GBS, green infrastructure, nature-based solutions etc.). We see greater value in seeking linkages and synergies between terms and concepts (see Kadykalo et al., 2019 for an example) than spending too much effort on "single-concept" approaches to urban planning, which might miss important aspects for a holistic approach. In fact, as our results show (see Section 3.2), an ES approach can be followed even if the term "ecosystem services" is not mentioned explicitly.

To promote an ES approach in urban planning processes, terms or labels that work best in a given context need to be identified. For example, green infrastructure or nature-based solutions might find better traction among stakeholders. The public might not recognize the term "ecosystem services", however frequently residents are well aware of the goods and services derived from urban green spaces (Włodarczyk-Marciniak et al., 2020), which does not prevent the possibility of application of the concept by practitioners. In the scientific literature Scott et al. (2018), for example, used the term "ecosystem science" as an umbrella term covering several terms (e.g. natural capital or ES) to capture approaches and tools located within a social-ecological systems perspective, in a spatial planning context.

As a rule, in the planning context of a country or region, it is decisive whether the ES concept is seen as an "add-on" solution or whether ES has been already integrated in the planning process. Existing literature provides some evidence supporting this observation. A study in Stockholm (Kaczorowska et al., 2016) showed that the promotion of urban ES – regardless of how beneficial it may be – will add further complexity to already strained workloads among planners, policy-makers and urban managers. Scott et al. (2018) argue that ES can be embedded into the existing work priorities and vocabularies of spatial planning practice using 'hooks' (linking ecosystem science to a key policy or legislative term, duty or priority that relate to a particular user group) and 'bridges' (linking ecosystem science to a term, concept or policy priority that is used and readily understood across multiple groups and publics).

Our studies highlighted cases in which the ES concept is most relevant and useful to urban planners and potentially for decision-makers and other stakeholders:

- The ES approach is useful to support quantified assessments of urban nature and the benefits for citizens arising from it. It supports the planning, design and development of GBS by revealing what stakeholders appreciate, identifying priorities and setting benchmarks. These can contribute to a methodological modernization of landscape and urban planning.
- As part of a broader, integrated valuation of ES (Jacobs et al., 2016), the monetary valuation of nature and landscapes could create important additional arguments for the protection and sustainable use of landscapes. Fundamental for this is that its shortcomings are acknowledged and communicated in a transparent way.
- The extension of landscape and urban planning through the ES approach can improve the analysis of conflicts as well as the derivation, communication and implementation of planning measures.
- The essential key of the ES approach lies in the communication with different planning stakeholders. By implementing the ES approach, the objectives, contents and benefits of landscape and urban planning can be better communicated.

Aligned with the notion of ES as a boundary object (Abson et al., 2014), the ES concept managed to bring a diverse group of stakeholders around a common table, as the case studies showed. This, in turn, can:

- provide additional arguments for nature conservation and/or implementation of new green infrastructure elements/nature-based solutions in cities with human health and well-being in the centre of attention;
- underline environmental aspects (e.g. role of nature-based solutions in air pollution control, climate and flood protection);
- contribute to a design that considers sustainable nature-based solutions and ecological principles;
- demonstrate the social, educational and health advantages of urban nature (learning, encountering, experiencing, increasing environmental justice, economic and cultural well-being etc.);
- support the communication of nature-related topics (visualizations, changes in space and time);
- identify/quantify ES supply, demand and flows.

A greater understanding of the many benefits provided by GBS is clearly shown within an ES framework. This provides an opportunity to regard urban nature from a new perspective. Through integrated urban planning and improved design we can achieve multiple outcomes in order to make cities more liveable. At the same time, this brings challenges and potential barriers to implementing an ES approach in decision-making and planning. These include its complexity, relative novelty as a concept compared to established thinking, guidelines on urban planning which have been evolving over many decades, and the need to take a holistic approach which considers many different sectors. There may be a need for scientific studies to provide further experimental evidence on the benefits of GBS, to provide evidence synthesis for easy communication to policy and decision-makers (see for example Raymond et al., 2017), and to help answer questions held by city managers and officials, which have not been previously considered.

GBS and ES play a particularly important role in times of crisis, such as during the COVID-19 pandemic when many people were expected to spend large parts of their day in their own homes, when journeys to distant destinations were not possible and even trips to the wider surroundings were only permitted to a limited extent. This makes it all the more important for people to be able to find and visit urban green spaces in their immediate living environment. The Coronavirus crisis has made it clear that urban planning is well advised to ensure that the greenery in residential areas is well designed (Kleinschroth and Kowarik, 2020; Venter et al., 2020).

Finally, based on our results we provide recommendations for implementing the ES approach in urban planning. Target groups for the application of the ES concept in practice are local politicians, urban planners and decision-makers, businesses, neighbourhood associations as well as citizens.

There is a need for long-term perspectives in ecological planning (spatial, urban, environmental, nature conservation planning) supported by new tools and methods for valuing ES (see also Kaczorowska et al., 2016). Further on, it is necessary to:

- modernise the methodological framework of urban planning (include the ES concept/framework);
- provide new arguments for spatially based decision-making, which could positively influence the well-being of city residents;
- establish method sets, standards and guidelines as well as provide supplementary databases for the application of new methods as a major requirement for successful integration of ES in urban planning;
- communicate the relationship between societal well-being and the structure and functioning of ecosystems and the services they provide to the broader public as well as to stakeholders and decision-makers;
- embed ES through new regulations and planning standards;
- promote professional training on ES-based quantitative methods, planning of measures and participatory methods.

In the process of planning and implementing physical measures on the ground (construction measures, restructuring of running waters, maintenance and upgrading of parks, gardens and green spaces, etc.), practice should be supported by science in implementing ES-related approaches. The following points should be noted by those responsible for such measures:

- consult partners/relevant stakeholders very early in the process of 'high profile' projects and create a shared conceptual framework around ES (=a conceptual bridge between state, NGOs and research institutions). Involve stakeholders in the co-design and co-creation of implementation projects (=scientific bridge between state, NGOs and research institutions). This echoes recommendations by Mauser et al. (2013) or Frantzeskaki and Kabisch (2016).
- allow research institutions – viewed as more impartial – to coordinate the co-creation processes (as recommended by Cowling et al., 2008). Provide time for co-creation and be patient, as there is a long time-lag before results are seen. Communicate results through various means.
- recognise the importance of stability and continuity of key positions (coordinators, project leaders, political appointees).
- identify key ES through participatory processes (see for example Mascarenhas et al., 2016). Use simple, spatially-explicit indicators for key ES (as recommended by Ruckelshaus et al., 2015), and ideally relevant to local context. Make it plausible; which ES are provided

and which actors are involved in handling their provision or even impairment and to what extent. Then goals and measures could be defined more purposefully and successfully than in many cases so far, and could be communicated within the framework of participation and find support (Spyra et al., 2019).

- integrate all forms of nature into urban development for people's nature experiences and benefits (Grunewald et al., 2018; Bastian et al., 2020). Use synergies in the implementation of ES approaches, in particular with biodiversity strategies, with climate mitigation and adaptation plans.
- create/use new opportunities for public actions (e.g. competitions, citizen science) in favour of nature in the city (such as nature-based solutions). In their implementation the aesthetics and recreation, despite their primary role for the public, should not play a too dominant role. Rather, the focus should be on multifuncionality of areas, in which designs that promote cultural ES are complemented by structures essential for regulating ES and biodiversity (cf. Sikorska et al., 2017; Brzoska et al., 2021).

5. Conclusions

Urban growth and densification as well as climate change adaptation and urban biodiversity strategies promote the interest in planning with ES as a vital parameter for urban qualities. The concept of urban ecosystem services makes it possible to demonstrate the many ways in which nature - in all its facets - contributes to people's prosperity and well-being, especially in cities. It helps to better explain and clarify the value of nature's services in the city to decision-makers and non-specialists. Although there are already numerous laws and instruments in place to protect nature in the city, the ES approach offers the opportunity to focus more on the impact on, and benefits for, residents, e.g. health (Sirakaya et al., 2017). Also, the demand perspective, which can be included e.g. by surveys, as well as the possibility of economic evaluations are special features of this concept.

We conclude that landscape and urban planning practices should be more open to the ES concept and its integration, and that it should be integrated in the form of supplementary contributions. This would not necessarily require an adaptation of the legal framework conditions. ES indicators for the local and regional level need to be adapted and developed by research/science in order to be able to use them in planning practice. The modernisation/further development of the methodological approaches of landscape and urban planning can be intensified by an assessment of nature and landscape performance, which is as quantifiable as possible. Quantifying ES in landscape and urban planning also enables the success of planning objectives to be monitored. In the context of integration, basic definitions of the ES concept need to be introduced in planning practice; however, the terms used should be kept as simple as possible. For public discourse and recognition of the concept in practice a targeted transfer of expertise is necessary.

The integration of ecosystem services into spatial decision-making processes is often associated with changes towards greater sustainability and protection of natural resources. We are convinced that the ES concept can also make a contribution in the sense of a comprehensive socio-ecological transformation, in which existing institutions and practices are tested, changed and/or replaced, thus breaking path dependencies.

Further integration is needed for the inclusion of ES in more strategic spatial planning. This is particularly important in the context of larger urban areas where ecosystems are a part of even larger metropolitan surroundings, requiring cross-administrative attention and strategic governance. According to our findings we can state that the ES tools suitable for practical implementation in urban planning should be co-developed by scientific experts and practitioners. The role of scholar-practitioners (scientists involved in planning processes) in proposing procedural and technical innovation of existing planning procedures, standards, norms and regulations could be crucial to integrate scholarly knowledge into daily technical and administrative domains. This approach would help to include the novel scientific findings as well as the needs of urban and environmental planners, politicians and other stakeholders.

Declaration of Competing Interest

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

Acknowledgements

Lenka Dubova's research was supported by project BIDELIN "The values of ecosystem services, biodiversity and green-blue infrastructure in cities using the examples of Dresden, Liberec and Decin" (Grant No. 100282320), financed by European fund for regional development (Interreg V-A 2014-2020 Saxony–Czech Republic). The work of Olaf Bastian, Patrycia Brzoska and Karsten Grunewald was also supported by the BIDELIN project (http://bidelin.ioer.eu/en/project/).

Claudia Dworczyḱs research was supported by research project ÖSKKIP (Ecosystem Services of Urban Regions – Mapping, Communicating and Integrating into Planning to conserve biodiversity during a changing climate) funded by the German Ministry of Education and Research (BMBF) under the funding code FKZ 16LC1604B.

Laurence Jones was supported by the EU Horizon 2020-project REGREEN (Grant Agreement No. 821016).

Jiri Louda's research was supported by project "Smart City – Smart Region – Smart Community" financed by the Operational Programme Research, Development and Education of the Czech Republic – Grant no. CZ.02.1.01/0.0/0.0/17_048/0007435 and project "Economic and Institutional Aspects of Planning and Implementation Nature Based Adaptation Solutions" (UJEP-IGA-JR-2021-45-008-2).

Daria Sikorska's research was supported as part of the project ENABLE, funded through the 2015–2016 BiodivERsA COFUND call for research proposals, with the national funders The Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning, Swedish Environmental Protection Agency, German aeronautics and space research centre, National Science Centre (Poland), The Research Council of Norway and the Spanish Ministry of Economy and Competitiveness.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2021.101273.

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Chapter 6

Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute?

Wübbelmann, T., Förster, K., Bouwer, L.M., Dworczyk, C., Bender, S., Burkhard, B.
Submitted to *Frontiers.*

Figure 15. Vegetation and unsealed soils help to prevent flooding during heavy rainfalls.
Photo: Jolanta Dworczyk

Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute?

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Keywords: Hydrological Modelling, Climate Adaptation, Ecosystem Services Supply and Demand, Mismatch Analysis, Scenarios, Cities, Extreme Rainfall. (Min.5-Max. 8)

Abstract

Urban areas are mostly highly sealed spaces, which often leads to large proportions of surface runoff. Simultaneously, heavy rainfall events are projected to increase in frequency and intensity with global climate change. Consequently, higher risks and damages from pluvial flooding can be expected. With the analysis of Flood Regulating Ecosystem Services (FRES), the benefits from nature to people to reduce surface runoff and runoff peaks can be determined. However, urban FRES are rarely studied for heavy rainfall events under changing climate conditions. Therefore, we first estimate the functionality of current urban FRES-supply and demand under changing climate conditions. Secondly, we identify the effects of nature-based solutions (NBS) on FRES-supply and demand and their potential future functionality and benefits concerning more intensive rainfall events.

A district of the city of Rostock serves as the case study area. Besides the reference conditions based on the current land use, we investigate two potential NBS: 1) increasing the number of trees; and 2) unsealing and soil improvement. Both NBS are applied for three heavy rainfall events. Besides a reference scenario, two future scenarios were developed to investigate the ecosystem service functionality, based on 21% and 28% more intense rainfall. While the potential FRES-demand was held constant, we assessed the FRES-supply and actual demand for all scenario combinations, using the hydrological model LEAFlood. Comparing the actual demand and supply indicates the changes in FRES-supply surplus and unmet demand increase.

Using FRES indicators from hydrological models to estimate future functionality under changing climate conditions and the benefits of NBS can serve as an analysis and decision-support tool for decision-makers to reduce future urban flood risk. In the next step, different scenarios for flood regulation demand and other adaptation measures can be tested with practical applications in other urban areas.

1 Introduction

Heavy rainfall is projected to increase in frequency and intensity due to climate change (Jacob et al., 2014; Rajczak and Schär, 2017; Villaseñor, 2021). Consequently, rainfall changes will have a major impact on pluvial flooding in urban areas. Flood Regulating Ecosystem Services (FRES) can function as measure to mitigate pluvial flooding. Ecosystem Services are defined as the linkage of ecosystems and society with direct or indirect contributions of ecosystem functions to human well-being (MEA, 2005; TEEB, 2010). Flood Regulating Ecosystem Services (FRES) in particular are ecosystem processes and functions that store water and consequently lower surface runoff, which benefits human well-being by protecting and securing livelihoods (Burkhard and Maes, 2017). Whereby, FRES-supply comprises the contribution of the ecosystem to lower the flood hazard, and the ecosystem delivers a service when there is a demand or need for this flood reduction by society. Therefore, climate change must be urgently taken into account in the assessment of FRES to prove their future functionality (Maes et al., 2020).

Different studies already address the impact of climate change on the future functionality of FRES using hydrological modelling (Shen et al., 2021; Wübbelmann et al., 2021). In general, the focus of FRES assessment is on fluvial floods in catchments on the regional or European scale (Nedkov and Burkhard, 2012; Stürck et al., 2014; Gaglio et al., 2019). However, cities are particularly affected by pluvial floods because of two reasons. Firstly, they are vulnerable due to the high population density and the large potential for social and economic damage. Secondly, the high degree of sealing has modified the water cycle, which contributes to higher surface runoff. Yet FRES has been less frequently applied at the local or urban scale (Shen et al., 2019; Wübbelmann et al., 2022).

Mismatch analyses of supply and demand can identify and visualise the benefits of FRES to society. The results can also reveal whether the demand for flood reduction can be met or not. In the case of heavy rain events, unmet demand may indicate flood risk to people and infrastructure. However, ES demand is less frequently spatial assessed and mapped (Campagne et al., 2020), causing research and knowledge gaps in mismatch analyses. For instance, Mori et al. (2022) mapped supply, demand and budget changes between 1990 and 2018 for a river basin using SWAT and Xiong and Wang (2022) conducted a mismatch analysis for an urban area. However, the future functionality of urban FRES under changing climate conditions for heavy rainfall events remains unclear.

To counteract flood risks and to adapt to climate change, different concepts of natural adaptation measures exist (Kabisch et al., 2017). One concept of adaptation measures are Nature-based Solutions (NBS). NBS are measures or actions, which are inspired or supported by nature and use or imitate its complex characteristics and processes (European Commission, 2015). They are "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges […] effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, xii). For a successful implementation, urban planners lack information on the performance and benefits of NBS (Zölch et al., 2017). With the concept of Ecosystem Services this knowledge gap can be closed by considering the supply of ecosystems and the contribution of green infrastructure on the flood regulation.

For sustainable development, the NBS must withstand climate change and should also contribute services under future conditions. However, strong evidence on the performance of NBS for climate adaptation is missing (Kabisch et al., 2016). Zölch et al. (2017) tested different NBS regarding their capacity and functionality under higher precipitation amounts with hydrological models and found out, that the regulation potential of NBS decreases. Other studies used system dynamic models for the long-term effectiveness of NBS under changing climate conditions in rural areas (Gómez Martín et al., 2021). Studies on water supply and regulation for the future functionality of NBS under changing climate conditions for a floodplain have been done using the InVEST model that analyses seasonal water yield (Gaglio et al., 2019; Natural Capital Project, 2020).

Most studies on FRES that reduce impacts from climate change and the usefulness of NBS are focused on floodplains and river catchments. The few existing studies on urban FRES are related to the current situation and lack the analysis of future scenarios. Therefore, the objective of this research is 1) to estimate future functionality of urban FRES under more intense rainfall events, and 2) to estimate the benefits of NBS on urban FRES under current and future climate conditions. For this, we determine the FRES-supply change, the change in actual demand, and finally, the change in the FRES budget. These objectives lead to the following research questions of this study:

- How does more extreme precipitation affect urban FRES-supply and as a consequence the urban FRES-actual demand?
- Can ecosystem-based climate adaptation by NBS enhance the urban FRES-supply and lower the actual demand and how significant is their benefit related to more intense rainfall events?
- Is our approach appropriate to test the future functionality of urban FRES and to identify mismatches between FRES-supply and demand?

2 Material and Methods

2.1 Study Area

The study location is in the southwest of Rostock (area of 182 km²) in northern Germany and has an area of 4.5 km² (see Figure 1). In the past, Rostock was affected by several heavy rainfall events. In particular, in the summer of 2011 several heavy rainfall events were detected (Miegel, 2011), which created awareness and resulted in several research projects. The study area, which includes the Holbeinplatz, was chosen because of the present critical infrastructure, the diversity of urban land use structures and the flooding observed in the past in the area, especially at the Holbeinplatz.

The dominant land-use types are green areas (parks, forests and woodland) with 50 % of the area, 23 % consisting of traffic areas and 25 % containing sealed areas (settlements, urban dense areas, and industry) (Steinbeis-Transferzentrum Geoinformatik, 2017). The predominant soil types are luvisol-pseudogley and regosol and the substrate textures of the soil are wet sandy loam and loamy sand (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz, 2019). The climate conditions in Rostock are mild-maritime due to the vicinity to the Baltic Sea. The mean annual temperature is 9.4 °C (1981-2010) (DWD Climate Data Center, 2022a) and the annual precipitation sum is 646.2 mm with summer precipitation of around 202 mm (DWD Climate Data Center, 2022b) at the DWD station Rostock-Warnemünde (closest weather station in ~ 9.6 km distance).

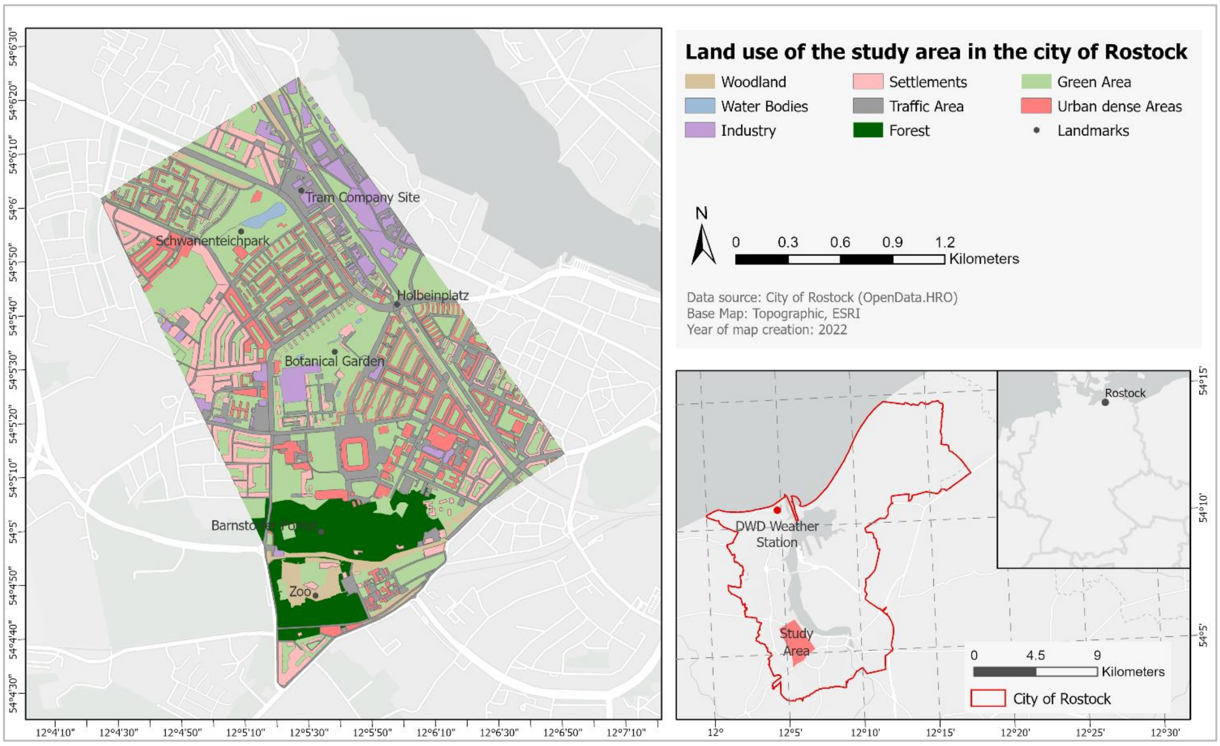

Figure 1 Location and land use of the research area in Rostock

2.2 Data

The hydrological modelling and FRES analysis require a bundle of datasets. Table 1 (supplements) shows a detailed overview of the data that was used.

The spatial geometry of the hydrological model is defined by using spatial data of land use, soil type, elevation, and tree coverage and characteristics. Temperature, relative humidity, solar radiation, wind speed and precipitation are the meteorological input of the model. For these meteorological data, observations were taken from the climate station Rostock-Warnemünde, operated by the German national weather service (DWD). The heavy precipitation event that was used for the present study was observed on the 6th of August 2011 and lasted over one hour with a rainfall total of 21.7 mm. Further spatial data about infrastructure, population density, land reference value, and appearance of monuments were used for the FRES-demand analysis (see table 1).

2.3 Hydrological Model LEAFlood

The hydrological model quantifies ES indicators for canopy interception and soil water for the supply, and the surface water depth for the actual demand. We used the hydrological model LEAFlood (Landscape vEgetAtion and Flood model) (Wübbelmann and Förster, 2022), which is based on the modular and open-source Python package "Catchment Modelling Framework" (CMF) (Kraft et al., 2011; Kraft, 2020). LEAFlood adopts and uses CMF functions to create a mesh out of a GIS shapefile. The model enables a detailed presentation of canopy interception, including through fall and canopy evaporation, and lateral surface runoff simulation, using a 2D kinematic wave approximation (Figure 2). In addition, one soil layer of 0.5m depth is used following the Green-Ampt infiltration approach (Rawls et al., 1993) and Brooks Corey Retention curve. The representation of canopy interception and runoff by LEAFlood was verified in detail by Camarena et al. (2022), who compared measured runoff and canopy interception observations with LEAFlood results. Furthermore, the model has already been applied for a FRES analysis under contemporary conditions by Wübbelmann et al. (2022).

The geometry in this analysis is the same as Wübbelmann et al. (2022). The basis was a shapefile of polygons with a size of approximately 1000m². The canopy cover was calculated by a quotient of the canopy area and polygon area. Each tree species was assigned a Leaf Area Index (LAI) and an interception capacity (Breuer et al., 2003). Missing values were filled by mean values. Afterward, mean LAI and interception capacity were calculated by an intersection of the tree point information and the polygon shapefile. For each polygon, the mean value of all contained trees was then calculated. The literature values by Breuer et al. (2003) depict the mean interception capacity including a range of different rainfall events regarding amount and duration, but they do not give information about the maximum interception during heavy rainfall events as investigated here. Therefore, based on the modelling results in a neighborhood in the city of Freiburg, Germany (Camarena et al., 2022), observation data on this site (Jackisch et al., 2013) and further interception measures from other studies (Asadian and Weiler, 2009; Alves et al., 2018) we have increased the interception values of all cells by a factor of 5.

The saturated conductivity (Ksat) was also variable over the area and depends on the sealing (see Table 5). Based on sandy loam, a baseline value of 0.3m/d was assumed and reduced for higher sealing degrees (Sponagel et al., 2005; Wübbelmann et al., 2022). Further soil parameters were constant in the area. In addition, each land use was assigned a surface roughness coefficient Manning (Wübbelmann et al., 2022).

The output of the model consists of surface water depth, soil water depth, intercepted water depth, and the outflow at the outlets. The outflow is detected as water that leaves the study area at the set boundary conditions (constant head). These results are generated per polygon and per time step.

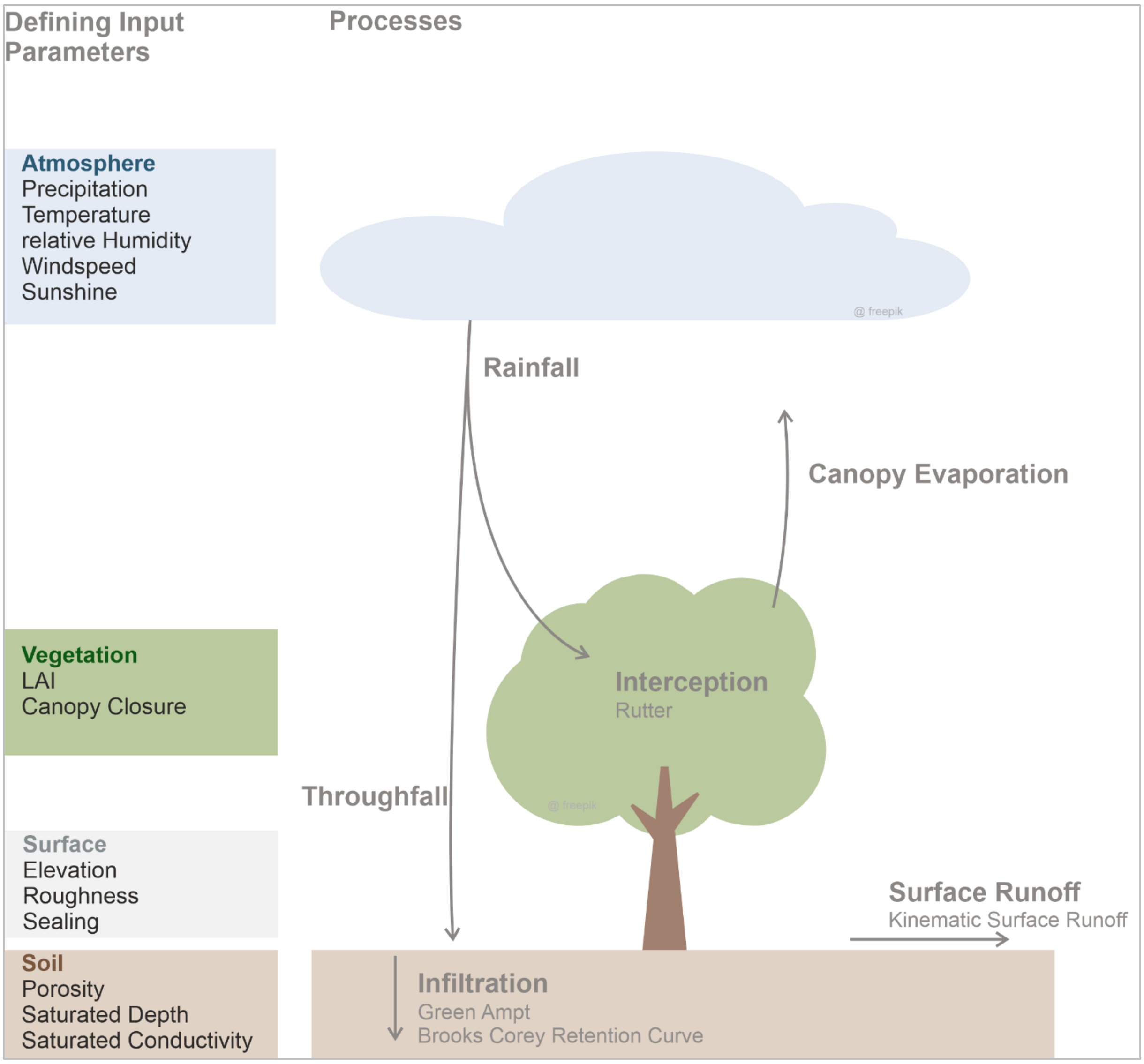

Figure 2 The hydrological processes of LEAFlood (Wübbelmann and Förster, 2022).

2.4 Flood regulating Ecosystem Services Analysis - Indicators and Quantification

The FRES analysis was done with a combination of ArcGIS Pro 2.8.0 by ESRI and statistical calculation with Python. The general method and indicators are based on Wübbelmann et al. (2022) and were adapted to a scenario analysis by using the changes to a reference scenario as indicators. Figure 3 shows the methodological framework of the analysis. Different indicators were used for the supply and demand analysis (see tab 2).

The hydrological modelling with LEAFlood delivered the indicators of soil water depth and intercepted water depth by the tree canopies in mm for the FRES-supply. Both storages are important flood regulation elements in urban areas and therefore necessary to be considered as indicators in urban FRES assessment. With LEAFlood the interception can be considered as an appropriate resolution of single landscape elements of the urban environments (such as parks or streets) and is reachable. For both storages (canopy interception and soil water storage), the difference between the maximum water depth over the whole period and the initial water depth at the beginning was used to calculate the sum of soil water and interception for the FRES-supply. Afterward, the difference was calculated for all scenarios, relative to the reference scenario, consisting of current land use, and the extreme rainfall event of 2011. This was then normalized to a relative scale from -1 to 1, where -1 indicates a very high decrease in supply, 0 no change, and 1 a very high increase in supply.

The potential demand was assumed to be constant among all scenario combinations to better estimate the effects of the NBS and the influence of future precipitation scenarios. We determined the potential demand as described in Wübbelmann et al. (2022). Five indicators – population density, monuments, land reference value, critical infrastructure, and traffic areas - were used following the approach of (Biota, 2014). As opposed to demand, the flood hazard has changed depending on the scenario. The corresponding indicator is the surface water depth [mm] of the model output. As the supply, the difference to the reference scenario was normalized to a relative scale from -1 (decrease of surface water) to 1 (an increase of surface water). The intersection of the hazard changed classes and potential demand gave the actual demand change with the same scale from -1 to 1.

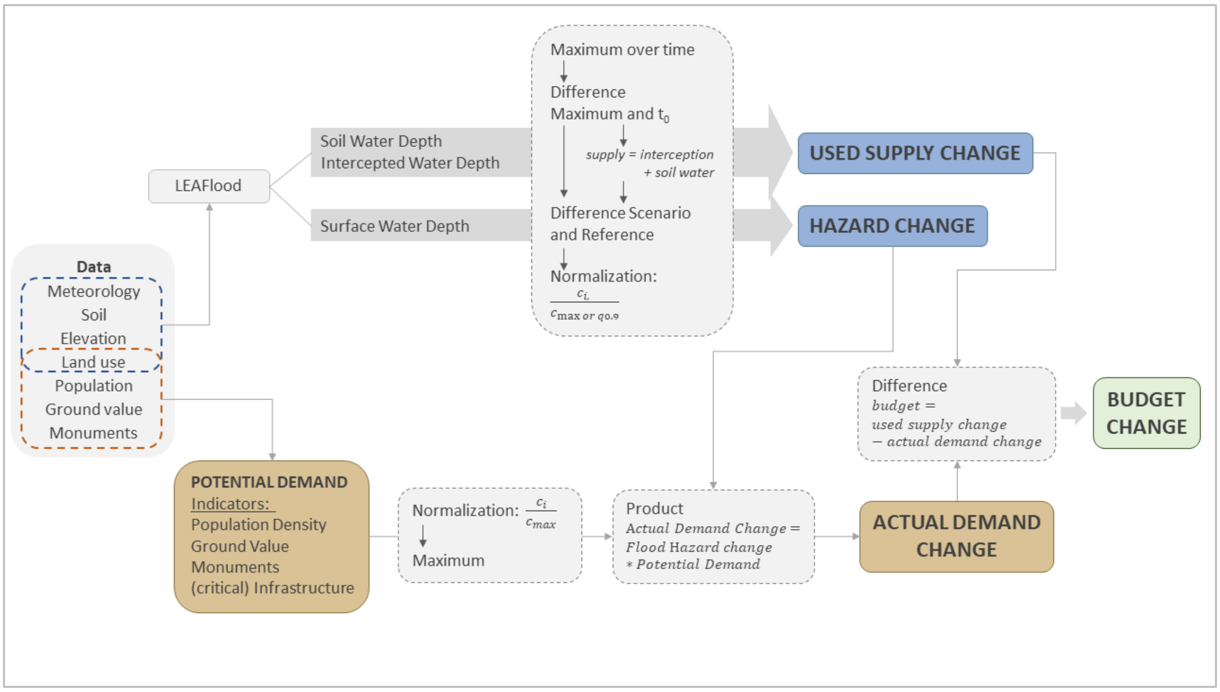

Figure 3 Workflow of the FRES analysis. t_0 is the first time step of the modelling, ci represents the water depth in one cell and $c_{max\ or\ q0.9}$ is the maximum or 90% quantile water depth for this hydrological parameter over all cells.

Finally, the difference between the classified supply and actual demand change resulted in the budget change. The resulting scale can therefore take values on bandwidth from -2 to 2.

2.5 Scenarios and adaptation measures

2.5.1 Rainfall scenarios

For the analysis of the current and future functionality of FRES in an urban area we used a reference scenario and two future scenarios (period 2050). They are based on an observed one-hour rainfall event in 2011 measured at the Rostock-Warnemünde station with a temporal resolution of one minute. The total rainfall amount in this hour was 21.74 mm with a maximum intensity of 2.93 mm/min after 29 minutes (see table 3). The event can be assigned to a three-years return period (DWD Climate Data Center, 2020), which corresponds to the design standards in the planning of urban drainage systems in residential areas (DIN-EN, 2017).

For the definition of the future scenarios, we used the super Clausius-Clapeyron (sCC) relation between atmospheric water vapour content and temperature, to scale (increase) the rainfall intensity of the observed 2011 event with temperature change (further global warming). Unlike the CC scaling approach, the sCC relation is more appropriate for sub-daily and convective events (Westra et al., 2014; Förster and Thiele, 2020). This sCC relation assumes an increase in precipitation intensity of up to 14 % per degree of temperature increase for short extreme events, at daily mean temperatures higher than

12 °C (Lenderink and van Meijgaard, 2008; Dahm et al., 2019; Förster and Thiele, 2020). We investigated scenarios of 1.5°C and 2°C warming compared to 2011. Therefore, with the sCC scaling factor of 14%, warming of 1.5°C and 2°C suggests an increase in precipitation intensity of 21% and 28% in 2011, respectively. Table 3 compiles major statistical characteristics for each scenario.

Table 3 Names and statistical description of the rainfall scenarios. The return period was estimated utilizing the KOSTRA dataset (DWD Climate Data Center, 2020).

Scenario		Abbreviation	Sum [mm/h]	Return period [a]	Maximum [mm/min]
Reference	2011	F0	21.74	3	2.93
Future 1.5°	+21%	F1.5	26.31	5 - 10	3.55
Future 2°	+28%	F2	27.83	5 - 10	3.75

For the definition of the future scenarios, we used the super Clausius-Clapeyron (sCC) relation between atmospheric water vapour content and temperature, to scale (increase) the rainfall intensity of the observed 2011 event with temperature change (further global warming). Unlike the CC scaling approach, the sCC relation is more appropriate for sub-daily and convective events (Westra et al., 2014; Förster and Thiele, 2020). This sCC relation assumes an increase in precipitation intensity of up to 14 % per degree of temperature increase for short extreme events, at daily mean temperatures higher than 12 °C (Lenderink and van Meijgaard, 2008; Dahm et al., 2019; Förster and Thiele, 2020). We investigated scenarios of 1.5°C and 2°C warming compared to 2011. Therefore, with the sCC scaling factor of 14%, warming of 1.5°C and 2°C suggests an increase in precipitation intensity of 21% and 28% in 2011, respectively. Table 3 compiles major statistical characteristics for each scenario.

According to regional climate model projections by Climate Service Center Germany (2019), 2011 was already around 0.8°C warmer than the annual mean temperature of the reference period 1971 – 2000. In the following, the earliest possible year (upper boundary of the projection bandwidth) in which climate projections for different RCP scenarios reach a 1.5°C or 2°C warming compared to 2011 is listed:

- 1.5°C warming for RCP 8.5 will be reached in 2032
- 1.5°C warming for RCP 4.5 will be reached in 2041
- 2°C warming for RCP 8.5 will be reached in 2046
- 2°C warming for RCP 4.5 will be reached in 2053

It must be mentioned that these climate projections have high bandwidth with uncertainties. The listed values are the upper boundaries of the ensemble. In a low emission scenario (RCP2.6) these warming scenarios compared to 2011 will not be reached (Climate Service Center Germany, 2019).

2.5.2 Adaptation measures

Besides the current land use and land cover conditions, we investigate the potential benefit of two measures where additional NBS solutions result in additional canopy area, and a reduction of sealed areas, and thereby improving infiltration (see table 4). These two measures were first applied separately; additionally, we applied the combination of both NBS in a model run. These NBS measures represent options for climate adaptation to reduce urban flood risk.

Table 4 Overview and description of the applied nature-based solutions

NBS measure	Abbreviation	Description
Reference land use	NBS_0	Aggregated and reclassified land use from the 'Realnutzungskartierung' from 2014 (Steinbeis-Transferzentrum Geoinformatik, 2017)
Additional trees	NBS_{tree}	Increased tree coverage by increasing the canopy cover over: • Forest land: minimum coverage of 90% • Green areas: minimum coverage of 30% • Traffic areas: minimum coverage of 30%
Unsealing	$NBS_{unsealing}$	Increased saturated conductivity (Ksat) for better infiltration (see table 5)
Combined	$NBS_{combined}$	A combination of both NBS. The increased tree coverage of NBS_{tree} and the enhanced saturated conductivity for better infiltration of $NBS_{unsealing}$ were applied

First, we implemented a higher canopy cover in the study area. For this, we defined a minimum canopy cover of 90% above forest land use polygons, 30% for green areas, and 30% for traffic areas. This leads to an increase in average canopy coverage from 18% to 33% throughout the study area. This percentage can be considered as a realistic and feasible option since other cities also show a canopy cover up to 30 % (e.g. Oslo or Singapore) (MIT Senseable City Lab; The Guardian, 2019). We have set the LAI to 5 and the Interception Capacity to 1.4, reflecting the mean of all main tree species in the study area.

The second adaption measure entails an unsealing of traffic areas and a soil improvement for green areas. Since the sealing is defined via the saturated conductivity in LEAFlood, we adjusted this parameter from 0.006 m/day to 0.1 m/day for traffic areas in the hydrological model. Because of possible numerical instability, we waived to create smaller polygons for green space along the street. Instead, we applied the adjustment to all traffic polygons. The saturated conductivity of the green areas was increased from 0.3 m/day to 0.4 m/day, respectively (see Table 5).

Table 5 Saturated conductivity (Ksat) for the Reference Scenario and the adaptation measure "Unsealing".

Land use	**Manning n**	**Saturated Conductivity [m/day]**	
		Reference	Unsealing
Urban dense areas	0.2	0	0
Settlements	0.12	0.015	0.015
Industry	0.12	0	0

Traffic area	0.03	0.006	0.1
Green area	0.05	0.29	0.4
Woodland	0.14	0.3	0.3
Forest	0.15	0.3	0.3
Water	0.03	0.015	0.015

Lastly, a combination of both NBS was tested. For this purpose, the canopy cover and saturated conductivity were adjusted Names and statistical description as described above.

3 Results

We analyzed flood regulation in two ways. In the first part, we aggregated all spatial elements by the median and 90%-quantile and only considered the temporal evolution of pluvial flooding. In a second step, we focused on the spatial distribution of supply and demand change, and computed the averaged values of demand and supply over time.

3.1 Timeline

Fig 4 shows the timeline for the supply (interception + soil water; upper plot), the surface water (middle plot), and the total outflow of the study area (lower plot). The solid line displays the median water depth and the dashed line the 90% quantile over all polygons. Orange indicates the reference land use (NBS0), green the tree NBS (NBStree), blue the unsealing NBS (NBSunsealing), and purple the combination of the NBStree and NBSunsealing (NBScombined), while darker colors denote the 1.5 and 2°C warming rainfall scenario with 21 and 28% higher intensities (F2) and lighter colors for the reference scenario of 2011 (F0).

The median supply was not significantly increased for higher rainfall intensities for all NBS measures. However, both NBS have a higher supply than the NBS0. While the supply increase by the NBSunsealing is relatively small, it is higher with the NBStree and highest with a combination of both NBS (for median and 90% quantile).

For the surface water, the NBStree leads to a higher decrease of the surface water than the NBSunsealing compared to the NBS0, whereas the effect is smaller for higher rainfall events (e.g. F2). The 90% quantile has greater differences between the NBS than the median. While the NBSunsealing again reduces surface water only slightly, the influence of the trees is visible (for all precipitation scenarios). The greatest reduction of surface water can be reached with the combination of both adaptation measures. The increase by higher rainfall intensities is comparatively high for the 90% quantile, while the impact is lower looking at the median.

In addition, we investigated the total outflow of the area by summarizing all outlets for each time step (fig 4). The maximum of the peak, the change of the peak to the reference scenario of NBS0 and F0, and the reduction by the single NBS compared to the NBS0 for the respective rainfall scenario is listed in tab 6. Higher rainfall amounts increased the outflow and the peak discharge by 17.33 m^3/min for the F1.5 scenario and by 23.51 m^3/min for the F2 scenario. Whereas, the NBS decrease the peak outflow for the F0 scenario by -7.5 [m^3/min] for NBStree, -1.4 [m^3/min] for NBSunsealing, and -8.7[m^3/min] for NBScombined. The NBStree had a higher impact by reducing the outflow and the peak discharge compared to the NBS0 for the same climate scenario (-9.2[m^3/min] for F1.5 and -9.9[m^3/min] for F2), than the NBSunsealing. The outflow of NBStree for scenario F2 is even lower than for the NBS0 and NBSunsealing for the climate scenario F1.5. The maximum outflow peak reduction for the

NBSunsealing is 1.6 [m³/min] for the F1.5 scenario. The combination of both NBS (NBScombined) reduces the outflow by about 1.2 – 1.4 [m³/min] more than the NBStree.

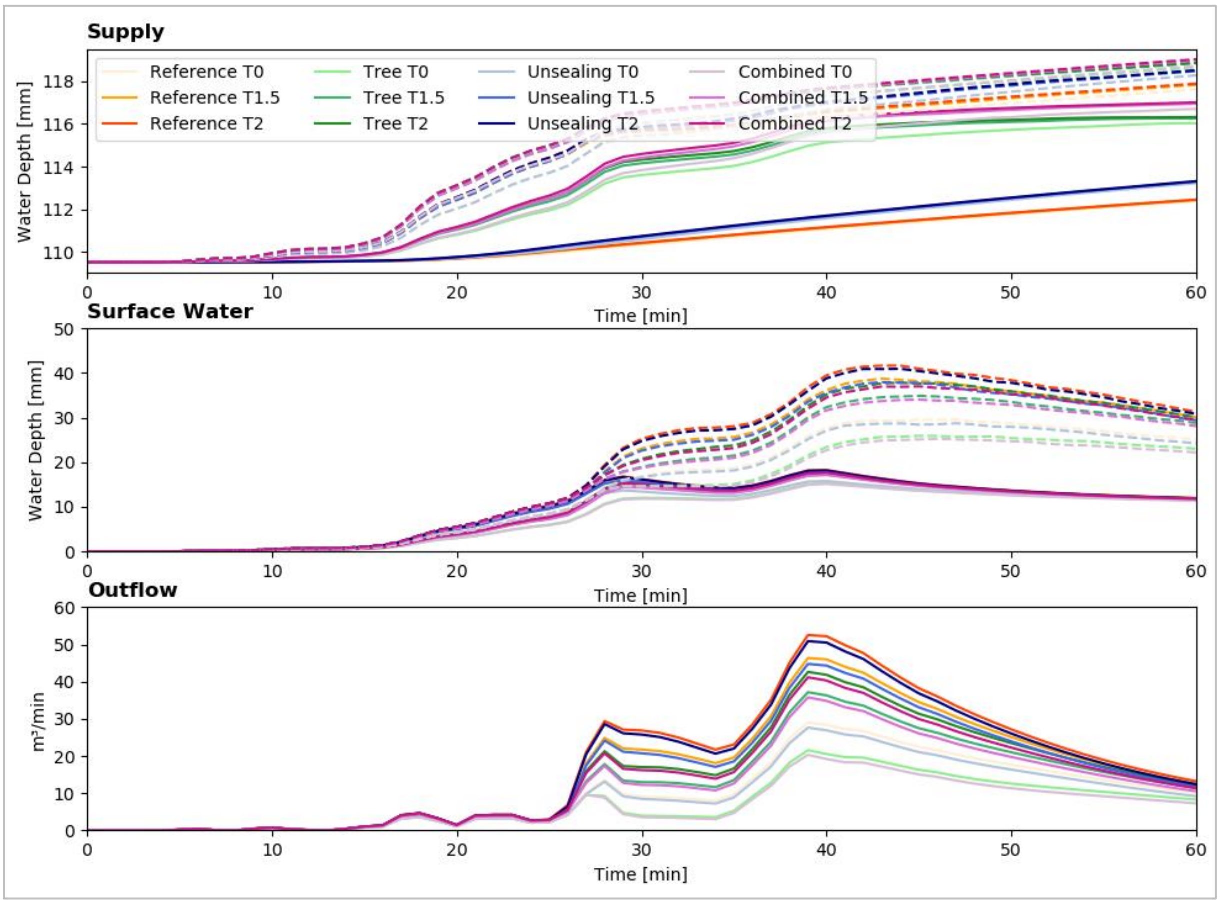

Figure 4 Above figure: Median (solid line) and 90% quantile (dashed line) FRES supply (interception + soil water) of all cells in the study area. Bottom figure: Median (solid line) and 90% quantile (dashed line) surface water depth of all cells in the study area.

Table 6 Peak Runoff and the changes to the reference scenarios for all combinations of rainfall scenarios and NBS. The first column displays the peak runoff, the second column the peak increase/ reduction compared to the reference scenario NBS_0 /F0, and the third column the reduction to the NBS_0 of each rainfall scenario.

	F0			F1.5			F2		
	Peak Max [m³/min]	Peak change to NBS_0/F0 [m³/min]	Reduction to NBS_0 [m³/min]	Peak Max [m³/min]	Peak change to NBS_0/F0 [m³/min]	Reduction to NBS_0 [m³/min]	Peak Max [m³/min]	Peak change to NBS_0/F0 [m³/min]	Reduction to NBS_0 [m³/min]
NBS_0	29.03	-	-	46.35	17.33	-	52.54	23.51	-
NBS_{Tree}	21.57	-7.45	-7.45	37.17	8.15	-9.18	42.62	13.59	-9.92

$NBS_{unsealing}$	27.64	-1.38	-1.38	44.77	15.75	-1.58	50.89	21.86	-1.65
$NBS_{combined}$	20.33	-8.70	-8.70	35.77	6.75	-10.58	41.17	12.14	-11.37

3.2 Supply Change

The supply change for each scenario and NBS combination compared to the reference scenario is mapped in fig 5, which also shows the mean change over the entire study area for each scenario and NBS combination. In addition, fig 6 shows the change in the individual land use classes. The maximum interception of all cells and time steps and all scenario combinations was 7.5mm, the soil water storage 3.9mm, and the total supply 11mm. Latter was the reference value for the computation of the supplies relative scale from 0 to 1.

Without any NBS but with increasing rainfall intensities, the supply did not increase over the entire study area. However, some parts of the study area had a slight increase with heavier rainfall events, which was highest in forest areas (fig 5).

With the NBStree a low supply increase in the total area average was detected. The future rainfall scenario F1.5 and F2 increased the supply even more (medium). However, the difference between F1.5 and F2 is very small (fig 5). In particular, traffic areas and green areas, over which the canopy closure has been significantly increased, were affected by the positive change in supply (Fig 6).

The increase in supply achieved through NBSunsealing was very low in the study area for all rainfall events. A positive supply change was mainly shown in green areas and traffic areas where the adaptation measure was implemented. The future rainfall scenarios led to a slight supply increase in these areas, but in total the supply in the area did not increase more than for F0.

The combination of both NBS (NBScombined) enhanced the supply even more than the NBStree. For all scenarios, a medium supply increase could be observed compared to the reference scenario of NBS0/F0. As for the NBStree and NBSunsealing the highest changes were detected on green areas and traffic areas.

3.3 Actual Demand Change

Fig 7 shows the spatial distribution of the actual demand change for all rainfall scenarios and NBS combinations, as well as the mean change over the study area. Note that in this map, red colors indicate demand increases; contrary to figure 5, where red indicates supply decreases. Fig 8 displays the actual demand change over individual land use classes. The maximum surface water of all cells and time steps and all scenario and adaptation measure combinations was 4682.3mm and the 90%-quantile was 36.7mm. The 90%-quantile further was used as the reference value for the relative scale from 0 to 1, while water depths above the quantile of 36.7mm were indicated as 1.

Without NBS (NBS0) and with higher rainfall intensities, the actual demand showed a low increase over the entire study area (fig 7). The change is very small between the future rainfall scenarios F1.5 and F2, both in the spatial distribution and on average over the entire area. The highest increase in actual demand was computed on traffic areas (fig 8).

The NBStree deacreased the actual demand very low for F0 in the study area. The decrease is highest on water bodies and traffic areas (low). Whereas the actual demand was very low it increased for the F1.5 scenario. In contrast to the F0 scenario, where a low decrease was observed on traffic areas, a low increase was shown for the F1.5 and F2 scenarios. However, the change is smaller between F1.5 and F2, than between F0 and F1.5. The relations of spatial patterns are similar to the F1.5 scenario with a slight increase.

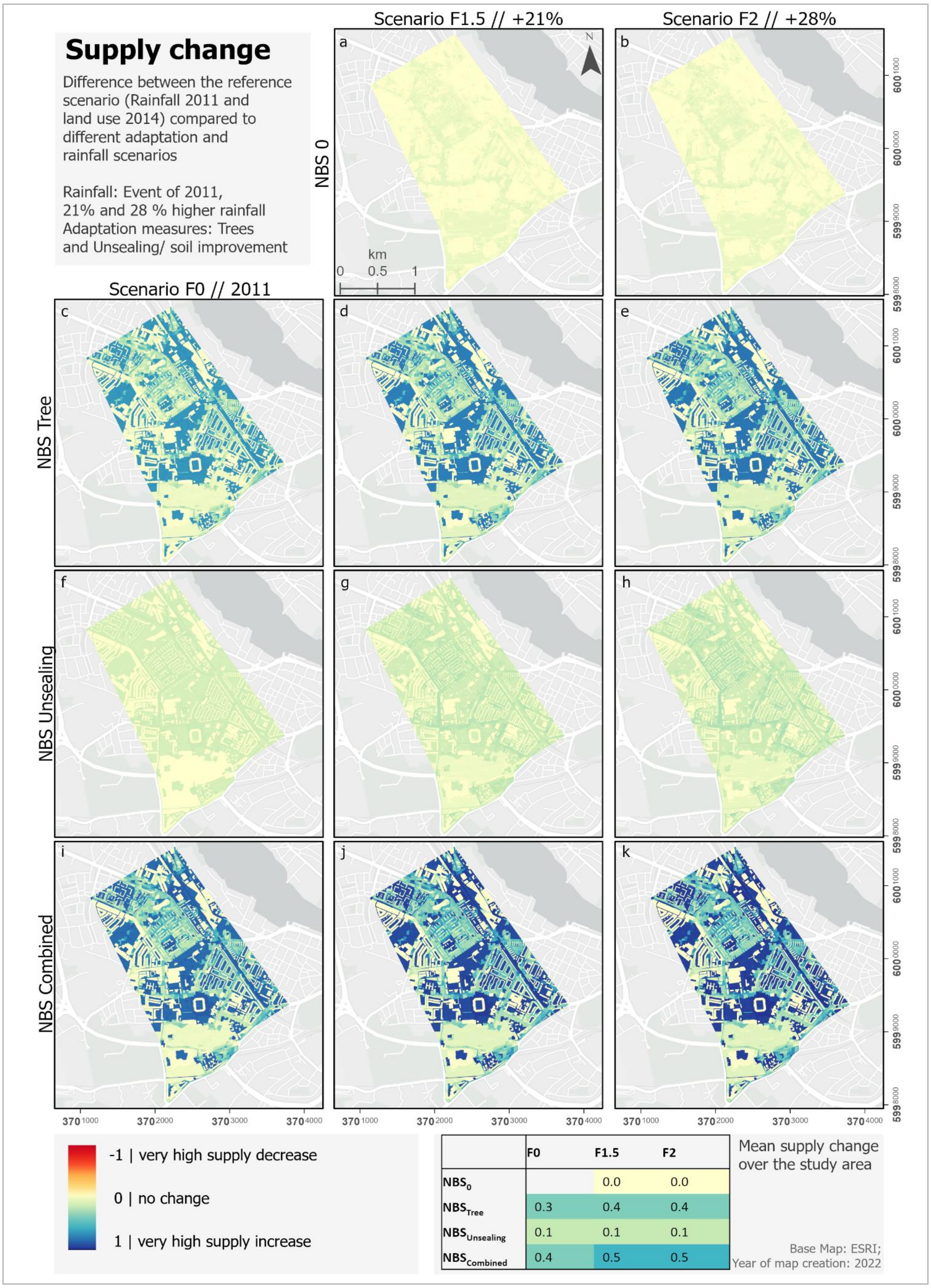

Figure 5 Map of the total FRES supply change by interception and soil water.

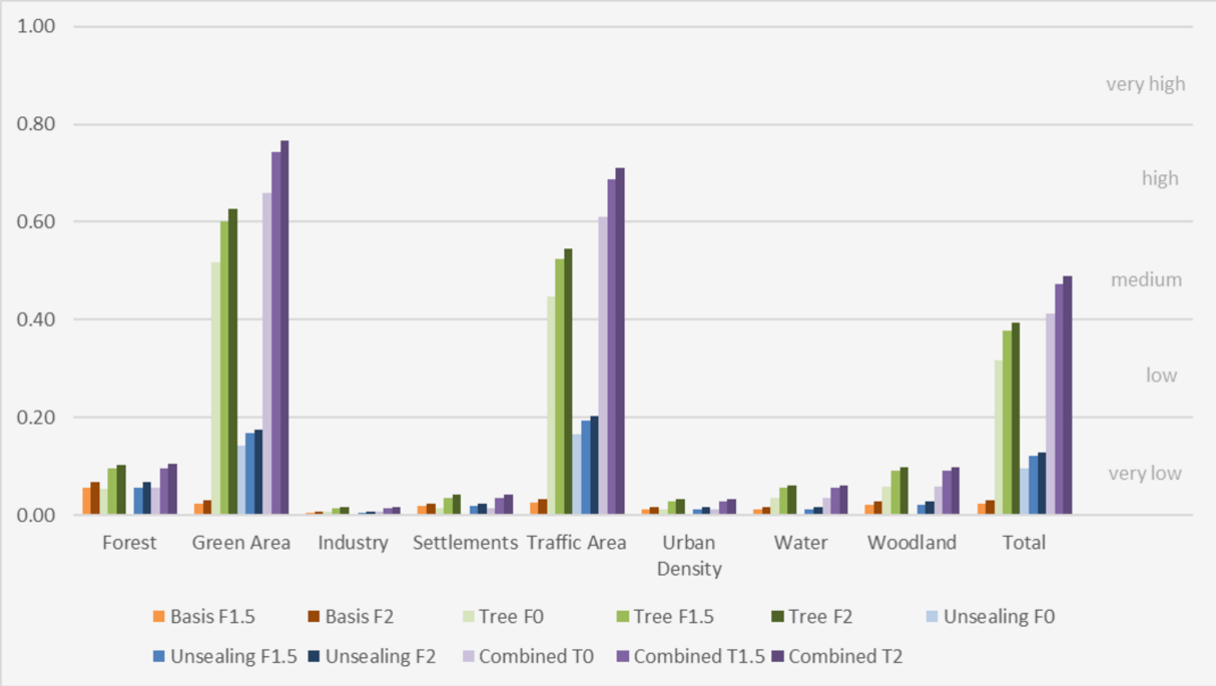

Figure 6 Area weighted FRES supply change by the NBS and rainfall scenarios over the different land uses.

The NBSunsealing did not lower the actual demand for the reference scenario F0. Only water land uses, traffic areas and green areas had a visible decrease in actual demand (fig 8). For both future rainfall scenarios (F1.5 and F2) a medium increase of actual demand with the adaptation measure was computed. The highest actual demand change was again shown over traffic areas that were comparable to the NBS0/F2 scenario.

The combination of trees and unsealing led to a very low decrease in actual demand for the reference rainfall scenario, a very low increase for F1.5, and a medium increase for F2. Thereby, the changes are similar to these of the NBStree (fig 7).

All NBS indicated similar hotspots for the respective rain scenario (see fig 8). In particular, the streets leading to the Holbeinplatz tended to have a high actual demand for future rainfall scenarios.

3.4 Budget change

For the budget change, we calculated the difference between the supply change and the actual demand change (fig 3). The results are mapped in figure 9. Positive values mean a higher supply change towards supply surplus (blue). Negative values instead indicate a higher actual demand change towards unmet demand (red). In fig 10 the budget change over the individual land uses is displayed.

The budget analysis showed a low increase in actual demand for NBS0 for both future scenarios. In general, traffic areas are most affected by a medium increase in unmet demand. In the entire area, no supply surplus increase can be observed.

The NBStree measure in contrast led to a medium supply increase for the reference scenario F0. While settlements and industrial areas had no or a very low increase in supply, green areas and traffic areas with higher tree coverage showed a high increase in supply surplus. The supply increase was lower for the future rainfall events F1.5 and F2 (very low), but the supply increase still exceeded the actual demand on average over the entire study area. In particular, green areas and traffic areas, where the NBS was implemented, benefitted from the measure. Some parts had a high or very high supply increase. Whereas settlements, urban dense areas and industry had a very low increase in unmet demand.

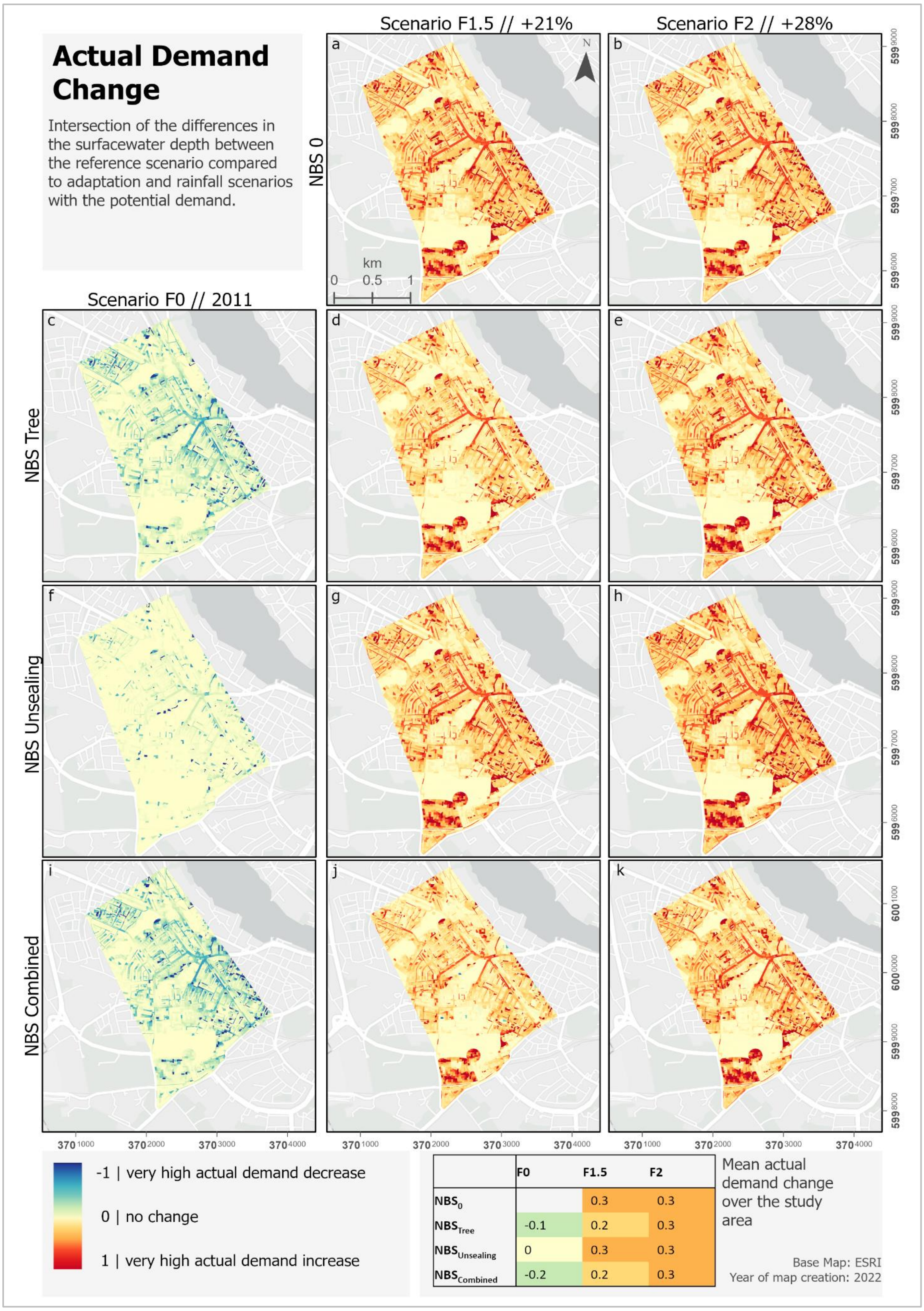

Figure 7 Map of the FRES actual demand change by interception and soil water.

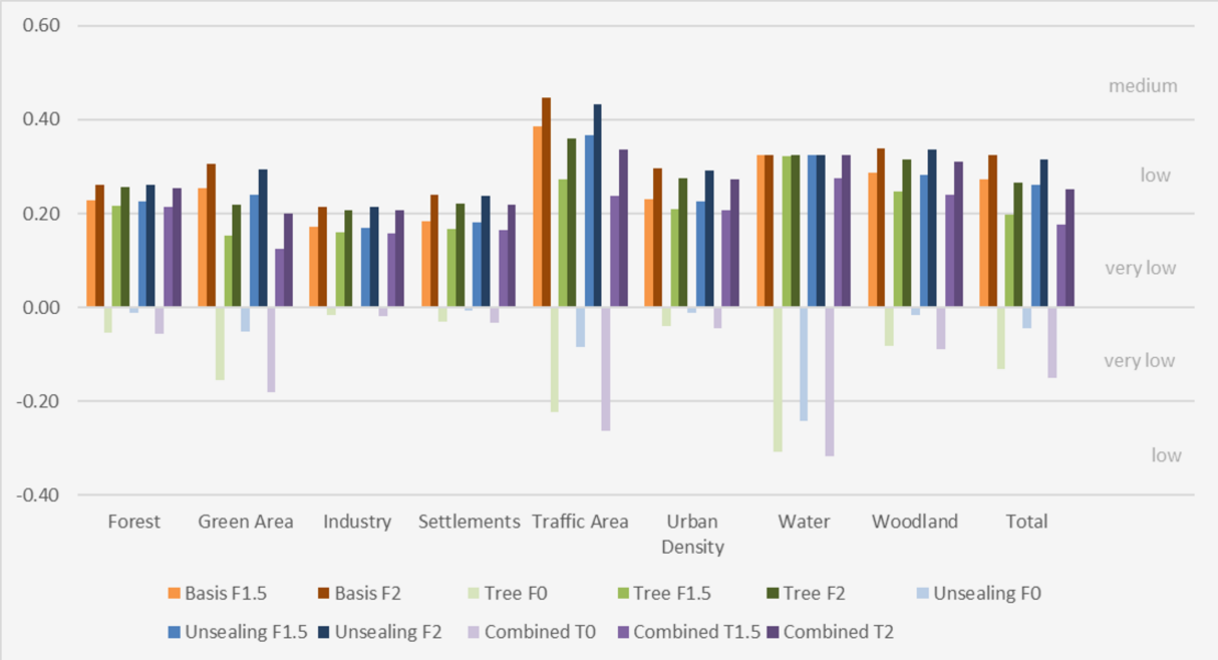

Figure 8 Area weighted FRES actual demand change by the NBS and rainfall scenarios over the different land uses.

The NBSunsealing measure led to a very low increase of supply in the area average for the F0 scenario. On average, green and traffic areas showed a low supply increase, while built areas were not affected by a demand change. Under the future climate scenarios F1.5 and F2, the demand increase exceeded the supply to a low actual demand increase, which is lower than for the NBS0. However, the land uses where the adaptation measure was not implemented had similar demand increases as without adaptation measures.

The combination of both NBS increased the supply high for the reference rainfall scenario F0, which also exceeded the effect of the NBStree. Higher rainfall amounts of the F1.5 scenario lowered the supply increase but it was still higher than the actual demand. Therefore, a medium supply surplus change was observed for F1.5 and a low supply exceed to the actual demand for the F2 scenario was shown. The spatial patterns were comparable to that of the NBStree, whereby the increase in supply exceeding the actual demand was more strongly over green and traffic areas for NBScombined.

All rainfall scenarios and NBS combinations showed hotspots on the west of the Botanical garden and in the south of the study area at the Zoo. While the supply increase is slightly higher than the actual demand increase for the NBStree and NBScombined at the Holbeinplatz, the actual demand exceeded the supply with the NBS0 and NBSunsealing.

4 Discussion

4.1 The benefit of NBS and the impact of heavier rainfalls

The fact that there is no supply increase for the measure NBS0 and F1.5 allows the conclusion that retention by soil and canopy interception has already reached a capacity limit for the reference scenario F0 (Figure 4 and Figure 5). The capacity is determined by some green areas. However, the large increase in actual demand on traffic areas means that adaptation measures are necessary thus, NBS were tested in the following.

The NBSs increased the supply, reduced the run-off, and lowered the actual demand. For the future scenarios, they are shown to be able to lower the discharge and flooding compared to the reference land use (NBS0) of the respective rainfall scenarios but do not increase the supply enough to prevent flooding under higher rainfall events of scenarios F1.5 and F2.

The measure where tree canopies were expanded (NBStree), had a higher positive flood-reducing effect than the unsealing. This measure increased the supply by interception and led to a low actual demand decrease. The adaptation measure NBStree was with a higher increase of supply than actual demand in the mismatch analysis. It also showed the highest reduction of outflow and surface water depth over the 60 min time period, which also resulted in less water being available to flow into depressions of water bodies, thus lowering water levels and actual demand. Because of the increasing supply with higher rainfall amounts for the F1.5 scenario, it can be assumed that the supply capacity was not reached with the measure NBStree for the reference scenario. Despite the higher supply, the surface water increased with the measure NBStree for higher rainfall events and consequently the actual demand. One possible consequence of higher surface water depth could be higher velocities and faster runoff. Still, some traffic areas (for instance around the Holbeinplatz) had a very high increasing actual demand by simultaneous increase of supply with higher rainfall events. This might be because of the high sealing combined with surrounding areas contributing to inundations at the depression of the Holbeinplatz.

Other studies had also proven the contribution of interception by trees to lower the peak runoff. Camarena et al. (2022) have shown that trees have a major effect on peak runoff. Even if those results were site-specific, a single tree stored one cup of coffee per second, which may not have a major impact on the site at first, but contributed significantly to flood regulation for the entire area and reduces the runoff for downstream areas. Also Yarnvudhi et al. (2021) found that 60% catchment runoff can be avoided by trees per year. Although we only come to a reduction of 28%, it must be taken into account that we are looking at heavy rainfall in ungauged urban areas, while Yarnvudhi et al. (2021) studied long-term balances of a catchment. Interception capacities therefore initially have a buffering effect, especially through an increase in tree cover (Zölch et al., 2017), but even their capacities are reached for extreme events at one point (Smets et al., 2019). In summary, the NBStree can be seen as an effective adaptation measure for current and future extreme events to increase retention supply and lower flood hazards.

On the contrary, the benefits of the NBSunsealing measure were smaller. The supply increase was very small and could not reduce the actual demand. It is worth mentioning that unsealing in our study has only been applied to a small areal fraction, for which this measure was viewed as reasonable. Indeed, a supply increase was only visible in the areas where the measure was applied (green spaces and traffic areas), while the impact on the actual demand was very low.

Local effects could still be observed and in addition, the timeline analysis showed a small reduction by the unsealing for all rainfall scenarios. Resulting from lower surface water levels, the actual demand was lower at the depressions of water bodies, which are mainly located within green areas where the NBS was applied. Therefore, a positive influence of the measure on surrounding deeper areas can be noted. The application of the measure to a limited number of elements and the aggregation of spatial or temporal elements in the further analysis, resulted in a small positive flood regulating impact for the NBSunsealing and therefore the change signal is mostly determined by the climate changes (Strasser et al., 2019). Furthermore, the used FRES-supply depends on the initial saturation. Thus, unsealing is still a very important flood prevention measure as it delivers multiple ES such as groundwater recharge, biodiversity and climate regulation.

The combination of both NBS partially improved the FRES compared to the individual measure NBStree and influenced the supply in particular. For the rainfall scenario F2 (+28%) both, the NBStree and NBScombined, seem to reach their supply capacity, because no significant increase was detected and also the supply timeline showed a similar level for both rainfall scenarios, while the actual demand increased.

Using extreme events to evaluate adaptation measures limited the effects of NBS because of their reached retention capacities. The NBS still lower the run-off and have a retention effect, but their relative contribution is smaller as the rainfall intensities increase. Further, apart from the timeline of the outflow we mainly observed the impacts of the NBS where they were implemented, which was focused on traffic and green areas. FRES improvement for settlements, urban areas, and industry was not determined. Consequently, it can be said that a single adaptation measure is probably not sufficient (Smets et al., 2019). Trees will reduce heavy precipitation that may occur under an RCP 8.5 partly, in particular, but flooding cannot be avoided by one single ecosystem-based adaptation measure. Furthermore, the NBS have synergy effects and co-benefits on other ecosystem services and are not only positive for flood regulation, but also biodiversity, urban climate regulation, pollination and recreation.

4.2 Uncertainties and limitations of the approach

We used the sCC relation to scale future possible extreme events. Although this is a simple approach, we consider it to be a valid approximation. It is an alternative to climate modelling, which currently do not provide reliable results on local and short-duration precipitation projections, but non-hydrostatic models are under development (Lenderink and van Meijgaard, 2008; Westra et al., 2014; Manola et al., 2018; Dahm et al., 2019). For a sensitivity analysis of ecosystem services the (super-) Clausius-Clapeyron scaling is an appropriate method and was also used by Lenderink and Attema (2015) for climate scenario analysis. Originally, the sCC is the scaling of precipitation using the dew point temperature following local convective atmospheric processes, which leads to more robust results than the temperature. However, since no detailed information was available, we used the temperature. With the assumption of constant relative humidity 1°C temperature rising is linear to a 1°C dew point rising (Lenderink et al., 2011). Yet, it is unclear whether the scaling approach of sCC is transferable to regions with higher temperatures (above 24°C) (Westra et al., 2014; Lenderink et al., 2017).

In future climate scenarios, we did not consider drier soil conditions. Projected longer and more intense dry periods in combination with higher temperatures cause a decrease in soil moisture in some regions in the future (Holsten et al., 2009; Villaseñor, 2021). Parched soils can absorb less water and have a low infiltration rate, which reduces flood regulation by soils and lead to higher surface water levels, and will consequently cause higher actual demand (Liu et al., 2011). With the current set-up of LEAFlood, we can not capture such an effect, but only the initial saturated depth to lower the water level in the soil and give more infiltration space.

We have adopted a simplified methodological approach for the unsealing of the NBSunsealing. Entire road sections were unsealed instead of separating smaller areas, which in reality would be the case with green stripes. Furthermore, we did not consider soil improvement by the NBStree. Rooting loosens the soil and improves infiltration (Smets et al., 2019). Indeed, only small open areas are created along roads and the soils there are very compact. Therefore, taking soil improvement at tree pits into account would probably not have much effect here. Moreover, the results of the unsealing measure and the combination of trees and unsealing already showed only minor effects of soil improvement.

The results showed that the supply continues to increase at the end of the simulations, while the surface water and the outflow decreased. To assess the long-term retention effect of the measure beyond the event, the modelling time must be extended. Since we focus on the flood regulating effect during the rainfall event, the investigated time period is suitable for this research question.

The used hydrological model LEAFlood defined three indicators. Modelling is always only a reflection of reality and therefore the input data is always event (e.g. saturated depth) and site-specific (e.g. Manning n, saturated conductivity, or vegetation parameters). For example, the interception capacity is also an effective parameter whose literature values cannot be directly transferred into the modelling. Literature values often represent an average over a longer period, whereas we considered an extreme event. In the absence of on-site measurements, we have to refer to literature and measurements from other areas. The comparative study by Camarena et al. (2022) showed that LEAFlood could reflect the measurements well. Based on these arguments and further literature (Asadian and Weiler, 2009; Jackisch et al., 2013; Alves et al., 2018), we can justify the increased initial interception capacity (Breuer et al., 2003) for our research question on heavy rain events.

The ES concepts serve as a communication tool with an indication of ES. The normalization of indicators into a relative scale from 0 to 1 brings the advantage that indicators of different units can be compared. This is in particular relevant for the intersection of social or economic units (people or euro) and biophysical units (mm or mm²) (Czúcz et al., 2018). It must be noted that relative scales are based on different maxima values due to the different units, but also indicators of the same unit. Consequently, the scale is site and event-specific. This also applies to the mismatch analysis, whose variables (supply and actual demand) are based on indicators of the same unit but of different ranges.

The demand might be overestimated due to neglecting the urban drainage system, while this does not influence the FRES-supply. Since this study 1) focus on the contribution of the natural ecosystem to flood regulation and 2) we investigate the high rainfall intensities that typically exceed the capacity of urban drainage systems, this limitation is acceptable here.

Further, the ES classification eliminates some effects and details regarding temporal resolution. The maximum or 90%-quantile over the event duration was considered, and hence features, in particular throughout the event, are aggregated through statistical summarization and classification. The concept is thus static and the temporal course, which is important in flood regulation for reducing and shifting peak discharges, is summarized in simple ES indicators. Therefore, it is also important to examine the model results and absolute values, which is why we have additionally consulted the time series.

The ES concept serves as a communication tool with simplified indicators. It highlights the supply of ecosystems, rather than focusing on flood hazards only (European Parliament, 2007; Oppenheimer et al., 2014) the mismatch analysis of FRES-supply and demand 1) the contribution of natural ecosystems to flood regulation can be quantified, and 2) missing FRES-supply can be identified on hotspots with high actual demand (Dworczyk and Burkhard, 2021).

Concerning the higher rainfall intensities due to climate change, the mismatch analysis helps to highlight areas where the actual demand increases more due to higher surface water than the provided water retention by natural ecosystems. By taking into account the FRES-supply, a value is attributed to the natural ecosystems and adaptation measures such as NBS can be tested regarding their sufficiency and long-term effectiveness to lower flood hazards and consequently the actual demand. Therefore, the FRES framework provides a useful tool for testing the potential impact of NBS under changing climate conditions. This study did not include feedback from stakeholder and decision-makers. However, involving stakeholder in future research approaches would improve the FRES framework, is beneficial for identification of the stakeholder needs, the science-praxis dialogue, and the practical application success of NBS in urban planning (Grunewald et al., 2021).

4.3 Outlook

In this paper, we have shown the benefit and contribution of single NBS measures under increasing rainfall events due to climate change by examining indicators of canopy interception and soil water storage for the supply and surface water depth as a component of the actual demand. Another interesting additional indicator to estimate the effects of the NBS measures and the climate change projections would be the flow velocity. High velocities can cause high damage and is therefore an interesting indicator to estimate FRES-demand.

The NBS measures and climate scenarios can be further extended by taking into account more details. For instance, trees not only increase the storage capacity by interception and evaporation, but also by infiltration in tree pits (Zölch et al., 2017), which can be implemented for further analysis by a coupling of interception and infiltration improvement. In addition, drier soil conditions due to longer and warmer dry periods should be investigated regarding their impact on the FRES-supply by soils.

Apart from that, to improve the flood regulating ES other NBS like green roofs or a combination of different adaptation measures can be tested which is probably needed and sustainable to deal with future extreme events (Zölch et al., 2017). Green roofs tend to have a large effect on annual stormwater runoff and peak runoffs (Bengtsson, 2005), while the retention for extreme events is small (Stovin et al., 2013). LEAFlood is capable to consider green roofs either in a simple way as land use with appropriate soil settings (Camarena et al., 2022) or it can be further developed and connected with the details CMF model setup of green roofs by Förster et al. (2021).

Before bringing these or other adaptation measures into practice, a feasibility study for practical application needs with stakeholders to be carried out. The NBS how they are applied here, are theoretical concepts. For instance, a tree cover of 30 % cannot be realized over all traffic areas. Likewise, it is not necessarily possible to unseal all traffic areas by implementing green strips, nor to increase saturated conductivity by improving soil conditions.

We tested different rainfall scenarios and land use measures, while we held the potential demand constant. However, demographic change, urbanization and digitalization will change the demand in the future and there is still a lack of analysis on the ES demand side (Campagne et al., 2020). For instance, Mori et al. (2022) analyzed the temporal dynamics of FRES-budget for a catchment basin by land use/ land cover changes from 1990 to 2018. Therefore, another future task would be to test different demand scenarios and assess the increasing vulnerability to more intense rainfall events using the ecosystem services concept.

Lastly, better guidance to policy and decision-makers is needed, applying comprehensive and holistic approaches that highlight synergies and benefits of NBS or ecosystem-based adaptations to support sustainable urban development (Zölch et al., 2018).

5 Conclusion

The capacity of existing ecosystems has already been reached and exceeded under past rainfall events. No noticeable increase in supply can be observed for projected higher amounts of short-duration (one hour) extreme rainfall events. Consequently, the flood hazard increases under the climate change scenarios of 1.5 and 2 degrees additional average annual warming that we studied, due to higher surface water depth and so the actual demand. The structure and landscape appearance of the investigated neighborhood in Rostock can be regarded as representative of the average of a medium-sized city in Germany. With this assumption, it can be expected that also in other cities with similar characteristics the existing green infrastructure is not sufficient for similar pluvial events.

Even though the study area already has a relatively high amount of green infrastructure in the form of trees and parks, this is not sufficiently shown by the future FRES assessment for today’s land uses. Both applied NBS partly increased the FRES-supply and reduced the flood hazard and consequently the actual demand for today’s rainfall events. The relative scale also indicated a higher increase in FRES-supply than the actual demand. For future projected heavy rainfall events, an impact of NBS can still be observed compared to modelling without NBS, but the supply cannot be noticeably increased and flooding and increasing actual demand cannot be prevented. The combination of both NBS behaves similarly to the results of the trees, which is why there is great FRES potential of trees to be mentioned here. As both NBS were applied on the same land uses (mainly traffic areas and green areas), we suggest to implementing a full set and combination of green infrastructure on different sites, such as settlements. Examples of measures within settlements are swales or green roofs or in addition. This is needed to adapt to extreme events associated with climate change and to create a resilient city over the entire area instead of single local measures.

Using the differences in the scenario and NBS combinations to the reference scenario NBS0 (no measures) F0 (current climate) appears to be an appropriate indicator to estimate the change and development of ES functions. Converting the results into relative scales make it possible to compare different indicators, although the use of the same units, such as monetary values in euro, would improve the results. The identification of FRES-supply and demand changes due to climate change and the benefits of NBS is a useful visualization tool for urban planning. Decision makers can be made aware of where natural ecosystems for sustainable city planning are missing and have the possibility to test the future functionality of adaptation measures.

6 Conflict of Interest

The authors declare no conflict of interest.

7 Author Contributions

Writing: TW; Study Design: TW, KF, LB, CD; Modelling: TW, KF; Reviewing: KF, LB, CD, BB; Supervision: SB, BB

8 Acknowledgments

The authors would like to thank Markus Groth and Simon Muwafu from GERICS for the internal review and language proof reading.

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Chapter 7

Synthesis

Figure 16. Urban areas have become important habitats for many wild animals. Photo: Jolanta Dworczyk

7. Synthesis

This Chapter summarises the main findings of the thesis and the individual Chapters and answers the research questions. Furthermore, this Chapter reflects challenges and limitations of this thesis. Finally, the thesis closes with conclusions and an outlook for future research.

7.1. Answers to research questions

7.1.1. What are the trends in mapping and assessing ecosystem services in urban areas?

Chapter 2 presented a literature review designed to analyse the trends in mapping ES in Europe. 177 articles were reviewed, and all mapped one or more ES in case study areas across Europe. The results showed that research on urban ES increased rapidly during 2010 - 2019. This trend underpins the rising relevance of the ES concept.

The case study areas of the reviewed publications were unequally distributed in Europe. Most studies were found in Germany, Great Britain, Spain, and Italy. Fewer records were found in South-East Europe. However, a closer look at research projects conducted during the screening process (e. g. ESMERALDA[7] research project, Geneletti et al., 2020) showed that research on urban ES was also conducted in South-Eastern European countries. The usage of only Scopus as a literature database could be a possible cause for this bias. Using additional databases (such as Google scholar) might identify further relevant records.

Nevertheless, the identified and screened articles revealed trends in mapping urban ES: The different case studies targeted urban ES on larger (neighbourhood, districts) to smaller spatial scales (city, region). The varying spatial scales can be related to the diversity of ES analysed and to targeted impacts of the study on urban or regional planning decisions (Haase et al., 2014). Research on a larger spatial scale could be aimed to influence strategies for urban planning and design. In comparison, research on a smaller spatial scale (e.g. regional and national scale) could be required for transboundary strategies or expanding Green Infrastructure (GI) (Grunewald et al., 2021; Maes et al., 2020).

In Chapter 2, CICES V5.1. (Haines-Young and Potschin, 2018) was used for classifying the ES analysed in the screened articles. The studies focused mostly on multiple ES from all categories (CICES sections), including abiotic services. Most frequently considered were regulating ES, followed by cultural ES and provisioning ES.

Generally, the articles screened showed that the research focus was concentrated on the following topics:

- Climate mitigation (e.g. carbon storage and sequestration) and climate adaptation (e.g. local climate regulation, flood protection, coastal protection);
- Mitigation of environmental pollution and related health impacts (e.g. regulation of air quality or water quality);
- Supporting urban biodiversity (e.g. maintaining nursery populations and habitats, pollination); and

[7] ESMERALDA - Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking, http://www.esmeralda-project.eu

- Supporting and maintaining non-transportable and non-replaceable ES (local climate regulation, noise attenuation, cultural ES).

Overall, those ES are expected to have high relevance for improving human health and the quality of life of urban dwellers (Gómez-Baggethun and Barton, 2013). Other reviews have also identified similar trends focusing on urban ES (e.g. Haase et al., 2014; Luederitz et al., 2015; Pulighe et al., 2016).

As diverse ES were considered in the articles studied, a variety of ES mapping methods and indicators were also used. Chapter 2 examined the indicators for local climate regulation as an example. The provision of this ES is influenced by complex climatic processes and site-specific factors. No standardised methods for assessing and mapping this ES were available when the literature review was carried out. Therefore, different methods and indicators were used in the studies and tested for their applicability. In some cases, unclear descriptions of the indicators as well as the very diverse mapping context of the respective studies made it difficult to compare the results.

Chapter 5 highlighted opinions and needs from scientists' and practitioners' perspectives from ten European urban case study areas. Both the scientists and practitioners acknowledged that the ES concept has the potential to deliver sustainable urban planning solutions. However, despite increasing urban ES assessments and mapping studies, the ES concept still has limited use and impact in policy and decision-making processes (see also Olander et al., 2017; Ronchi et al., 2020; Tezer et al., 2020). Here, the unclearly communicated added value of ES concept, lack of legal obligations, and conceptual and methodological challenges and obstacles were mentioned as barriers. These challenges and obstacles are discussed in more detail in the Subchapters 7.1.2 and 7.1.3 below.

7.1.2. What are the conceptual challenges in mapping ecosystem service supply and demand in urban regions?

The conceptual challenges in mapping ES supply and demand were addressed in Chapters 3-5. Chapter 3 in particular dealt with conceptual and methodological questions that remain to be addressed on the subject of ES demand. Table 2 provides an overview of the main conceptual challenges in mapping ES supply and demand and proposes solutions for researchers and map-makers.

Table 2. Overview of the main conceptual challenges in mapping ecosystem services supply and demand.

Challenges	Description	Solutions for researchers and map-makers
ES terminology	Issues related to ambiguous ES terminology	Use of existing guidelines and glossaries; Define key terms in every study; Communicate key terms as simply as possible
Identification of the (urban) ecosystem types	Issues related to urban definitions	Use of the global methodological manual *Applying the Degree of Urbanisation* (Eurostat, 2021); Use of existing classification systems of ecosystem types
Determining the spatial relationships between the different components of the ES supply and demand	Issues related to the allocation of Service Providing Areas (SPA), Service Benefiting Areas (SBA), Service Demanding Areas (SDA), and Service Connecting Areas (SCA)	Use of the conceptual backgrounds to spatial-structural approaches; Draught visualisations of the spatial relationships between relevant ES components

Challenge 1: ES terminology

As already specified above, differences in the use and understanding of important key terminology of the ES concept can result in mapping and implementation barriers (see Chapter 3 and 5, Palomo et al., 2018). Capturing and synthesising the diversity of definitions and conceptualisations has also been one of the major challenges of this thesis. Terms such as *ecosystem structures*, *processes*, *functions*, *services*, *benefits*, *ES supply*, *ES demand*, or *ES flow* are important for understanding the links between ecosystems and humans, but the labels are far from being used consistently in scientific literature or real-world applications and are frequently discussed from different scientific points of view (Grunewald et al., 2021; Potschin and Haines-Young, 2011). The discussions already start with the term ES itself. For example, it was recently suggested that the term 'nature's contributions to people' should be used instead of 'ecosystem services' (Díaz et al., 2018; IPBES, 2019). With this label, the scientists want to avoid the (alleged) dominance of economics and natural sciences in the ES concept and to strengthen perspectives from social sciences, including local knowledge from citizens and indigenous people (Díaz et al., 2018).

Ambiguous differences exist between ES supply and ES potential (Maes et al., 2020; Wei et al., 2017). According to the MAES glossary, the most significant difference is that human inputs (e.g. fertiliser, management practices) are not included in the definition of ES potential (Maes et al., 2020; Potschin-Young et al., 2018). A differentiated consideration of ES supply and ES potential is beneficial in the case of provisioning ES. Maes et al. (2020) provide methodologies and indicators that disentangle human and ecosystem contributions and enable the quantification of ES, such as food provisioning, strictly in relation to the amount of yield attributable to the ecosystem's role. Such results can certainly be useful for the agricultural sector, as this sector aims to maximise crop productivity and to reduce additional costs, such as fertilisers (Maes et al., 2020). However, for other ES, such as cultural ES, it is questionable whether the exclusion of human interventions and contributions would provide valuable information for policy and decision-makers at all (Burkhard and Maes, 2017; Chen et al., 2018; Geijzendorffer et al., 2015; Rioux et al., 2019). In urban contexts and from the perspective of practitioners, one acknowledged advantage of the ES concept is that it delivers arguments for the implementation of sustainable development policies which take into account all of the factors involved and consider their environmental, economic and social aspects (Grunewald et al., 2021). Human influences on the provisioning capacity of ES should, therefore, not be excluded from the assessment in this context.

Conceptual challenges exist especially on the subject of ES demand (Dworczyk and Burkhard, 2023, 2021). ES demand can be understood from an economic or social perspective (Wolff et al., 2015). From an **economic perspective,** demand can be understood as the "intention and willingness of economic units (e.g. businesses, governments or households) to buy goods, products or services" (Dworczyk and Burkhard, 2021, p. 7). The focus lies here on the actual use or consumption of the products, goods and services, which are supplied by an ecosystem and which flow from the ecosystem to the consumers. Therefore, the actual use or consumption of ES is often used synonymously as ES flow or ES demand in the ES mapping literature (Baró et al., 2016; Baró et al., 2015; Burkhard et al., 2014; Burkhard et al., 2012; Geijzendorffer et al., 2015; Villamagna et al., 2013). This understanding is also applied in the SEEA EA, which records the actual flow of ES between ecosystem assets and economic units in supply and use tables (United Nations, 2019). The SEEA EA follows standard accounting principles, according to which "the measure of the supply and use are equivalent and will be equal to the actual flow between the ecosystem asset and people" (United Nations, 2021, p. 117).

From a more **social perspective,** ES demand is directly associated with the beneficiaries (individuals, interest groups or society) expressing their consumption, needs, wants or preferences for the benefits of ES (Potschin-Young et al., 2018; Villamagna et al., 2013; Wolff et al., 2017). This is an important distinction as expressed needs, desires and preferences for ES may differ from the actual ES received and used. Furthermore, trade-offs between the beneficiaries' needs, desires and preferences of the beneficiaries can exist (Cavender-Bares et al., 2015). This is because people differ in their cultural and demographic characteristics (such as age, gender and ethnicity), have different levels of education, interests, motivation, financial resources or consumption patterns (Hegetschweiler et al., 2017; Pascual et al., 2014).

The variations of definitions can be attributed to inter- and transdisciplinary research, which is needed and desired *per se* by the holistic nature of the ES concept. Nonetheless, it is not helpful to expand all ES terms further semantically, as practitioners and stakeholders are already deterred by the complexity of the ES concept (Grunewald et al., 2021). A more important requirement is helpful and easy-to-follow guidelines and glossaries for ES researchers and ES map-makers (Burkhard and Maes, 2017; Dworczyk and Burkhard, 2021; Grunewald et al., 2021).

To overcome the variety of definitions, MAES has already harmonised existing definitions with an explicit focus towards the research topic of mapping and assessing ES (Potschin-Young et al., 2018). Yet, the MAES glossary needs to be better known and used among researchers and map-makers. In addition, researchers and map-makers still need to navigate between co-existing definitions and glossaries from, for instance, MA (2005a), TEEB (2010), SEEA-EA (with a strong economic focus) (United Nations, 2021), or the new terminology of Natures Contributions to People (IPBES, 2019). All terms are being harmonised, maintained and improved according to the current state of research. Furthermore, to promote the ES concept to practitioners, local stakeholders or the wider public, the terms and labels are often renamed for better communication. This happens because practitioners might not understand the ES terms, prefer to use terms from familiar approaches or are sceptical about the novelty of the ES concept (old ideas in new words) (Grunewald et al., 2021).

It is crucial for every study to decide, define and consistently use clear definitions of the terms used, as the understanding has a direct impact on the choice of methods, indicators, spatial scale and thus on the overall result (Dworczyk and Burkhard, 2021; Grunewald et al., 2021; Scott et al., 2018). This is especially important when results as well as the lessons learnt are aimed to be included in future case studies and research projects (Grunewald et al., 2021).

Challenge 2: Identification of the (urban) ecosystem types

Almost every urban ES mapping study faces the questions: *What is urban? What is an urban region? Where are the boundaries of a city? Where are the boundaries of an urban ecosystem?* The questions are not easy to answer and subject for discussions in the scientific articles (see Chapter 2, 3 and 5). Already the definitions or classifications of a city vary between countries and continents (Seto et al., 2013). Some countries use a minimum number of inhabitants for the definition of a city. However, this number can vary greatly between countries and can range from 200 (Denmark) to 50,000 or more (Japan) (UN Habitat, 2020; United Nations, Department of Economic and Social Affairs, Population Division, 2019b). Other countries use administrative boundaries to divide urban areas from rural areas. However, these boundaries may differ from the actual built-up area due to e.g. urban sprawl dynamics and may neglect the less densely populated commuting zone which has a labour market is strongly linked with the city (Dijkstra and Poelman, 2014; Maes et al., 2013).

Recently, to facilitate international comparisons, a new global methodological manual *Applying the Degree of Urbanisation* (Eurostat, 2021), has classified area typologies (cities, suburbs, suburban or peri-urban areas, villages, dispersed rural areas and largely uninhabited areas) depending on the degree of urbanisation. Furthermore, this manual provides guidelines for the delimitation of the *EU classification of territorial units for statistics (NUTS)* (Eurostat, 2021). MAES recommends using the manual's typologies to achieve consistent comparisons of urban ecosystem assessments across the EU (Dworczyk and Burkhard, 2020; Maes et al., 2016b).

Furthermore, Maes et al. (2016b) or European Environment Agency (2016a) provide guidance in the identification of ecosystem types for the EU. Those classification systems have the additional advantage that they are tailored to the needs of the EU Biodiversity strategy (Burkhard et al., 2018) and part of LULC data sets, such as CORINE Land Cover (European Environment Agency, 2019) or Urban Atlas (European Environment Agency, 2016b).

Challenge 3: Determining the spatial relationships between the different components of ES supply and demand

This challenge refers to the difficulties of determining the spatial relationships between the different components of the ES concept. A reoccurring conceptual question faced by researchers and map-makers is: *where should ES be mapped?* This question has been explored in detail in Chapter 3.

ES are spatially heterogeneously distributed and can change over time (Fisher et al., 2009). They are provided in process or function-related landscape units and LULC types such as, for example, ecosystems, biotopes or watersheds (Dworczyk and Burkhard, 2021; Syrbe and Walz, 2012). These areas (also called Service Providing Areas, SPA) can include both natural and anthropogenic elements and characteristics and provide multiple ES in various forms and quantities (Dworczyk and Burkhard, 2021; La Notte et al., 2019).

In contrast, the area in which people's demand for ES can be located, represents the Service Demanding Areas, SDA. ES demand is, however, multifaceted and can change over time, which makes spatially-explicit mapping difficult. The demand for ES and their related benefits can differ highly between individuals or subgroups of the population, as the use, consumption, wishes or preferences vary from person to person as well as from situation to situation (Dworczyk and Burkhard, 2021). Researchers and map-makers have different options for expressing ES demand: they can emphasise a) different preferences, wishes, values and norms; b) patterns of use and consumption of goods and final benefits, or c) the dependence on functioning (local) ecosystems for risk reduction/prevention and increased security (Dworczyk and Burkhard, 2021; Wolff et al., 2017; Wolff et al., 2015).

Between SPA and SDA, different forms of ES flow and transport mechanisms can appear and be visualised with the Service Connecting Areas (SCA). For many regulating ES, the possible extent of the SCA is determined, for example, by ecological functions and processes. The SCA can be interrupted by barriers or restrictions (Dworczyk and Burkhard, 2021).

Finally, the Service Benefitting Areas (SBA) describes the areas where people benefit from the ES of interest (Dworczyk and Burkhard, 2021). This area is not easy to map, as it needed the aforementioned spatial locations of SPA, SDA and SCA.

In every study, it is possible to map different types of spatial relations between SPA, SDA, SBA, and SCA (see Chapter 3, Figure 2). The different types of spatial relations (for example, in situ*,* directional, non-directional or spatially separated connections between SPA and SDA) are described in more detail in Chapter 3, where the descriptions are intended to illustrate that ES supply and demand can arise in different locations and that the benefits may be unavailable or out of reach. These are factors which researchers and map-makers need to bear in mind when exploring measures that address strengthening and protecting the capacity of an ecosystem to provide required services.

Chapter 6 used the adapted spatial-structural approach to a) define relevant indicators for the ES mismatch analysis, b) map ES supply and demand in the case study region, and c) analyse how different climate adaption measures increase or decrease the ES supply under future climate conditions. The study considered an *in-situ* situation: Heavy rainfall events can lead to severe flooding and cause several risks for the urban population. Therefore, a high capacity of vegetation and soils to regulate the amount of water needs to appear in the same area. Suppose the urban vegetation and soils can retain the rainwater, the urban population benefits directly from this ES. The study showed that low ES supply and high demand result in unmet demand: these areas need to be sufficiently protected by the available urban natural elements and are at risk for flooding. Identifying current and potential future ES mismatches can be a helpful visualisation tool for urban planning. The results provide evidence for sustainable policy- and decision-making on relevant spatial and temporal scales (Goldenberg et al., 2017; González-García et al., 2020).

7.1.3. What application obstacles do commonly applied ecosystem service mapping approaches face and how can these best be overcome?

Several obstacles of different ES mapping approaches were addressed in Chapters 4 and 6. Table 3 provides an overview of the main issues and proposes solutions for researchers and map-makers.

Table 3. Overview of the main obstacles in ecosystem services mapping approaches.

Obstacles	Descriptions	Solutions for researchers and map-makers
Selection of ecosystem services	Issues related to the process of selecting relevant ES	Establish criteria for determining the ES to be prioritised; Select ES according to the research purpose; Stakeholder involvement
Spatial and temporal scales	Issues related to spatial and temporal scales	Identify the needed spatial scale by using the spatial-structural approach; Research on and use of scalable indicators and data
Methodology	Issues related to select adequate ES mapping methods	Tiered approach for ES mapping; Decision trees for methods selection; Clearly define ES mapping purpose
Indicator selection	Issues related to select adequate ES indicator	Checklist for ES indicator selection; Stakeholder involvement
Data availability and accessibility	Issues related to data limitations	Open access data; FAIR principles

Obstacle 1: Selection of ecosystem services

This issue refers to the broad range and variety of ES that an ecosystem can provide. In urban ecosystems, for example, manifold ES are all essential for human well-being and health. CICES 5.1. lists more than 90 ES and abiotic services, which could be assessed and mapped in more detail. However, such a task would include an unaccountable amount of appropriate methods, indicators, data, and the necessary time and financial resources to assess and map them. Unsurprisingly, the same question arises in many ES case studies: *How do we prioritise and select the most relevant ES for the respective case study area?*

The selection of ES in a case study is a crucial step, as it influences the whole ES assessment and the outcomes for policy and decision-making (Boeraeve et al., 2018). Researchers and map-makers can get guidance for the ES selection process, for example, from literature reviews. Literature reviews are intended to highlight the trends, state of the art of ES mapping, availability of data, or research and knowledge gaps on a specific subject (Dworczyk and Burkhard, 2020; La Rosa et al., 2016; Luederitz et al., 2015). Furthermore, MAES provides summarised knowledge and frameworks (e.g. Maes et al., 2020; Maes et al., 2016b), which can be helpful in the first scoping phase of a project. In addition, criteria (e.g. spatial significance, relevance for the local population and ongoing decision processes, reference to binding agreements or strategies, such as the EU Biodiversity Strategy) can be determined to prioritise ES (Rabe et al., 2016).

However, the selection of ES solely based on literature or data availability often does not consider the individual urban settings and socio-cultural context in the case study areas (Boeraeve et al., 2018). Therefore, it can also be beneficial to include local stakeholders in the ES selection process (Boeraeve et al., 2018). With participatory processes, potentially important ES and the information requirements of local stakeholders can be identified (see also Chapter 5). Furthermore, a participatory process provides an opportunity to introduce and communicate the multifunctionality of ecosystems (Mascarenhas et al., 2016).

Obstacle 2: Spatial and temporal scales

This obstacle refers to the scale aspects that need to be considered in ES mapping. Ecosystem processes and underlying ecosystem functions occur on multiple spatial and temporal scales (Maes, 2017). The spatial scale can range from a local to a global extent, while the temporal scale can range from seconds to decades. The most suitable scale depends on the individual ES (Liu et al., 2017). In Germany, for example, pollination occurs only in warmer seasons, when insects (like bees) are active and can pollinate nearby plants. Comparatively, global climate regulation is determined globally by large-scale processes and functions whose impact can take decades to be seen (Maes, 2017).

Trade-offs and synergetic relationships among ES (Liu et al., 2017) or the spatial relationships between ES supply, demand and flow can appear on different scales (Kleemann et al., 2020; Schröter et al., 2018; Syrbe and Walz, 2012). Understanding the different spatial relationships is a prerequisite for defining the spatial scale, which addresses ES-related problems and solutions for policy and decision-making (Kleemann et al., 2020). However, selecting the most appropriate spatial scale for identifying trade-offs, synergies or ES mismatches can be challenging. Knowledge gaps still exist, in particular, as regards the temporal scales (Maes, 2017).

Chapter 3 focused on the complex spatial relationships between ES, highlighting how ES demand is generated on different spatial scales. It illustrated and clarified eight possible types of spatial relations between Service Providing Areas (SPA), Service Demanding Areas, Service Benefitting Areas (SBA) and Service Connecting Areas (SCA). The chapter's figures and examples are intended to act as guidelines for the identification of the most suitable spatial scale. For example, in a locally confined situation *(in-situ)*, ES are provided and demanded in the same area. Therefore, a local spatial scale would be deemed the most suitable for capturing potential ES mismatches and providing solutions for policy and decision-makers (see also Chapter 6). However, in the case of many other ES, ES supply and demand do not appear in the same geographical locations or on the same spatial scales. For example, a city's demand for food can normally only be met by ES provided beyond the city's boundaries and this food then needs to be imported into the city. In this situation, La Notte et al. (2019) distinguished between different categories of ES actors who influence the spatial relationships of ES supply and demand: a) beneficiaries, who directly use, consume or benefit from the flow of ES, and b) enablers, who either influence trade and logistics or decisions on land use and management practices. These dynamics can also be subdivided according to different institutional scales and this extra level of distinction should be considered (Ronchi, 2018; Syrbe and Grunewald, 2017).

Identifying these complex spatial relationships requires different ES mapping approaches, indicators and data (Maes, 2017). Cross-scale comparisons are, however, challenging to perform, as suitable methods and comparable indicators first need to be available (Lindborg et al., 2017; Liu et al., 2017). For example, Chapter 4 aimed to map ES supply and demand in the urban regions of Rostock and Munich, which would have provided the opportunity to conduct ES mismatch analyses. The expert-based ES matrix approach was used (alongside other approaches) to generate the required data. Local stakeholders were then asked to fill in the matrix, but they found it challenging to estimate the demand for regulating ES at a regional scale due to the more local scope of many ecosystem processes and underlying ecosystem regulating functions. The lack of indicators and data available at the required spatial scale hampered simple GIS mapping and prevented the use of available models like InVEST. There was a particular lack of suitable regional and local indicators for provisioning ES. The recommended indicators and data for provisioning ES primarily exist on a national scale, these are, however, not detailed enough for the purposes of regional mapping. To address these challenges, future ES research should provide and use scalable indicators which can be monitored over time (Lindborg et al., 2017; Liu et al., 2017; Maes, 2017).

Obstacle 3: Methodology

As described already in the introduction (Chapter 1.5), the selection of adequate methods is a challenging task. This issue has also been described in Chapter 4 (Dworczyk and Burkhard, 2023) and identified as one of the key challenges encountered during ES mapping processes (Palomo et al., 2018).

The tiered approach for ES mapping (see Chapter 1.5.2), decision trees for selecting biophysical, socio-cultural and monetary methods (Harrison et al., 2017), or online platforms such as the MAES Methods Explorer (ESMERALDA, 2020) can help to select methods regarding the research purpose, knowledge, data and resource availability. The different purposes of ES mapping can have low to high quality requirements concerning the maps' reliability, accuracy, spatial and temporal resolution and clarity (Jacobs et al., 2017). For communication or awareness rising, for example, ES maps produced with low to medium spatial resolution and data accuracy might be suitable enough to show spatial patterns. However, detailed maps with high accuracy are required for other purposes, such as ecosystem accounting or urban planning measures (Grunewald et al., 2021; Jacobs et al., 2017). Therefore, it is helpful to define the ES mapping exercises' purpose and check the available resources (data, time, knowledge, money).

However, despite carefully selecting the ES mapping methods, other challenges and obstacles can hinder the ES mapping process. Chapter 4, for example, mapped with different methods (expert-based matrix approach, simple GIS mapping, models) ES demand and supply for selected ES. The expert-based ES matrix approach is appreciated for its simple and fast technique that can provide spatially explicit results (Burkhard, 2017; Campagne et al., 2020; Harrison et al., 2017). Although ES demand has been estimated with the expert-based ES matrix approach in other studies (Campagne et al., 2020), discussions with local stakeholders on the subject of ES demand revealed that this component needs a clarified understanding and further research (Chapter 4). An alternative methodological design which uses questionnaires and joint discussions instead of a blank matrix could be a solution to avoiding this challenge. GIS mapping using proxy indicators and data was also only partially successful. Unfortunately, recommended and well-tested indicators and accessible data were still missing for either ES supply or demand (see Issue 3 – Indicator selection). Simple ES models like InVEST are not yet available for all individual ES at the selected spatial scale or the models do not consider both ES supply and demand (The Natural Capital Project, 2021b).

In addition, some ES are well-studied, such as flood regulation, which means that several models are available (Lüke and Hack, 2018; Nedkov and Burkhard, 2012; Stürck et al., 2014; The Natural Capital Project, 2021b; Wübbelmann et al., submitted). However, the differences in the model structure and the required data basis lead to differences in the outcomes that can be generated. Hence, the question arises: *which models should be selected for the respective research question and which can generate the "best" results?*

Burkhard (2017) suggested comparing the results of different methods using the ES matrix method. With this method, map comparisons can be facilitated by normalising and classifying different results into a comparable scale. Such a map comparison was carried out in Chapter 4. There, the different methods' results were compared to determine whether they showed spatial differences. Unsurprisingly, differences emerged depending on the information reflected by the chosen indicator (see Obstacle 4 - Indicator selection). However, the map comparisons revealed that the expert-based ES matrix approach identified similar spatial patterns as the other methods tested. This result showed that ES mapping methods with lower map quality requirements do not necessarily provide less reliable results on a regional scale. This finding matches other map comparisons on this subject (Lüke and Hack, 2018; Roche and Campagne, 2019; Wei et al., 2017).

Obstacle 4: Indicator selection

This obstacle refers to the challenge to select adequate ES indicators. Indicators describe or reflect a phenomenon of interest (here, individual ES) (Potschin-Young et al., 2018) and can be captured and mapped using methods and models of different disciplines (e.g. sociology, economics or natural sciences) and varying complexity (ESMERALDA, 2020; Harrison et al., 2017; Maes et al., 2020).

In the ES literature, tested and proposed indicators are of varying quality and informational content (Czúcz et al., 2018a; La Rosa et al., 2016; van Oudenhoven et al., 2018).

Chapter 4, for example, mapped for communication and awareness-raising reasons several ES with GIS using proxy indicators and data (LULC, literature or statistical data). Proxy indicators (especially those that are based on just one variable or data set) can only reflect a certain phenomenon of the comprehensive object (Czúcz et al., 2018a). The causality between variables used and the actual phenomenon of interest can often only be assumed (Czúcz et al., 2018b; Schröter et al., 2020). Baró et al. (2016) and Schulp et al. (2014) warned that there is a high potential for bias when using proxy variables, especially in spatially explicit approaches. To tackle this problem, several proxy indicators can be used to reflect the complexity of an object (Müller and Burkhard, 2012). In an urban context, for example, proxy indicators that can measure environmental, economic and demographic aspects should be used (La Rosa et al., 2016). This recommendation was followed up in the assessment of ES demand for coastal protection in Chapters 4 and 6. Here, several proxy indicators express the variations of coastal flood risks for different protected assets (human health, infrastructure, economic, environment, and human economic activities). The indicators have the additional advantage that they are directly linked to the EU Floods Directive (Directive 2007/60/EC) (European Union, 2007).

Many scientific articles noted that scientific information is most likely to be effective for decision-making processes if the quality of the selected indicator is perceived to be credible, salient, legitimate and feasible (Cash et al., 2003; Grunewald et al., 2017; van Oudenhoven et al., 2018). On the subject of ES, *credibility* refers to the scientific adequacy of the information and technical evidence that the indicator provides (Cash et al., 2003; van Oudenhoven et al., 2018). This means, that, alongside other considerations, the indicator is agreed upon by experts and the scientific community and backed by scientific literature and high-quality data (ibid.). *Salience* refers to the relevance and usefulness of the assessment to the needs of policy- and decision-makers (ibid.). This means that the indicator is understandable, can raise awareness about important topics in the case study, is transferable and scalable, and can monitor changes of time (ibid.). *Legitimacy* reflects that the indicator has been chosen for acceptable and fair reasons. This includes behaving in an unbiased and objective manner and respectfully and appropriately treating stakeholders' divergent values, views, interests and beliefs (ibid.). Furthermore, the *feasibility* reflects whether there are adequate data, time, knowledge and resources to continuously assess and monitor proposed and selected ES indicators. Continuous assessment and monitoring reveals changes over time, which can be of value for decision-makers (van Oudenhoven et al., 2018).

Van Oudenhoven et al. (2018) provided guidance for the indicator selection process and a checklist for selected indicators. A collaborative selection of indicators with experts and (local) stakeholders can be helpful (Czúcz et al., 2018b; Mascarenhas et al., 2016). Locally selected and agreed indicators provide an optimal balance between credibility, salience, legitimacy and feasibility (Czúcz et al., 2018b; Olander et al., 2017).

Obstacle 5: Data availability and accessibility

The availability of and accessibility to appropriate data and statistics at the required spatial and temporal scale significantly affects the selection of indicators and methods (Palomo et al., 2018; Sylla et al., 2021). The study in Chapter 4 in particular faced different reasons for data unavailability and inaccessibility during the ES mapping process. Several methods and indicators were considered to be of interest in the indicator selection process, but could not be used since the required data a) simply did not exist, b) was expensive or restricted due to data protection laws (for example InVeKoS

(Integrated Administration and Control System) (Bay.StMELF, 2021)), or c) not available at the required spatial and temporal scale (see also Obstacle 2).

To tackle some of those issues, researchers and map-makers should, whenever possible, use open data and publish developed mapping methods, models and generated results under, for example, the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles (Wilkinson et al., 2016).

7.2. Limitation and uncertainties of this thesis

Several uncertainties and limitations are inherent in the individual parts of this thesis. Most of the uncertainties and limitations can be related to the aforementioned conceptual challenges in mapping ES supply and demand in urban regions and the persistent issues in ES mapping approaches. In the following, the most important limitations and uncertainties are synthesised.

One of the major challenges of this thesis dealt with the existing variety of ES terms and their definitions. Despite using the MAES glossary (Potschin-Young et al., 2018), uncertainties in the use of the key terms may be present. This is particularly noticeable in the different understanding of the term 'ES demand' in Chapter 3.

Chapter 3 provided an initial overview of the spatial relationships between the different components of the ES concept. This being the case, various aspects (e.g. spatial or temporal changes) that might influence the distribution of individual ES still need to be included. Chapter 6 used the spatial structural-approach for structuring its analysis. The study focused on an *in-situ* situation, where ES supply (capacity of vegetation and soils to retain the amount of heavy rainfall), demand (assets at risk of pluvial flooding), and benefits (prevented pluvial flooding through vegetation and soils) appear in the same area. However, upstream or downstream effects can appear in a heavy rainfall event. To include those effects, consideration of the ES flow and mapping the SCAs might be useful.

Methodological uncertainties can be found in the Chapters 2-6. For example, in Chapter 2, only peer-reviewed studies from Europe were included. However, scientific research from other regions of the world, such as China and the USA (Georgia et al., 2022), also contribute valuable information. However, the increasing amount of scientific literature on the subject of ES required a narrowing focus. Chapter 3 (Dworczyk and Burkhard, 2021) focused on the development of an adapted spatial approach. For the development, existing reviews and theoretical articles that focus on ES supply and demand were highly relevant. The review included only English literature and peer-reviewed studies from 2015 to 2020. This period was chosen because previous publications were already considered in a comprehensive review by Wolff et al. (2015). The use of broader keywords (such as 'use', 'need') would eventually have provided a larger number of topic-related articles. Other articles might also address issues of ES demand without mentioning the term in the title, keywords, or abstract.

This thesis used a set of ES that were compiled in the ÖSKKIP research project (Barkmann et al., 2020; Barkmann et al., 2019). These ES were selected by the research team and local stakeholders at workshops in Rostock and Munich. The selection of participants involved a previously conducted stakeholder analysis. Potential participants were selected and invited according to their professional backgrounds and how they related to the targeted ES. Here, attention was paid to the fact that the local stakeholders already had knowledge about certain topics that could be linked to certain ES. Of the 132 people invited, only 30 participated in the workshops. A different selection and invitation of local stakeholders would most likely have resulted in a selection of different ES. Furthermore, the mapping issues mentioned above (e.g. availability and accessibility of data) resulted in the fact that only some of the ES selected by the stakeholders could be considered in Chapter 4 (Dworczyk and Burkhard, 2023). In particular, cultural ES were missing in this study.

Chapter 4 (Dworczyk and Burkhard, 2023) aimed to map ES supply and demand for several selected ES. However, it was challenging to find appropriate methods, indicators and data for the chosen mapping purpose. For the simple GIS mapping, datasets from different sources (for example literature, official statistics, LULC data) and different spatial and temporal resolutions have been used. As in all GIS mapping and modelling, the quality and spatial resolution of the used input data had an influence on the results (Wübbelmann et al., submitted).

Chapter 5 (Grunewald et al., 2021) collected the scientific experts' perspectives through questionnaires and the practitioners' perspectives through semi-structured interviews. Different methods might lead to bias in identifying or not identifying existing barriers and opportunities of the ES concept. The number of interviewed practitioners also varies between the study areas.

Chapter 6 (Wübbelmann et al., submitted) focused on only one ES, namely flood regulation, which is primarily caused by the complexity and time-consuming nature of the LEAFlood model. It would, however, be advantageous to include multiple ES in scenario and ES mismatch analyses. The results could be used to inform policy and decision-makers on sustainable urban design and the wise use of multiple ES in the future (Geijzendorffer et al., 2015; Palacios-Agundez et al., 2015).

7.3. Conclusion and prospects for future research

ES in urban areas is a very active research field that addresses social challenges in the context of climate change, biodiversity loss, environmental pollution, unsustainable land-use management and environmental justice. Despite the increasing number of urban ES assessments and mapping studies, the ES concept still only sees limited policy use and is yet to have any significant influence upon real-world decision-making processes. And, this limited application at a policy making level can at least partially be attributed to the field's persisting conceptual challenges and to problems intrinsic to ES mapping approaches themselves.

In urban contexts, the conceptual challenges of the ES concept can be traced back to three main issues: ambiguous ES terminology, the distinction between urban and non-urban areas across administrative boundaries, and difficulties in determining the spatial relationships between the different components of the ES concept across spatial scales.

The proliferation of ambiguous ES terminologies can be attributed to the inter and transdisciplinary character of the ES concept and is seen as a natural consequence of the field's concurrent development within multiple disciplines. Were each individual study to start by transparently communicating its own research purpose and specific intradisciplinary understanding of the ES concept, then this would help contribute to clarifying one's own stance and to overcoming interdisciplinary differences in perception and definition. For example, *An operational framework for integrated Mapping and Assessment of Ecosystems and their Services (MAES)* (Burkhard et al., 2018) provides several practical steps for more structured ES mapping processes. An essential part of this framework is the necessity to define and report key terminologies.

A standardised approach is also recommended for identifying and describing urban areas, ecosystem types and ES. To facilitate EU-wide comparisons of urban case studies, the following classification systems are recommended:

- For urban typologies: the global methodological manual, *Applying the Degree of Urbanisation*, by Eurostat (2021);
- For ecosystem types: common classification systems such as presented by Maes et al. (2016b) or the European Environment Agency (2016a);
- For ES classification: the categorisations proposed by the *Common International Classification System of ES* (CICES) (Haines-Young and Potschin, 2018).

While comprehensive, it should, however, be stated that CICES is a very complex and academic publication. Therefore, its descriptions of classifications require some interpretation before being used with actors outside academia.

Overall, a standardised approach is desirable and necessary for assessing and mapping ES. However, this thesis has shown that existing research gaps need to be filled for this to be achieved. This thesis lists several key criteria which play a role in determining which ES mapping approaches can be applied. These criteria can be grouped into five topics: 1) the selection of ecosystem services, 2) the determination of spatial and temporal scales, 3) the selection of appropriate methods, 4) the selection of suitable indicators, and, 5) data availability and accessibility. To summarise, ES mapping is particularly in need of low-cost and accessible data, scalable, transferable and high-quality indicators and methods that provide easily understandable results.

The EU working group MAES has provided a good example of how to proceed going forwards, working to recommend frameworks, methods and indicators which have been developed and tested in numerous research activities. MAES's groundwork should be built upon to ensure that outstanding indicators and methods are developed in consultation with practitioners and with a clear practice orientation. This will ensure that researchers are able to guarantee that their work is orientated towards the needs of practitioners and provides a robust basis for decision-making.

In addition to improved standardisation, a stronger focus on ES demand and its feedback loops for ES supply is urgently needed. The growth in urban populations worldwide puts increased pressure on multiple ES. The concurrent and ongoing overexploitation of ecosystems and their services is one of the causes of climate change, which itself further compromises the ability of ecosystems to provide ES and poses increased risks to human health and well-being.

New studies are required which map and assess the economic and social perspectives of ES at the desired urban-regional scales. Such studies would make a significant contribution to future research prospects. In particular, comprehensive and transdisciplinary research would help to assess the multifaceted nature of ES demand and to provide more detailed analysis of the many factors at work. Research could, for example, look to facilitate identification of the drivers determining land-use management practices in urban areas or to explore the impact of different measures in future climate change scenarios. Whatever the scenario, the more comprehensive the data on the multifaceted nature of ES interaction, the greater our chances of providing information that really helps to formulate more sustainable and equitable urban design and land-use decisions.

It would also be advantageous to better utilise existing connections to relevant legislation and proven approaches within the ES concept. Using indicators and data employed in policies such as the EU Floods Directive (Directive 2007/60/EC) could help increase the ES concept's impact and enhance the understanding and acceptance of research results amongst local stakeholders. Furthermore, non-ES native approaches, such as life cycle (Guinée et al., 2011; Luca Peña et al., 2022; Othoniel et al., 2016) or ecological footprint (Global Footprint Network, 2022; Mancini et al., 2018) assessments, have been developed to highlight the impact of human activities upon demand for natural resources and provide excellent communication and awareness-raising tools (Nadalini et al., 2021), with which the problems of high ES demand can be highlighted for local stakeholders. These methodologies could all be used as alternative or additional approaches for assessing the connections between urban and peri-urban areas (Seto et al., 2012), ES flows (Kleemann et al., 2020; Schröter et al., 2018) and ES demand for provisioning ES, and selected regulating and cultural ES (Othoniel et al., 2016). However, the initial ideas for integrating these approaches into the ES cascade framework will require some additional development before they can provide site-specific information on multiple ES (Luca Peña et al., 2022; Rugani et al., 2019).

Overall, better integration of the demand side of the ES concept will be crucial if we are to achieve the EU's Biodiversity Strategy objective of halting biodiversity loss and the ongoing degradation of ecosystems and their services. Meaningful interpretations of ES supply and demand will need to be available to inform decision-makers about the best ways of reducing ES trade-offs and mismatches. The adapted spatial-structural approach developed here contributes to this by providing helpful support for understanding the spatial linkages and interdependencies between ES supply and demand. Maintaining healthy ecosystems and their services in urban and peri-urban areas will be key to ensuring the future sustainable and equitable development of cities, especially in the face of increased urbanisation and climate change. And, overcoming the identified conceptual challenges and application barriers forms a significant first step towards increasing the use and impact of the ES concept in policy and decision-making processes in these regions.

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9. Acknowledgements

I want to thank all those who have contributed to completing this thesis.

I wrote my cumulative dissertation as a research assistant at the Institute of Physical Geography and Landscape Ecology at Leibniz Universität Hannover, where numerous colleagues contributed to and encouraged my work.

Many thanks to Prof. Benjamin Burkhard from the Leibniz University of Hanover for supervising my doctoral thesis. I highly appreciated his expertise, experience, and advice on ecosystem services. He encouraged me to continue my work on this project, despite all the setbacks. I highly appreciated and enjoyed working with him.

I also want to thank Prof. Nadja Kabisch for her reviews, advice and motivation. I am looking forward to working with her on new projects going forwards.

A very sincere thank you to the entire Phygeo team. The discussions during our coffee breaks were always a welcome addition to my daily work routine. Special thanks to Marie, Malte, Ina, Simone, Jenny and Alex, who accompanied me as doctoral students. Special thanks also to Thea for our joint writing sessions.

I also want to thank all my editors and reviewers for their valuable feedback. Without them, the published articles would not have been possible. Many thanks to Matt, Ann and Angie for English proof-reading.

During the last few years, I have had the opportunity to participate in the ALTERnet Summer School in Peyresq (France) and Ecosystem Services Partnership conferences in San Sebastian (Spain), Hanover (Germany), Heraklion (Greece) and (virtually in) Tartu (Estonia). Due to their close relationship to the ES topic, these conferences were very inspiring, despite the adventurous journeys to and from them in some cases.

My research was supported by the research project ÖSKKIP (an acronym for Ecosystem Services of Urban Regions – Mapping, Communicating and Integrating into Planning to conserve biodiversity in a changing climate) funded by the German Ministry of Education and Research (BMBF). And, I want to thank the whole ÖSKKIP project team for the exchange of expertise and their valuable contributions.

Last but not least, I thank my family and friends for their support and encouragement. Special thanks to my parents, my sister Nicole and to my sister Jolanta, who has enriched this work with her fantastic photographs. Most importantly, I am grateful to Matthew for his emotional support, patience and motivation.

10. Declaration of own contributions

Surname, first name	Dworczyk, Claudia Anna
Doctoral field	Natural Sciences
Topic of dissertation	Conceptual and methodological challenges of ecosystem services mapping in urban regions

Numbered list of the submitted texts within the dissertation:

1 Urbane Ökosystemleistungen erfassen und bewerten. Stand der Forschung, Indikatoren und zukünftige Perspektiven; Dworczyk, C., Burkhard, B.; Naturschutz und Landschaftsplanung (2020) 52, 176–183

2 Conceptualising the demand for ecosystem services – an adapted spatial-structural approach; Dworczyk, C., Burkhard, B.; One Ecosystem (2021) 6, e65966.

3 Challenges entailed in applying ecosystem services supply and demand mapping approaches: a practice report, Dworczyk, C., Burkhard, B.; *Land (2023) 12.*

4 Lessons learned from implementing the ecosystem services concept in urban planning; Grunewald, K., Bastian, O., Louda, J., Arcidiacono, A., Brzoska, P., Bue, M., Cetin, N.I., Dworczyk, C., Dubova, L., Fitch, A., Jones, L., La Rosa, D., Mascarenhas, A., Ronchi, S., Schlaepfer, M.A., Sikorska, D., Tezer, A. *Ecosystem Services* (2021) 49, 101273.

5 Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute? Wübbelmann, T., Förster, K., Bouwer, L.M., Dworczyk, C., Bender, S., Burkhard, B.; Submitted to *Frontiers.*

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Re. no. 1 Writing: C.D., B.B.; Concept development: C.D., B.B.; Literature review/data collection: C.D.

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Re. no. 3 Conceptualization, C.D., B.B.; methodology, C.D.; software, C.D.; formal analysis, C.D.; investigation, C.D.; resources, C.D.; data curation, C.D.; writing—original draft preparation, C.D.; writing—review and editing, C.D., B.B.; visualization, C.D.; supervision, C.D.; project administration, C.D., B.B.; funding acquisition, B.B.

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11. List of Publications

Barkmann, T., Heitmann, A., Wessels, A., Dworczyk, C., Matschiner, J., Neumann, C., Savaşçı, G., Burkhard, B., Deppisch, S., 2020. Ökosystemleistungen in den Stadtregionen: Angebot, Nachfrage und Planungsrelevanz - Bericht über die Durchführung und Ergebnisse der zweiten Workshopreihe in den Pilot-Stadtregionen Rostock und München, 64 pp.

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Dworczyk, C.; Burkhard, B. (2020): Urbane Ökosystemleistungen erfassen und bewerten. Stand der Forschung, Indikatoren und zukünftige Perspektiven. In: *Naturschutz und Landschaftsplanung* 52 (04), S. 176–183.

Dworczyk, C.; Burkhard, B. (2021): Conceptualising demand for ecosystem services – an adapted spatial-structural approach. In: *One Ecosystem* 6: e65966. DOI: 10.3897/oneeco.6.e65966.

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12. Scientific communications

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13. Appendices

List of supplementary information for Chapter 2-6 and their page number

Online-Supplement zur Veröffentlichung:
DWORCZYK, C., BURKHARD, B. (2020): Urbane Ökosystemleistungen erfassen und bewerten. Stand der Forschung, Indikatoren und zukünftige Perspektiven. Naturschutz und Landschaftsplanung 52 (4), 176-183.

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Tabellen

Tab. A1: Liste der untersuchten Literatur.

Autoren	Titel	Jahr	Zeitschrift	Band (Ausgabe) Seitenangaben	Untersuchungsgebiet
AEVERMANN T., SCHMUDE J.	Quantification and monetary valuation of urban ecosystem services in Munich, Germany	2015	Zeitschrift fur Wirtschaftsgeographie	59(3):188-200	Muinch, Germany
ALBERT C., VON HAAREN C.	Implications of Applying the Green Infrastructure Concept in Landscape Planning for Ecosystem Services in Peri-Urban Areas: An Expert Survey and Case Study	2017	Planning Practice and Research	32(3):227-242	Hanover, Germany
ANDERSSON K., ANGELSTAM P., ELBAKIDZE M., AXELSSON R., DEGERMAN E.	Green infrastructures and intensive forestry: Need and opportunity for spatial planning in a Swedish rural-urban gradient	2013	Scandinavian Journal of Forest Research	28(2):143-165	Sweden (119 municipalities)
ARNOLD J., KLEEMANN J., FÜRST C.	A differentiated spatial assessment of urban ecosystem services based on land use data in Halle, Germany	2018	Land	7(3), 101	Halle (Saale), Germany
ARTMANN M.	Assessment of soil sealing management responses, strategies, and targets toward ecologically sustainable Urban land use management	2014	Ambio	43(4): 530-541	Leipzig, Germany Munich, Germany
ARTMANN M.	Urban gray vs. urban green vs. soil protection — Development of a systemic solution to soil sealing management on the example of Germany	2016	Environmental Impact Assessment Review	59:27-42	Munich, Germany Leipzig, Germany
ARTMANN M., BASTIAN O., GRUNEWALD K.	Using the concepts of green infrastructure and ecosystem services to specify leitbilder for compact and green cities-The example of the landscape plan of Dresden (Germany)	2017	Sustainability	9(2), 198	Dresden, Germany
BARÓ F., CHAPARRO L., GÓMEZ-BAGGETHUN E., LANGEMEYER J., NOWAK D.J., TERRADAS J.	Contribution of ecosystem services to air quality and climate change mitigation policies: The case of urban forests in Barcelona, Spain	2014	Ambio	43(4)	Barcelona, Spain
BARÓ F., GÓMEZ-BAGGETHUN E., HAASE D.	Ecosystem service bundles along the urban-rural gradient: Insights for landscape planning and management	2017	Ecosystem Services	24:147-159	Barcelona, Spain
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BARÓ F., PALOMO I., ZULIAN G., VIZCAINO P., HAASE D., GÓMEZ-BAGGETHUN E.	Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region	2016	Land Use Policy	57:405-417	Barcelona, Spain
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BORYSIAK J., MIZGAJSKI A., SPEAK A.	Floral biodiversity of allotment gardens and its contribution to urban green infrastructure	2017	Urban Ecosystems	20(2):323-335	Poznan, Poland
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COHEN M., BAUDOIN R., PALIBRK M., PERSYN N., RHEIN C.	Urban biodiversity and social inequalities in built-up cities: New evidences, next questions. The example of Paris, France	2012	Landscape and Urban Planning	106(3):277-287	Paris, France
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NIELSEN A.B., HEDBLOM M., OLAFSSON A.S., WISTRÖM B.	Spatial configurations of urban forest in different landscape and socio-political contexts: identifying patterns for green infrastructure planning	2017	Urban Ecosystems	20(2):379-392	all Danish and Swedish cities >10,000 inhabitants
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ONUR A.C., TEZER A.	Ecosystem services based spatial planning decision making for adaptation to climate changes	2015	Habitat International	47:267-278	Istanbul, Turkey
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QUATRINI V., TOMAO A., CORONA P., FERRARI B., MASINI E., AGRIMI M.	Is new always better than old? Accessibility and usability of the urban green areas of the municipality of Rome	2019	Urban Forestry and Urban Greening	37:126-134	Rome, Italy
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	provided by urban green		Planning		
RIECHERS M., STRACK M., BARKMANN J., TSCHARNTKE T.	Cultural ecosystem services provided by urban green change along an urban-periurban gradient	2019	Sustainability	11(3), 645	Berlin, Germany
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SAMUELSSON K., GIUSTI M., PETERSON G.D., LEGEBY A., BRANDT S.A., BARTHEL S.	Impact of environment on people's everyday experiences in Stockholm	2018	Landscape and Urban Planning	171:7-17	Stockholm, Sweden
SANTOS A., PINHO P., MUNZI S., BOTELHO M.J., PALMA-OLIVEIRA J.M., BRANQUINHO C.	The role of forest in mitigating the impact of atmospheric dust pollution in a mixed landscape	2017	Environmental Science and Pollution Research	24(13):12038-12048	Leiria, Portugal
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SCOTT A., DEAN A., BARRY V., KOTTER R.	Places of urban disorder? Exposing the hidden nature and values of an English private urban allotment landscape	2018	Landscape and Urban Planning	169:185-198	Dudley, UK
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Yli-Pelkonen V.			Assessment Policy and Management		Lahti, Finland
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Spanò M., Leronni V., Lafortezza R., Gentile F.	Are ecosystem service hotspots located in protected areas? Results from a study in Southern Italy	2017	Environmental Science and Policy	73:52-60	Bari, Italy
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Szücs L., Anders U., Bürger-Arndt R.	Assessment and illustration of cultural ecosystem services at the local scale - A retrospective trend analysis	2015	Ecological Indicators	50:120-134	Göttingen, Germany
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Tratalos J.A., Haines-Young R., Potschin M., Fish R., Church A.	Cultural ecosystem services in the UK: Lessons on designing indicators to inform management and policy	2016	Ecological Indicators	61:63-73	Nottingham, UK
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Van de Voorde T.	Spatially explicit urban green indicators for characterizing vegetation cover and public green space proximity: a case study on Brussels, Belgium	2017	International Journal of Digital Earth	10(8):798-813	Brussels, Belgium
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Vieira J., Matos P., Mexia T., Silva P., Lopes N., Freitas C., Correia O., Santos-Reis M., Branquinho C., Pinho P.	Green spaces are not all the same for the provision of air purification and climate regulation services: The case of urban parks	2018	Environmental Research	160:306-313	Almada, Portugal
Votsis A.	Utilizing a cellular automaton model to explore the influence of coastal flood adaptation strategies on Helsinki's urbanization patterns	2017	Computers, Environment and Urban Systems	64:344-355	Helsinki, Finland
Wamsler C., Niven L., Beery T.H., Bramryd T., Ekelund N., Jönsson K.I., Osmani A., Palo T., Stålhammar S.	Operationalizing ecosystem-based adaptation: Harnessing ecosystem services to buffer communities against climate change	2016	Ecology and Society	21(1), 31	Helsingborg, Sweden Kristanstad, Sweden Lomma, Sweden Malmö, Sweden
Wandl A., Rooij R., Rocco R.	Towards Sustainable Territories-in-Between: A Multidimensional Typology of Open Spaces in Europe	2017	Planning Practice and Research	32(1):55-84	Europe
Weber F., Kowarik I., Säumel I.	A walk on the wild side: Perceptions of roadside vegetation beyond trees	2014	Urban Forestry and Urban Greening	13(2):205-212	Cologne, Germany
Willemen L., Hein L., Verburg P.H.	Evaluating the impact of regional development policies on future landscape services	2010	Ecological Economics	69(11):2244-2254	Gelderse Vallei, Netherlands
Wurster D., Artmann M.	Development of a concept for non-monetary assessment of urban ecosystem services at the site level	2014	Ambio	43(4):454-465	Salzburg, Austria
Xiu N., Ignatieva M., van den Bosch C.K., Chai Y., Wang F., Cui T., Yang F.	A socio-ecological perspective of urban green networks: the Stockholm case	2017	Urban Ecosystems	20(4):729-742	Stockholm, Sweden
Zepp H., Mizgajski A., Mess C., Zwierzchowska I.	A preliminary assessment of urban ecosystem services in Central European urban areas. A methodological outline with examples from Bochum (Germany) and Poznan (Poland)	2016	Berichte Geographie und Landeskunde	90(1):67-84	Bochum, Germany Poznan, Poland
Zhou T., Koomen E., van Leeuwen E.S.	Residents' preferences for cultural services of the landscape along the urban–rural gradient	2018	Urban Forestry and Urban Greening	29:131-141	Maastricht, Netherlands
Zölch T., Maderspacher J., Wamsler C., Pauleit S.	Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale	2016	Urban Forestry and Urban Greening	20:305-316	Munich, Germany

**Tab. A2: Einheiten und Dimensionen, verändert nach CZÚCZ et al. (2018: Appendix C).
Die Vereinheitlichung der Einheiten und Dimensionen ist für weitere Analysen hilfreich.**

Abkürzung	Beispiele
m:	Menge/Masse (kg, g, mg, Konzentrationen etc.)
l, l^2, l^3:	Länge (m, cm, km etc.), Fläche (m^2, ha etc.), Volumen (m^3, ml etc.)
t:	Zeitangaben (Stunden, Jahre etc.)
p:	Bevölkerungseinheit (Personen, Haushalte etc.)
n:	Anzahl / Nummer (von etwas)
T:	Temperatur (°C, K)
E:	Energie (J, MJ)
0:	Dimensionslose Einheiten

Tab. A3: Indikatoreneinteilungsmuster, angelehnt an VAN OUDENHOVEN et al. 2012.

Obergruppe	Unterteilung in Untergruppen		Beispiele
Eigenschaften des Ökosystems	A1	Klimatologische Indikatoren	Temperatur, Niederschlag
	A2	Landbedeckung und Landschaftsstruktur	Landbedeckung (Art, Flächengröße), Landnutzung (Typ, Flächengröße), Zusammenhang und Anteil von Landbedeckung und Landschaftselementen, Anzahl, Flächengröße und räumliche Ausdehnung von z. B. Landschaftsstrukturen
	A3	Flora und Fauna	Arten Lebensraum/Lebensraumbedarf der Arten, Verbreitung von Arten, Vegetationsmerkmale (z. B. Nettoprimärproduktion (NPP, Blattflächenindex)
	A4	Boden	Bodenart, Bodentyp
	A5	Wasser	Grundwasserlevel

	A6	Luft	Luftqualität
	A7	Infrastruktur	Natürlichkeitsgrad, städtische Elemente (z. B. Straßen, Gebäude), Anzahl und Ausstattung von Freizeiteinrichtungen
	A8	Bevölkerung*	Demografie Bewertungen/Einschätzungen (Informationen, generiert durch Umfragen, Interviews etc. Beispiel: Zahlungsbereitschaft)
Ökosystemfunktion	B		Anzahl an Nutztieren Gespeicherter Kohlenstoff in Böden, Biomasse etc. Filtration von z. B. Feinstaub durch Vegetation, Lebensraumeignung für bestimmte Arten, Besucherkapazität von Umweltbildungseinrichtungen
Ökosystemleistung	C1	ÖSL-Angebot	Lebensmittelproduktion; Veränderung z. B. der Feinstaubbelastung in der Luft
	C2	ÖSL-Potenzial	Klimaregulierungspotenzial der Vegetation
	C3	ÖSL-Nachfrage	Hitzewellen-, Hochwasserrisiko

* Die Bevölkerung ist Teil eines urbanen Ökosystems. Diese Indikatoren liefern Informationen über verschiedene Bevölkerungsmerkmale (z. B. Demografie, sozio-kulturelle oder sozio-ökonomische Aspekte).

Tab. A3: Indikatoreneinteilungsmuster, angelehnt an VAN OUDENHOVEN et al. 2012.

Obergruppe	**Unterteilung in Untergruppen**		**Beispiele**
Eigenschaften des Ökosystems	A1	Klimatologische Indikatoren	Temperatur, Niederschlag
	A2	Landbedeckung und Landschaftsstruktur	Landbedeckung (Art, Flächengröße), Landnutzung (Typ, Flächengröße), Zusammenhang und Anteil von Landbedeckung und Landschaftselementen, Anzahl, Flächengröße und räumliche Ausdehnung von z. B. Landschaftsstrukturen
	A3	Flora und Fauna	Arten Lebensraum/Lebensraumbedarf der Arten, Verbreitung von Arten, Vegetationsmerkmale (z. B. Nettoprimärproduktion (NPP, Blattflächenindex)
	A4	Boden	Bodenart, Bodentyp
	A5	Wasser	Grundwasserlevel
	A6	Luft	Luftqualität
	A7	Infrastruktur	Natürlichkeitsgrad, städtische Elemente (z. B. Straßen, Gebäude), Anzahl und Ausstattung von Freizeiteinrichtungen
	A8	Bevölkerung*	Demografie Bewertungen/Einschätzungen (Informationen, generiert durch Umfragen, Interviews etc. Beispiel: Zahlungsbereitschaft)
Ökosystemfunktion	B		Anzahl an Nutztieren Gespeicherter Kohlenstoff in Böden, Biomasse etc. Filtration von z. B. Feinstaub durch Vegetation, Lebensraumeignung für bestimmte Arten, Besucherkapazität von

			Umweltbildungseinrichtungen
Ökosystemleistung	C1	ÖSL-Angebot	Lebensmittelproduktion; Veränderung z. B. der Feinstaubbelastung in der Luft
	C2	ÖSL-Potenzial	Klimaregulierungspotenzial der Vegetation
	C3	ÖSL-Nachfrage	Hitzewellen-, Hochwasserrisiko

* Die Bevölkerung ist Teil eines urbanen Ökosystems. Diese Indikatoren liefern Informationen über verschiedene Bevölkerungsmerkmale (z. B. Demografie, sozio-kulturelle oder sozio-ökonomische Aspekte).

Tab. A4: Ergebnistabelle. Identifizierte Indikatoren für die ÖSL „lokale Klimaregulation". Die vereinheitlichten Einheiten und Dimensionen nach Czúcz et al. (2018) werden in den eckigen Klammern angegeben.

CICES-Code	CICES-Klasse	Einfache Beschreibung		Indikator (deutsch)	Indikator (englisch)	Quellen
2.2.6.2	Regulierung von Temperatur und Luftfeuchtigkeit, inkl. Luftaustausch und Verdunstung	Regulierung der physischen Luftqualität für Menschen	A	Eigenschaften des Ökosystems		
			A1	Klimatologische Indikatoren		
				Oberflächentemperatur (°C) [T]	Surface temperature (°C) [T]	Kremer et al. 2018
				Physiologisch äquivalente Temperatur (°C) (PET) [T]	Physiologically equivalent temperature (PET) (°C) [T]	Zölch et al. 2016
			A2	Landbedeckung und Landschaftsstruktur		
				Urbane Landschaftsstruktur (Klassifikation) [%]	Urban landscape structure (classification) [%]	Kremer et al. 2018
				Vegetationsfläche (ha) [l²]	Sum of vegetated area (ha) [l²]	Neuenschwander et al. 2014
				Parkform	Park shape	Giedych & Maksymiuk 2017
				Gewässer	Water bodies	Giedych & Maksymiuk 2017
				Ökologisch wirksames Gebiet [0]	Ecologically effective area [0]	Dennis & James 2016
			A3	Flora und Fauna		
				Urbane Grünflächentypen	Urban green space type	Derkzen et al. 2015
				Vegetationsstruktur	Vegetation structure	Giedych & Maksymiuk 20172017
				Bäume [n]	Sum of trees [n]	Neuenschwander et al. 2014
				Blattflächenindex [0]	Leaf area index [0]	Gómez-Baggethun et al. 2013
				Flechtenvielfalt	Lichen diversity	Vieira et al. 2018
				Baumschattenfläche [%]	Tree shade area [%]	Baró et al. 2015
			A4	Boden		
			A5	Wasser		
			A6	Luft		
			A7	Infrastruktur		
			A8	Bevölkerungsmerkmale		
				Bewertungen/Einstufungen [0]	Ratings [0]	Derkzen et al. 2017
				Zahlungsbereitschaft (€) [Währungseinheit]	Willingness to pay (€) [monetary unit]	Derkzen et al. 2017
				Bewertungen/Einstufungen [0]	Ratings [0]	Kothencz et al. 2017
			B	Ökosystemfunktion		

				f-Evapotranspiration [0]	f-evapotranspiration [0]	SCHWARZ et al. 2011 LARONDELLE & HAASE 2013 LARONDELLE et al. 2014 HOU et al. 2015 KAIN et al. 2016 SZUMACHER & PABJANEK 2017
				Evapotranspirationrate von Bäumen (g m^{-2} s^{-1}) [ml^{-2}t^{-1}]	Evapotranspiration rate of trees (g m^{-2} s^{-1}) [ml^{-2}t^{-1}]	MOSS et al. 2019
				Evapotranspiration aus Stadtwäldern (kg s^{-1}; kg s^{-1} km^{-2}; kg h^{-1} Baum^{-1}) [ml^{-2}t^{-1}; ml^{-2}n^{-1}]	Evapotranspiration from urban forest (kg s^{-1}; kg s^{-1} km^{-2}; kg h^{-1} tree^{-1}) [ml^{-2}t^{-1}; ml^{-2}n^{-1}]	MOSS et al. 2019
				Oberflächen-Emissivitäts-Index [0]	(Land) surface emissivity index [0]	SCHWARZ et al. 2011 HAASE et al. 2012 LAUF et al. 2014 LARONDELLE & HAASE 2013 LARONDELLE et al. 2014 DEPIETRI et al. 2016 KAIN et al. 2016 SZUMACHER & PABJANEK 2017
			C	Ökosystemleistung		
			C1	**Ökosystemleistungs-Angebot**		
				Temperaturabnahme durch Baumbedeckung (C°) [T]	Temperature decrease by tree cover (C°) [T]	GÓMEZ-BAGGETHUN et al. 2013
				Temperaturabsenkung (K) [T]	Temperature reduction (K) [T]	KAIN et al. 2016
				Reduzierung von Hitzeinseln (C°) [T]	Heat island mitigation (C°) [T]	HOLT et al. 2015
			C2	**Ökosystemleistungs-Potenzial**		
				Kühlungspotenzial durch Bäume	Tree cooling potential	LARONDELLE & HAASE 2013
				Klimaregulierungspotenzial von ökologisch wirksamen Gebieten (£m^{-2}yr^{-1}) [Währungseinheit l^{-2} t^{-1}]	Climate regulation potential of ecologically effective area (£m^{-2}yr^{-1}) [monetary unit l^{-2} t^{-1}]	DENNIS & JAMES 2016
				Mögliche Auswirkungen der Evapotranspiration auf die Gebäudekühlungssysteme (£ h^{-1} Baum^{-1}) [Währungseinheit l^{-2} n^{-1}]	Potential energy impact of evapotranspiration on building cooling systems (£ h^{-1} tree^{-1}) [monetary unit l^{-2} n^{-1}]	MOSS et al. 2019
			C3	**Ökosystemleistungs-Nachfrage**		
				Hitzewellenrisiko (Tage) [t]	Heat wave risk (days) [t]	BARÓ et al. 2015
				Bevölkerung, die in einem Umkreis von 100 m um eine grüne oder blaue Fläche von mindestens 0,05 ha in Städten, die häufig von Hitzewellen getroffen werden, leben [%]	People living within 100m from a green or blue area of, at least 0.05 ha in cities that are frequently struck by heat waves [%]	RODRÍGUEZ-RODRÍGUEZ et al. 2015

				Exposition (Stadtteile, die Hitzewellen ausgesetzt sind, basierend auf der Einwohnerzahl pro Stadtteil und der mittleren Oberflächentemperatur) [0]	Exposure (city districts that are exposed to heat waves, based on number of inhabitants per city district and mean surface temperatures) [0]	DEPIETRI et al. 2013
				Exposition (Stadtteile, die Hitzewellen ausgesetzt sind, basierend auf der Fähigkeit verschiedener Landbedeckungstypen, das lokale Mikroklima zu regulieren) [0]	Exposure (city districts that are exposed to heat waves, based on the capacity of different land covers types to regulate the urban microclimate) [0]	DEPIETRI et al. 2013
				Anfälligkeit/Empfindlichkeit (Bevölkerungsanteil, der während Hitzewellen besonders verwundbar ist, basierend auf dem prozentualen Anteil der Bevölkerung älter als 65 Jahre pro Stadtbezirk und dem prozentualen Anteil der Arbeitslosen pro Stadtbezirk) [0]	Susceptibility (population that are vulnerable to heat waves, based on the percentage of the population per city district older than 65 years and the percentage of unemployed per city district) [0]	DEPIETRI et al. 2013
				Mangelnde Widerstandsfähigkeit (Mangelnde Widerstandsfähigkeit der Bevölkerung gegenüber Hitzewellen pro Stadtbezirk, basierend auf dem Anteil der alleinlebenden Senioren pro Stadtbezirk und dem Anteil der von Stadtwäldern bedeckten Fläche pro Stadtbezirk) [0]	Lack of resilience (lack of resilience of the population to heat waves per city district based on percentage of elderly living alone per city district and percentage of the surface covered by urban forest per city district) [0]	DEPIETRI et al. 2013

Suppl. material 1: Reviewed articles.

Table S1: Reviewed articles.

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
Baró et al. 2015	*"ES demand, defined here as the amount of service required or desired by society"* (p.3, after Villamagna et al. 2013).	Yes	Air purification, global climate regulation, urban temperature regulation	Institution	Local	Mapping of statistical/literature data
Baró et al. 2016	*"ES demand as the amount of service required or desired by society"* (p.3, after Villamagna et al. 2013).	Yes	Air purification, outdoor recreation	Institution	Regional	Mapping of statistical/literature data
Beichler 2015	No explanation.	Yes	Aesthetics and Inspiration, spiritual and religious, cultural heritage and identity, recreation, knowledge and education, natural heritage and intrinsic value of biodiversity	Individuals represented local planning institutions, economic organizations, environmental and a social NGO, civil protection department, science department	Regional	Participatory method (participatory mapping), spatial analysis
Bryan et al. 2018	Description of ES demand understanding.	Yes	Food production, raw material, air quality, climate regulation, Water supply, waste treatment, soil retention, biodiversity services (pollination, seed dispersal, pest and disease control,	No explanation.	Regional	Economic approach (demand was calculated as a function of population, wealth, and income elasticity) valuation and parameterization scenarios

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
			habitat maintenance and other benefits), recreation and culture			
Chen et al. 2019	Description of ES demand understanding.	Yes	Water, recreation, air quality, global climate regulation	Citizens, trade/industry, institution	Regional	Mapping of statistical/literature data, spatial analysis
Chen et al. 2018	Description of ES demand understanding.	Yes	Food, raw materials, medicinal resources, ornamental resources, water purification, water regulation, maintaining healthy waterways and reservoirs, waste assimilation, natural hazard regulation, pollination, biological pest control, recreation and aesthetic values, cultural heritage values, discriminating features and sense of place	Farmers, rural population	Regional	Participatory method (ES matrix method), spatial analysis, statistical analysis (principal component analysis)
Cimon-Morin und Poulin 2018	Description of ES demand understanding.	Yes	Carbon storage, Existence value of rare and threatened	No explanation.	Regional	Mapping of statistical/literature data,

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
			species, Cooling islands, Potential for ornithological activities, Surface runoff management, Aesthetics, Recharge of groundwater, Potential for recreational activities, Water flow mitigation			Multi-criteria decision analysis, systematic conservation planning approach, monetary valuation, conservation scenario analysis, conservation network analysis
Cortinovis und Geneletti 2018	No explanation.	Yes	Urban cooling, Recreation	Vulnerable people (young children (<5 years) and the elderly (>65 years))	Local	Participatory method (online questionnaire), multi-criteria analysis
Goldenberg et al. 2017	Description of ES demand understanding.	Yes	Local climate regulation; Storm water regulation	No explanation.	Regional	Mapping (ES matrix method), spatial analysis
González-García et al. 2020	*"ES demand is understood as "the amount of a service required or desired by society" (p. 2;* after Villamagna et al. 2013).	Yes	Global climate regulation; outdoor recreation; water for drinking purposes	No explanation.	Regional	Mapping of statistical/literature data, spatial analysis
Kokkoris et al. 2019	No explanation.	No	Raw material, Hunting, Fishing, Food, Grassland biomass, Erosion control, Water regulation,	Local stakeholders.	Local	Scenario approach

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
			Water purification, Global climate regulation, Habitat for pollinators, Biodiversity maintenance, Hydrological cycle support, Recreation, Cultural identity maintenance, Research and education, Symbolism, Archeological and historic value, Religious value, Environmental awareness			
Li et al. 2016	Description of ES demand understanding.	Yes	Local climate regulation, Air quality regulation, Water flow regulation, Water purification, Erosion regulation, Natural hazards regulation, Pollination, Crops, Biomass for energy,	Experts	Regional	Participatory method (ES matrix method), spatial analysis

Paper included	**ES Demand Definition**	**Mismatches identified**	**Ecosystem Service(s)**	***Where does the demand for ecosystem services come from?***	**Spatial scale**	**Method (ES demand)**
			Livestock (domestic), Timber, Fishing, Water, Shipping, Recreation & tourism, Landscape aesthetics and inspiration, Knowledge systems, Cultural heritage and cultural diversity, Natural heritage and natural diversity			
Palacios-Agundez et al. 2015	No explanation.	No	Carbon storage and sequestration, air quality, recreational activities, traditional knowledge, environmental education, aesthetics and spiritual values	Key stakeholders from the region	Regional	Participatory method (qualitative participatory scenarios)
Palomo-Campesino et al. 2018	No explanation.	Yes	Water for humans and irrigation, agricultural products, livestock	Key stakeholders/local stakeholders from different sectors	Regional	Participatory method (participatory mapping), statistical analysis

Paper included	**ES Demand Definition**	**Mismatches identified**	**Ecosystem Service(s)**	***Where does the demand for ecosystem services come from?***	**Spatial scale**	**Method (ES demand)**
			products, habitat for species, air quality, soil fertility, tourism, aesthetic value, traditional ecological knowledge			
Quintas-Soriano et al. 2019	No explanation.	Yes	Food from traditional agriculture, food from intensive agriculture, climate regulation, air quality, water regulation, soil protection, tourism, local identity	Random individuals	Regional	Participatory method (Face-to-face survey; preference assessment), statistical analysis (principal component analysis, cluster analysis)
Rioux et al. 2019	*"The amount of a service required or desired by society"* (p.4, after Villamagna et al. 2013).	No	Carbon storage, urban cooling, pollination	No explanation.	Local	Simple ES mapping, spatial analysis
Sahle et al. 2018a	No explanation.	Yes	Global climate regulation	No explanation.	Regional	Mapping of statistical/literature data, spatial analysis
Sahle et al. 2018b	No explanation.	Yes	Food	Households	Regional	Mapping of statistical/literature data, participatory method (survey, field work), spatial analysis

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
Sauter et al. 2019	No explanation.	Yes	Flood protection, nearby recreation (habitat quality/biodiversity)	No explanation.	Regional	Mapping of statistical/literature data, Scenario approach of land-use changes, spatial analysis
Schägner et al. 2016	No explanation.	No	Outdoor recreation	No explanation.	International	Recreational demand modelling (National park visitor model), monetary valuation, statistical analysis
Schirpke et al. 2018	Description of ES demand understanding.	Yes	Outdoor recreation	Residents and tourists	Regional	Mapping of statistical/literature data, Recreational demand modelling (Combination of Recreation Model of InVEST and spatial/statistical analysis), spatial analysis, statistical analysis (cluster analysis)

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
Schirpke et al. 2019a	*"Demand for ES […] represents the amount of a service required or desired by society, expressed through stated preferences and values or direct use"* (p. 929, after Wolff et al. 2015)	Yes	Drinking water, grassland biomass, fuel wood, filtration of surface water, protection against natural hazards, carbon sequestration, outdoor recreation, symbolic plants and animals	No explanation.	Regional	Mapping of statistical/literature data, spatial analysis, statistical analysis (correlation analysis, principal component analysis, cluster analysis, random forest analysis)
Schirpke et al. 2019b	Description of ES demand understanding.	Yes	Fresh water Grassland biomass Fuel wood Filtration of surface water Protection against mountain hazards Carbon sequestration Outdoor recreation	No explanation.	Regional	Mapping of statistical/literature data, spatial analysis, statistical analysis (cluster analysis)
Schulp et al. 2014	Description of ES demand understanding.	Yes	Pollination	No explanation.	International	Pollination demand modelling, spatial analysis
Shen et al. 2019	Description of ES demand understanding.	Yes	Flood regulation	No explanation.	Local	Flood regulation demand modelling, land use scenarios, monetary valuation, spatial analysis, statistical analysis
Vallecillo et al. 2019	Description of ES demand understanding.	Yes	Nature-based recreation	No explanation.	International	Mapping of statistical/literature

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	***Where does the demand for ecosystem services come from?***	Spatial scale	Method (ES demand)
						data, monetary valuation, spatial analysis.
Verhagen et al. 2017	Description of ES demand understanding.	Yes	Air quality, carbon sequestration, flood regulation, urban leisure	No explanation.	International	Mapping of statistical/literature data, spatial analysis (spatial prioritization approach)
Watson et al. 2019	*"[…] demand (desired amount of human consumption of that supply, which depends on peoples' desire for and access to ESs)"* (p. 943)	Yes	Flood mitigation, crop pollination, nature-based recreation	No explanation.	Local	Mapping of statistical/literature data, monetary valuation, spatial analysis (spatial prioritization approach)
Wolff et al. 2017	Description of ES demand understanding.	Yes	Animal pollination, wild medicinal plants, outdoor recreation	Consumer; people who are reliance on wild medicinal plants	International	Recreational demand modelling, pollination demand modelling, wild medicinal plants demand modelling
Yuan et al. 2019	Description of ES demand understanding.	Yes	Water	Households	Regional	Mapping of statistical/literature data, monetary valuation (water-pricing model),

Paper included	ES Demand Definition	Mismatches identified	Ecosystem Service(s)	*Where does the demand for ecosystem services come from?*	Spatial scale	Method (ES demand)
						water scarcity scenarios
Zhao und Sander 2015	*"demand for ecosystem services reflects those services actually consumed or desired by beneficiaries"* (p. 2, after Wolff et al. 2015)	Yes	Global climate regulation	Interest groups from different sectors	Regional	Mapping of statistical/literature data, spatial analysis
Zhao et al. 2019a	Description of ES demand understanding.	Yes	Pollination	No explanation.	Local	Mapping of statistical/literature data, field work, spatial analysis
Zhao et al. 2019b	No explanation.	Yes	Cultural ES	Visitors	Regional	Participatory method (survey), Recreation demand modelling (viewer days model), spatial analysis (supply-demand and budget modelling)

Spatial Scale: Local, regional, national, international

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Suppl. material 2: Ecosystem Services

Table S2: Ecosystem Services

Category	Group	Number of occurrences
Provisioning Services		**34**
	Cultivated terrestrial plants for nutrition, materials or energy	20
	Water	8
	Reared animals (terrestrial and aquatic) used for nutritional purposes	3
	Wild animals (terrestrial and aquatic) used for nutritional purposes	3
Regulating Services		**69**
	Regulation of chemical composition of atmosphere and oceans (e.g. global climate regulation)	14
	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	13
	Air purification	9
	Pollination	7
	Regulation of temperature and humidity, including ventilation and transpiration (e.g. local climate regulation)	6
	Control of erosion rates	4
	Maintaining nursery populations and habitats (Including gene pool protection)	4
	Protection against natural hazards	4
	Water quality	3
	Mediation of wastes of anthropogenic origin by living processes	2
	Pest control (including invasive species)	1
	Regulation of soil quality	1
	Other	1
Cultural Services		**56**
	Physical and experiential interactions with natural environment (e.g. outdoor recreation)	23
	Other biotic characteristics that have a non-use value (e.g. natural heritage and intrinsic value of biodiversity, historical values)	7
	Characteristics of living systems that enable aesthetic experiences	6
	Spiritual, symbolic and other interactions with natural environment	6
	Characteristics of living systems that are resonant in terms of culture or heritage	5
	Characteristics of living systems that enable education and training	5
	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	2
	Other	2

land

MDPI

Challenges entailed in applying ecosystem services supply and demand mapping approaches: a practice report

Supplementary Materials S1

Table S1. Data used for the ES supply/demand mapping and assessments.

Data	Temporal resolution	Spatial resolution	Source
Administrative boundaries of Europe	2020	1:1 Mio	[1]
Urban Atlas	2012	Minimum Mapping Unit: Class 1: 0.25 ha Class 2 - 5: 1 ha Minimum Mapping Width: 10 m	[2]
Corine Land Cover	2012	Minimum Mapping Unit: 10 ha / 25 ha	[3]
Population density	2011	100 m x 100 m grid	[4,5]
Tree cover density	2015	20 m	[6]
Potential evapotranspiration over grass	2019	1 km x 1 km	[7]
Potential evapotranspiration	2019	Point data	[8]
Temperature	2019	Point data	[9]
Nightly magnitude of the urban heat island effect	2019	1 km x 1 km	[10]
Flood hazard and flood risk	2019	Polygon and point data	[11]
ATKIS	2017	1:25.000	[12]
Biotops	2015	1:10.000	[11]
Run-off paths	2013	Polylines	[13]
Digital elevation model (DEM)	2020	10 m x 10 m	[12]
Crop coefficient (K_c)	-	Literature data	[14]
Crop coefficient (K_c) values for LULC	-	Literature data	[15,16]
Albedo values for LULC	-	Literature data	[17]
Building intensity values for LULC	-	Literature data	[17]
Nesting suitability and floral resources for LULC	-	Literature data	[18]

Table S2. Overview of the indicators, methods and categorisation used. If possible, indicators were mapped at a regional scale.

Ecosystem services	Component	Indicator (Unit)	Method	Tier	Data categorisation
Food (from cultivated terrestrial plants)	Supply	Agricultural area (%)	Calculation of the percentage of agricultural area in a 10-ha x 10-ha grid.	1	5 – very high: >80 - 100 4 – high: >60 - ≤80 3 – medium: >40 - ≤60 2 – low: >20 - ≤40 1 – very low: >0 - ≤20 0 – not relevant: 0
	Demand	Population density (Inhabitants ha^{-1})	Spatial join of population density data with a 100-m x 100-m grid [4,5]	1	5 – very high: >100 4 – high: >75 - ≤100 3 – medium: >50 - ≤75 2 – low: >25 - ≤50 1 – very low: >0 - ≤25 0 – not relevant: 0
Raw materials (from cultivated terrestrial plants)	Supply	Forest area (%)	Calculation of the percentage of forest area in a 10-ha x 10-ha grid.	1	5 – very high: >80 - 100 4 – high: >60 - ≤80 3 – medium: >40 - ≤60 2 – low: >20 - ≤40 1 – very low: >0 - ≤20 0 – not relevant: 0

Ecosystem services	Component	Indicator (Unit)	Method	Tier	Data categorisation
	Demand	Population density (Inhabitants ha^{-1})	Spatial join of population density data with a 100-m x 100-m grid [4,5]	1	5 – very high: >100 4 – high: >75 - ≤100 3 – medium: >50 - ≤75 2 – low: >25 - ≤50 1 – very low: >0 - ≤25 0 – not relevant: 0
Pollination	Supply	Pollinator Abundance (Index 0 to 1, Dimensionless)	Wild bee abundance has been modelled using InVEST "Pollinator Abundance: Crop Pollination" [19]	2-3	5 – very high: >0.8 - 1 4 – high: >0.6 - ≤08 3 – medium: >0.4 - ≤0.6 2 – low: >0.2 - ≤0.4 1 – very low: >0 - ≤0.2 0 – extreme low: 0
	Demand	Dependence of crops on pollination by insects (%)	Dependence of crops on pollination by insects [18,20] was assigned to relevant LULC.	1	5 – very high: >80 - 100 4 – high: >60 - ≤80 3 – medium: >40 - ≤60 2 – low: >20 - ≤ 40 1 – very low: >0 - ≤20 0 – extreme low: 0
Local climate regulation	Supply	Green and blue areas (%)	Calculation of the percentage of green and blue area in a 10-ha x 10-ha grid.	1	5 – very high: >80 - 100 4 – high: >60 - ≤80 3 – medium: >40 - ≤60 2 – low: >20 - ≤40 1 – very low: >0 - ≤20 0 – extreme low: 0
	Supply	f-evapotranspiration (f-ETP) (Index 0 to 1, dimensionless)	Value-transfer of literature data [21,22].	1	5 – very high: >0.8 - 1 4 – high: >0.6 - ≤0.8 3 – medium: >0.4 - ≤0.6 2 – low: >0.2 - ≤0.4 1 – very low: >0 - ≤0.2 0 – extreme low: 0
	Demand	Surface emissivity (Index 0 to 1, dimensionless	Value-transfer of literature data [21,22].	1	5 – very high: >0.8 - 1 4 – high: >0.6 - ≤0.8 3 – medium: >0.4 - ≤0.6 2 – low: >0.2 - ≤0.4 1 – very low: >0 - ≤0.2 0 – extreme low: 0
Coastal protection	Demand	Coastal flood risk (Index 0 to 1, dimensionless)	Calculation of the coastal flood risk for the assets (human health, the environment, infrastructure and human economic activities) by multiplying flood hazard with the potential damage of each asset [13].	1-2	See explanations below.

Table S3. Overview of the indicators used in the ES modelling. If possible, indicators were mapped at a regional scale.

Ecosystem services	Component	Indicator (Unit)	Method	Tier	Data categorisation
Pollination	Supply	Pollinator Abundance (Index 0 to 1, Dimensionless)	Wild bee abundance has been modelled using InVEST "Pollinator Abundance: Crop Pollination" [19]	2-3	5 – very high: >0.8 - 1 4 – high: >0.6 - ≤0.8 3 – medium: >0.4 - ≤0.6 2 – low: >0.2 - ≤0.4 1 – very low: >0 - ≤0.2

Ecosystem services	Component	Indicator (Unit)	Method	Tier	Data categorisation
					0 – extreme low: 0
Local climate regulation	Supply	Heat mitigation (Index 0 to 1, Dimensionless)	Heat mitigation index has been modelled using InVEST "Urban Cooling Model" [23].	2-3	5 – very high: >0.8 - 1 4 – high: >0.6 - ≤0.8 3 – medium: >0.4 - ≤0.6 2 – low: >0.2 - ≤0.4 1 – very low: >0 - ≤0.2 0 – extreme low: 0

1. Food (from cultivated terrestrial plants)

LULC data can be used as proxies for ES supply [24]. We calculated the percentage of LULC types (Urban Atlas 2012), which are highly associated with producing food (arable land, permanent crops (vineyards, fruit trees, olive groves)) in geospatial units. The calculation of the percentage share can also be applied to official administrative units. Since these vary in size in the urban regions, we decided to use a uniform raster with a grid size of 10 ha. The demand for food has been mapped using population density data (inhabitants/ha) [4,5].

2. Raw materials (from cultivated terrestrial plants)

For ES supply, we calculated the percentage of LULC types, which are highly associated with providing timber (forest). We used a uniform raster with a grid size of 10 ha. The demand for food has been mapped using population density data (inhabitants/ha) [4,5].

3. Pollination

ES supply has been assessed using the indicator pollinator abundance [19], calculated with the InVEST Model P*ollinator Abundance: Crop Pollination*. This model considers that wild bees need suitable nesting sites and sufficient floral resources to survive. If these resources are available, the insects can fly to nearby plants and pollinate them. We used CLC 2012 and Urban Atlas 2012 and intersected them (see Table S4).

Table S4. Selected LULC classes from CORINE Land Cover (CLC) and Urban Atlas.

CORINE Land Cover (CLC)		**Urban Atlas**		**Selected LULC classes for InVEST Models**	
Code	Label	Code	Label	CLC	Urban Atlas
111	Continuous urban fabric	11100	Continuous urban fabric (S.L.: > 80%)		x
112	Discontinuous urban fabric	11210	Discontinuous dense urban fabric (S.L.: 50% - 80%)		x
112	Discontinuous urban fabric	11230	Discontinuous medium-density urban fabric (S.L: 30% - 50%)		x
112	Discontinuous urban fabric	11220	Discontinuous low-density urban fabric (S.L.: 10% - 30%)		x
112	Discontinuous urban fabric	11240	Discontinuous very low-density urban fabric (S.L.: < 10%)		x
121	Industrial or commercial units	12100	Industrial, commercial, public, military and private units		x
122	Road and rail networks and associated land	12210	Fast transit roads and associated land		x
122	Road and rail networks and associated land	12230	Railways and associated land		x
122	Road and rail networks and associated land	12220	Other roads and associated land		x
123	Port areas	12300	Port areas	x	
124	Airports	12400	Airports	x	
131	Mineral extraction sites	13100	Mineral extraction and dump sites	x	
132	Dump sites	13100	Mineral extraction and dump sites	x	
133	Construction sites	13300	Construction sites	x	
141	Green urban areas	14100	Green urban areas		x

142	Sport and leisure facilities	14200	Sports and leisure facilities		x
211	Non-irrigated arable land	21000	Arable land (annual crops)	x	
212	Permanently irrigated land	21000	Arable land (annual crops)	x	
213	Rice fields	21000	Arable land (annual crops)	x	
221	Vineyards	22000	Permanent crops (vineyards, fruit trees, olive groves)	x	
222	Fruit trees and berry plantations	22000	Permanent crops (vineyards, fruit trees, olive groves)	x	
223	Olive groves	22000	Permanent crops (vineyards, fruit trees, olive groves)	x	
231	Pastures	23000	Pastures	x	
241	Annual crops associated with permanent crops	0		x	
242	Complex cultivation patterns	24000	Complex and mixed cultivation patterns		x
243	Land principally occupied by agriculture, with significant areas of natural vegetation	25000	Orchards		x
244	Agro-forestry areas	0		x	
311	Broad-leaved forest	31000	Forests	x	
312	Coniferous forest	31000	Forests	x	
313	Mixed forest	31000	Forests	x	
321	Natural grasslands	32000	Herbaceous vegetation associations (natural grassland, moors…)	x	
322	Moors and heathland	32000	Herbaceous vegetation associations (natural grassland, moors…)	x	
323	Sclerophyllous vegetation	32000	Herbaceous vegetation associations (natural grassland, moors…)	x	
324	Transitional woodland-shrub	32000	Herbaceous vegetation associations (natural grassland, moors…)	x	
331	Beaches, dunes, sands	33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	x	
332	Bare rocks	33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	x	
333	Sparsely vegetated areas	33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	x	
334	Burnt areas	33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	x	
335	Glaciers and perpetual snow	33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	x	
411	Inland marshes	40000	Wetlands	x	
412	Peat bogs	40000	Wetlands	x	
421	Salt marshes	40000	Wetlands	x	
422	Salines	40000	Wetlands	x	
423	Intertidal flats	40000	Wetlands	x	
511	Water courses	50000	Water		x
512	Water bodies	50000	Water		x
521	Coastal lagoons	50000	Water		x
522	Estuaries	50000	Water		x
523	Sea and ocean	50000	Water		x
		11300	Isolated Structures		x
		13400	Land without current use		x

The data has been transferred into a raster (2.5 x 2.5 m resolution). The model needs a) a biophysical table with nesting suitability and floral resources across seasons for each LULC type (Table S5) and b) a guide table with information about wild bee species' active seasons, nesting preferences, mean flight distances, and relative abundances for each species or group of wild pollinators [19]. Information about twenty wild bee species (=average wild bee species) was combined for the guide table. For the biophysical table, values from Zulian et al. (2013) [18] were used and adapted for the Urban Atlas LULC (Table S6).

Table S5. Biophysical table, adapted from Zulian et al. (2013) [18]. Marked LULC (*) shows adjusted values for the Urban Atlas dataset.

lucode	Label	nesting_cavity_availability_index	nesting_ground_availability_index	floral_resources_index
1	Water bodies*	0	0	0
2	Sea and ocean	0	0	0
3	Peat bogs	0.3	0.3	0.5
4	Inland marshes	0.3	0.3	0.75
5	Beaches, dunes, sands	0.3	0.3	0.1
6	Transitional woodland-shrub	1	1	0.85
7	Natural grasslands	0.8	0.8	1
8	Broad-leaved forest	0.8	0.8	0.9
9	Coniferous forest	0.8	0.8	0.3
10	Mixed forest	0.8	0.8	0.6
11	Fruit trees and berry plantations	0.4	0.4	0.9
12	Pastures	0.3	0.3	0.2
13	Complex cultivation patterns*	0.4	0.4	0.4
14	Land principally occupied by agriculture, with significant areas of natural vegetation *	0.7	0.7	0.75
15	Non-irrigated arable land	0.2	0.2	0.2
16	Green urban areas*	0.3	0.3	0.25
17	Sports and leisure facilities*	0.3	0.3	0.05
18	Land without current use*	0	0	0
19	Mineral extraction sites	0.3	0.3	0.05
20	Dump sites	0.05	0.05	0
21	Construction sites	0.1	0.1	0
22	Fast transit roads and associated land	0.3	0.3	0.25
23	Other roads and associated land	0.3	0.3	0.25
24	Railways and associated land	0.3	0.3	0.25
25	Port areas	0.3	0.3	0
26	Airports	0.3	0.3	0.1
27	Continuous urban fabric (S.L.: > 80%)	0.1	0.1	0.05
28	Discontinuous dense urban fabric (S.L.: 50% - 80%)	0.2	0.2	0.175
29	Discontinuous medium-density urban fabric (S.L: 30% - 50%)	0.3	0.3	0.3
30	Discontinuous low-density urban fabric (S.L.: 10% - 30%)	0.3	0.3	0.2875
31	Discontinuous very low-density urban fabric (S.L.: < 10%)	0.3	0.3	0.2625
32	Isolated structures*	0	0	0
33	Industrial or commercial units *	0.1	0.1	0.05

Table S6. Guide table for the InVEST model *Pollinator Abundance: Crop Pollination*.

SPECIES	nesting_suitability_index	foraging_activity_spring_index	alpha	relative

				abundance
average_bee	1	0,5	600	1

The ES demand for pollination was assessed using the degree to which a crop is dependent on pollination by insects. This degree was first assessed by Klein et al. (2007) [20], who provided a list of important crops and their dependence on animal pollinators. These values are also used at the EU level to assess ES demand for pollination (Zulian et al. 2013) [18]. In an ideal situation, information on the pollination dependence of crops is linked to agricultural cultivation data to obtain explicit spatial information on ES demand. In Germany, these data are saved in an agricultural database (Integrated Administration and Control System, InVeKoS), which has restricted access for data protection reasons [25]. Therefore, we followed a methodological approach used by Schulp et al. 2014 [26] and Perennes et al. (2021) [27], who linked land use data on which potentially pollinator-dependent crops can grow with pollinator dependence values. We have assigned exemplary pollination dependencies to the LULC classes. For example, rapeseed is in Germany an important crop that is dependent on pollination by insects. The location of rapeseed fields usually changes annually due to crop rotations, varying market prices and changing political regulations and subsidies. Hence, the demand for pollination of rapeseed can potentially occur on all arable land [27]. Similar considerations took place in allocating crops for land-use "permanent crops (vineyards, fruit trees, olive groves)". We used the EUROSTAT dependence levels for these crop types as used in Zulian et al. (2013) [18] (Table S7).

Table S7. Pollination dependencies (%) of crops that could grow on selected LULC (adapted from Zulian et al. (2013) [18]).

Land use and land cover	**Crop type**	**Pollination dependence**
Arable land (annual crops)	Rape seed	25 %
Fruit trees and berry plantations	Apples, pears & peaches	65 %

4. Local climate regulation

Indicator *green and blue areas (%):* We calculated the percentage of green and blue areas (forests, agricultural areas, wetlands, water bodies, urban green areas, cemeteries and other vegetation areas) in each grid cell (10 ha).
Indicator *f-evapotranspiration (f-ETP)*: Evapotranspiration (ETP) covers water evaporation from soil surfaces (evaporation) and vegetation (transpiration) [28]. In this process, heat energy is converted into latent heat of vaporisation, which can result in a noticeable cooling effect [21]. We used the *f-ETP* index as a proxy to assess the ES supply for local climate regulation. Schwarz et al. (2011) and Larondelle et al. (2014) provided standardised ETP values for CLC and Urban Atlas LULC classes [21,22].
Indicator *surface emissivity:* ES demand for local climate regulation has been assessed using *surface emissivity* as a proxy. Surface emissivity expresses the land surface thermal emissions, which indicate the total amount of energy that is emitted by a surface [22]. For this indicator, too, Schwarz et al. (2011) and Larondelle et al. (2014) provided standardised surface emissivity values for CLC and Urban Atlas LULC classes [21,22].
We used an equation (1) that normalises the f-ETP and surface emissivity values to a scale between 0 and 1, where 0 indicates low and 1 high ES potential/demand:

$$ES' = (ES - ES_{min})/(ES_{max} - ES_{min}) \quad (1)$$

where ES' is the normalised ES, ES_{min} is the minimum and ES_{max} is the maximum value of ES [29]. Finally, those values were classified into the six ES matrix classes.

We used the InVEST Model *Urban Cooling* [23]. This model calculates a heat mitigation index that estimates the cooling effect of urban green areas based on shade, evapotranspiration, albedo, building intensity, and the distance from green and open spaces. This information must be provided in a biophysical table and linked to LULC types (see Table S5 and S6). We used LULC data, which has also been used for the InVEST pollination model, in raster format (5 x 5 m resolution).
Shade has been calculated using Tree Cover Density [6] from 2015 and the ArcGIS tool zonal statistics to table. For the values of albedo and building intensity, literature data from Stewart and Oke (2012) [17] were used. We used the monthly 1 x 1 km raster of the potential evapotranspiration (ETp) over grass [7] to calculate the crop coefficient (K_c), which is needed in the biophysical table. The Food and Agriculture Organization of the United Unions provides K_c values for crops and for the different crop growth stages [14]. Nistor (2018; 2016) [15,16] provided a list of the different crop growth stages (spring (k_c ini), summer (k_c mid), autumn (k_c end), and winter (k_c cold)) for each LULC of the CLC dataset. We adapted those values for the Urban Atlas classes (see Figure S1).

Code CLC	CLC Label	Kc cold	Kc ini	Kc mid	Kc end	Urban Atlas Code	Urban Atlas Label	Kc cold	Kc ini	Kc mid	Kc end
111	Continuous urban fabric	0	0.2	0.4	0.25	11100	Continuous urban fabric (S.L. : > 80%)	0	0.2	0.4	0.25
112	Discontinuous urban fabric	0	0.1	0.3	0.2	11210	Discontinuous Dense Urban Fabric (S.L. : 50% - 80%)	0	0.1	0.3	0.2
						11220	Discontinuous Medium Density Urban Fabric (S.L. : 30% - 50%)	0	0.17	0.51	0.34
						11230	Discontinuous Low Density Urban Fabric (S.L. : 10% - 30%)	0	0.22	0.69	0.46
						11240	Discontinuous very low density urban fabric (S.L. : < 10%)	0	0.26	0.78	0.51
121	Industrial or commercial units	0	0.2	0.4	0.3	12100	Industrial, commercial, public, military and private units	0	0.2	0.4	0.3
121	Road and rail networks and associated land	0	0.15	0.35	0.25	12210	Fast transit roads and associated land	0	0.15	0.35	0.25
121		0	0.15	0.35	0.25	12230	Railways and associated land	0	0.15	0.35	0.25
122		0	0.15	0.35	0.25	12220	Other roads and associated land	0	0.15	0.35	0.25
123	Port areas	0	0.3	0.5	0.4	12300	Port areas	0	0.3	0.5	0.4
124	Airports	0	0.2	0.4	0.3	12400	Airports	0	0.2	0.4	0.3
131	Mineral extraction sites	0	0.16	0.36	0.26	13100	Mineral extraction and dump sites	0	0.16	0.36	0.26
132	Dump sites	0	0.16	0.36	0.26	13100	Mineral extraction and dump sites	0	0.16	0.36	0.26
133	Construction sites	0	0.16	0.36	0.26	13300	Construction sites	0	0.16	0.36	0.26
141	Green urban areas	0	0.12	0.32	0.22	14100	Green urban areas	0	0.12	0.32	0.22
142	Sport and leisure facilities	0	0.1	0.3	0.2	14200	Sports and leisure facilities	0	0.1	0.3	0.2
211	Non-irrigated arable land	0	1.1	1.35	1.25	21000	Arable land (annual crops)	0	1.12	1.33	1.07
212	Permanently irrigated land	0	1.2	1.45	1.35						
213	Rice fields	0	1.05	1.2	0.6						
221	Vineyards	0	0.3	0.7	0.45	22000	Permanent crops (vineyards, fruit trees, olive groves)	0	0.42	0.82	0.53
222	Fruit trees and berry plantations	0	0.3	1.05	0.5						
223	Olive groves	0.5	0.65	0.7	0.65						
231	Pastures	0	0.4	0.9	0.8	23000	Pastures	0	0.4	0.9	0.8
241	crops	0	0.5	0.8	0.7						
242	Complex cultivation patterns	0	1.1	1.35	1.25	24000	Complex and mixed cultivation patterns	0	1.1	1.35	1.25
243	Land principally occupied by agriculture, with significant areas of natural vegetation	0	0.7	1.15	1	25000	Orchards	0	0.7	1.15	1
244	Agro-forestry areas	0.3	0.9	1.1	1.05						
311	Broad-leaved forest	0.6	1.3	1.6	1.5	31000	Forests	0.6	1.3	1.6	1.5
312	Coniferous forest	1	1	1	1						
313	Mixed forest	0.8	1.2	1.5	1.3						
321	Natural grasslands	0	0.3	1.15	1.1	32000	Herbaceous vegetation associations (natural grassland, moo	0	0.5375	1.0125	0.95
322	Moors and heathland	0	0.8	1	0.95						

Figure S1: Standardised Kc values for CORINE Land Cover and Urban Atlas, adapted from Nistor (2018; 2016) [61,62].

We used 120 m as the maximum air temperature blending distance based on the literature values of Huang et al. (2018) and Goldenberg et al. (2017) [30,31]. The Climate Data Center (CDC) provided data for the rural reference temperature (°C) [9]. The Global Surface UHI Explorer [10] provided the nightly magnitude of the urban heat island effect, which expresses the difference between the maximum temperature in the city and the rural areas by night.

Table S8. Biophysical table for the InVEST model *Urban Cooling*, urban region of Munich.

lucode	lulc_desc	shade	kc	albedo	green_area	building_intensity
211	Non-irrigated arable land	0.02	1.09	0.2	1	0.05
222	Fruit trees and berry plantations	0.02	0.69	0.225	1	0.05
311	Broad-leaved forest	0.75	1.38	0.15	1	0.05
312	Coniferous forest	0.84	1	0.15	1	0.05
313	Mixed forest	0.82	1.32	0.15	1	0.05
321	Natural grasslands	0.17	0.79	0.2	1	0.05
322	Moors and heathland	0.68	0.8	0.225	1	0.05
324	Transitional woodland-shrub	0.65	0.8	0.225	1	0.05
331	Beaches, dunes, sands	0.03	0.23	0.275	0	0.05
332	Bare rocks	0.07	0.15	0.225	0	0.05
333	Sparsely vegetated areas	0.20	0.46	0.25	1	0.05
411	Inland marshes	0.19	0.34	0.225	1	0.05
412	Peat bogs	0.25	0.29	0.225	1	0.05
512	Water bodies	0.03	0.5	0.06	1	0.05
11100	Continuous urban fabric (S.L.: > 80%)	0.05	0.29	0.15	0	0.55
11210	Discontinuous dense urban fabric (S.L.: 50% - 80%)	0.14	0.2	0.15	0	0.55
11220	Discontinuous medium-density urban fabric (S.L: 30% - 50%)	0.14	0.35	0.185	0	0.3
11230	Discontinuous low-density urban fabric (S.L.: 10% - 30%)	0.12	0.47	0.185	1	0.3
11240	Discontinuous very low-density urban fabric (S.L.: < 10%)	0.05	0.53	0.185	1	0.15
11300	Isolated Structures	0.06	0.53	0.185	1	0.15

12100	Industrial, commercial, public, military and private units	0.07	0.29	0.185	0	0,35
12210	Fast transit roads and associated land	0.09	0.25	0.2	0	0,4
12220	Other roads and associated land	0.08	0.25	0.2	0	0,4
12230	Railways and associated land	0.10	0.25	0.2	0	0,4
12300	Port areas	0.00	0.38	0.16	0	0,25
12400	Airports	0.02	0.29	0.225	0	0,05
13100	Mineral extraction and dump sites	0.02	0.26	0.275	0	0,05
13300	Construction sites	0.03	0.26	0.275	0	0,05
13400	Land without current use	0.15	0.2	0.25	0	0,05
14100	Green urban areas	0.41	0.22	0.2	1	0,05
14200	Sports and leisure facilities	0.13	0.2	0.2	1	0,05
21000	Arable land (annual crops)	0.05	1.07	0.2	1	0,05
22000	Permanent crops (vineyards, fruit trees, olive groves)	0.05	0.59	0.2	1	0,05
23000	Pastures	0.03	0.65	0.2	1	0,05
31000	Forests	0.53	1.38	0.175	1	0,05
32000	Herbaceous vegetation associations (natural grassland, moors…)	0.05	0.75	0.2	1	0,05
40000	Wetlands	0.14	0.34	0.06	1	0,05
50000	Water	0.17	0.53	0.06	1	0,05

Table S9. Biophysical table for the InVEST model *Urban Cooling*, urban region of Rostock.

lucode	lulc_desc	shade	kc	albedo	green_area	building_intensity
211	Non-irrigated arable land	0.01	1.11	0.2	1	0.05
222	Fruit trees and berry plantations	0.01	0.71	0.225	1	0.05
311	Broad-leaved forest	0.79	1.4	0.15	1	0.05
312	Coniferous forest	0.79	1	0.15	1	0.05
313	Mixed forest	0.79	1.33	0.15	1	0.05
321	Natural grasslands	0.08	0.8	0.2	1	0.05
322	Moors and heathland	0.1	0.82	0.225	1	0.05
333	Sparsely vegetated areas	0.04	0.47	0.25	1	0.05
334	Burnt areas	0.74	0.47	0.275	0	0.05
411	Inland marshes	0.17	0.34	0.225	1	0.05
412	Peat bogs	0.24	0.29	0.225	1	0.05
511	Water courses	0	0.5	0.06	1	0.05
512	Water bodies	0	0.5	0.06	1	0.05
521	Coastal lagoons	0	0.5	0.06	1	0.05
523	Sea and ocean	0	0.5	0.06	1	0.05
11100	Continuous urban fabric (S.L.: > 80%)	0.02	0.29	0.15	0	0.55
11210	Discontinuous dense urban fabric (S.L.: 50% - 80%)	0.1	0.21	0.15	0	0.55
11220	Discontinuous medium-density urban fabric (S.L: 30% - 50%)	0.1	0.35	0.185	0	0.3
11230	Discontinuous low-density urban fabric (S.L.: 10% - 30%)	0.08	0.48	0.185	1	0.3
11240	Discontinuous very low-density urban fabric (S.L.: < 10%)	0.09	0.54	0.185	1	0.15
11300	Isolated Structures	0.06	0.54	0.185	1	0.15

12100	Industrial, commercial, public, military and private units	0.05	0.3	0.185	0	0.35
12210	Fast transit roads and associated land	0.05	0.25	0.2	0	0.4
12220	Other roads and associated land	0.08	0.25	0.2	0	0.4
12230	Railways and associated land	0.11	0.25	0.2	0	0.4
12300	Port areas	0.03	0.38	0.16	0	0.25
12400	Airports	0.02	0.3	0.225	0	0.05
13100	Mineral extraction and dump sites	0.02	0.26	0.275	0	0
13300	Construction sites	0.02	0.26	0.275	0	0.05
13400	Land without current use	0.18	0.21	0.25	0	0.05
14100	Green urban areas	0.4	0.23	0.2	1	0.05
14200	Sports and leisure facilities	0.16	0.21	0.2	1	0.05
21000	Arable land (annual crops)	0.01	1.1	0.2	1	0.05
22000	Permanent crops (vineyards, fruit trees, olive groves)	0.15	0.6	0.2	1	0.05
23000	Pastures	0.04	0.66	0.2	1	0.05
31000	Forests	0.66	1.4	0.175	1	0.05
32000	Herbaceous vegetation associations (natural grassland, moors…)	0.29	0.77	0.2	1	0.05
33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	0.01	0.47	0.275	0	0.05
40000	Wetlands	0.16	0.34	0.06	1	0.05
50000	Water	0.17	0.54	0.06	1	0.05

5. Coastal protection

The demand for coastal protection can be expressed in different ways. It can, for example, be expressed by the need or desire of the population to reduce or avoid the risks caused by flooding, increased current velocities, storm surges, sediment erosion or sea-level rise. The assessment of the demand can be assessed following the Floods Directive (Directive 2007/60/EC) of the European Parliament on the assessment and management of flood risks. In Germany, the Floods Directive is used to assess and manage flood risks and to protect assets (in german: Schutzgüter) like human health, the environment, cultural heritage and human economic activities. The directive considers both river and coastal flood events. Flood hazard and risk maps show areas at significant risk, expected flood extents and water depths for three scenarios [11]. We mapped an exemplary coastal flood event with a statistical 200-year recurrence interval and followed the methodology steps from INTEK (2014) [13]:

1. Classification of expected water depths (=flood hazard) into six classes (see Table S10);

Table S10: Classification of flood hazard

Classification	Flood hazard	Expected water depth (m)
5	Very high	>4
4	High	>2 - ≤4
3	Medium	>1 - ≤2
2	Low	>0.5 - ≤1
1	Very low	>0 - ≤0.5
0	Extreme low	0

2. Classification of the potential damage for each asset into six classes (Table S11 – Table S14). The assets were derived from population density, biotopes, runoff paths, digital elevation model, historical buildings, LULC;

Table S11: Classification of the potential damage for the asset cultural heritage.

Classification	Potential damage	Buildings
5	Very high	Historical buildings

4	High	-
3	Medium	-
2	Low	-
1	Very low	-
0	Extreme low	-

Table S12: Classification of the potential damage for the asset environment.

Classification	**Potential damage**	**Biotops**
5	Very high	-
4	High	-
3	Medium	-
2	Low	Biotopes downstream of industrial buildings classified as IED buildings/areas (Industrial Emissions Directive (2010/75/EU))
1	Very low	Other biotopes
0	Extreme low	Water and wetland biotopes

Table S13: Classification of the potential damage for the asset infrastructure.

Classification	Potential damage	Infrastructure
5	Very high	-
4	High	-
3	Medium	Main roads, port facilities, railway lines
2	Low	Other streets
1	Very low	Paths
0	Extreme low	-

Table S14: Classification of the potential damage for the asset human economic activities.

Classification	**Potential damage**	**LULC**
5	Very high	-
4	High	Industrial and commercial area, residential area
3	Medium	Tree nursery, orchard, garden, sport and leisure area
2	Low	Cemetery
1	Very low	Agricultural area, pastures, forest
0	Extreme low	-

3. Calculation of the coastal flood risk by multiplying flood hazard values with the potential damage values;
4. Classification of the coastal flood risk of each asset into six ES classes (Table S15).

Table S15: Classification of the coastal flood risks into six ES classes

Asset	**Classification**
Human health	5 – very high: >100 4 – high: >75 - ≤100 3 – medium: >50 - ≤75 2 – low: >25 - ≤50 1 – very low: >0 - ≤25 0 – extreme low: 0

Cultural heritage	5 – very high: ≥4.5 4 – high: ≥3.5 - <4.5 3 – medium: ≥2.5 - <3.5 2 – low: ≥1.5 - <2.5 1 – very low: >0 - <1.5 0 – extreme low: 0
Environment	5 – very high: >7 4 – high: >5 - ≤7 3 – medium: >3 - ≤5 2 – low: >2 - ≤3 1 – very low: >1 - ≤2 0 – not relevant: 0
Infrastructure	5 – very high: >7 4 – high: >5 - ≤7 3 – medium: >3 - ≤5 2 – low: >2 - ≤3 1 – very low: >1 - ≤2 0 – not relevant: 0
Human economic activities	5 – very high: >7 4 – high: >5 - ≤7 3 – medium: >3 - ≤5 2 – low: >2 - ≤3 1 – very low: >1 - ≤2 0 – not relevant: 0

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Supplementary Materials S2

Table S16. Expert-based ES matrix approach, ES supply, urban region of Rostock, n=15. Weighted mean values.

	Food (from cultivated terrestrial plants)	Raw materials (from cultivated terrestrial plants)	Drinking water	Maintaining nursery populations and habitats	Pollination	Flood and coastal protection	Local climate regulation	Recreation	Aesthetic
Water bodies	1.07	1.74	4.69	4.00	1.37	3.67	3.91	3.74	4.03
Agricultural areas	4.41	3.94	2.10	2.42	2.90	1.68	2.55	1.74	2.76
Forests	1.11	3.40	2.75	4.25	3.48	2.99	4.53	4.17	4.21
Open vegetation	0.90	1.21	2.30	3.82	3.70	2.45	3.18	2.81	3.48
Wetlands	0.44	0.83	3.12	4.04	3.30	3.82	4.05	2.33	3.66
Urban green areas	0.33	0.46	1.51	3.21	3.13	1.59	3.66	3.73	3.29
Residential area	0.25	0.15	0.54	1.16	0.74	1.02	0.83	0.66	0.98
Infrastructure	0.00	0.00	0.17	0.58	0.34	0.64	0.29	0.82	0.52
Industrial and commercial areas	0.30	0.31	0.49	1.24	0.92	0.65	0.77	0.36	0.33

Table S17. Expert-based ES matrix approach, ES supply, urban region of Munich, n=12. Weighted mean values.

	Food (from cultivated terrestrial plants)	Raw materials (from cultivated terrestrial plants)	Drinking water	Maintaining nursery populations and habitats	Pollination	Flood and coastal protection	Local climate regulation	Recreation	Aesthetic
Water bodies	0.00	0.36	1.32	3.10	0.00	2.96	2.95	3.30	3.02
Agricultural areas	3.96	3.37	1.28	2.10	1.93	1.73	2.59	2.45	1.17
Forests	0.66	3.33	2.61	3.18	2.67	2.47	3.67	3.75	3.34
Open vegetation	0.51	1.02	1.93	3.62	3.40	2.06	2.76	3.74	3.33
Wetlands	0.83	1.01	1.82	3.36	2.58	3.34	3.30	2.91	3.10
Urban green areas	0.25	0.56	0.78	2.83	3.01	1.80	3.41	4.42	3.67
Residential area	0.15	0.00	0.06	1.07	0.44	0.22	0.38	0.20	0.46
Infrastructure	0.00	0.16	0.00	0.86	0.46	0.02	0.26	0.40	0.22
Industrial and commercial areas	0.16	0.33	0.06	0.59	0.38	0.48	0.71	0.09	0.07

Table S18. Similarity values of the map comparison between the maps from expert estimates (expert-based ES matrix approach) and the indicator *green and blue area (%)* (LULC data) in the urban region of Munich. 0 indicates no similarity. and 1 very high similarity between the compared maps.

LULC	Mean	Std. dev.

Residential area	0.92	0.08
Industrial and commercial areas	0.88	0.07
Urban green areas	0.52	0.20
Water bodies	0.52	0.13
Agricultural areas	0.58	0.13
Forests	0.49	0.22
Open vegetation	0.57	0.14
Wetlands	0.46	0.14
Infrastructure	0.92	0.12

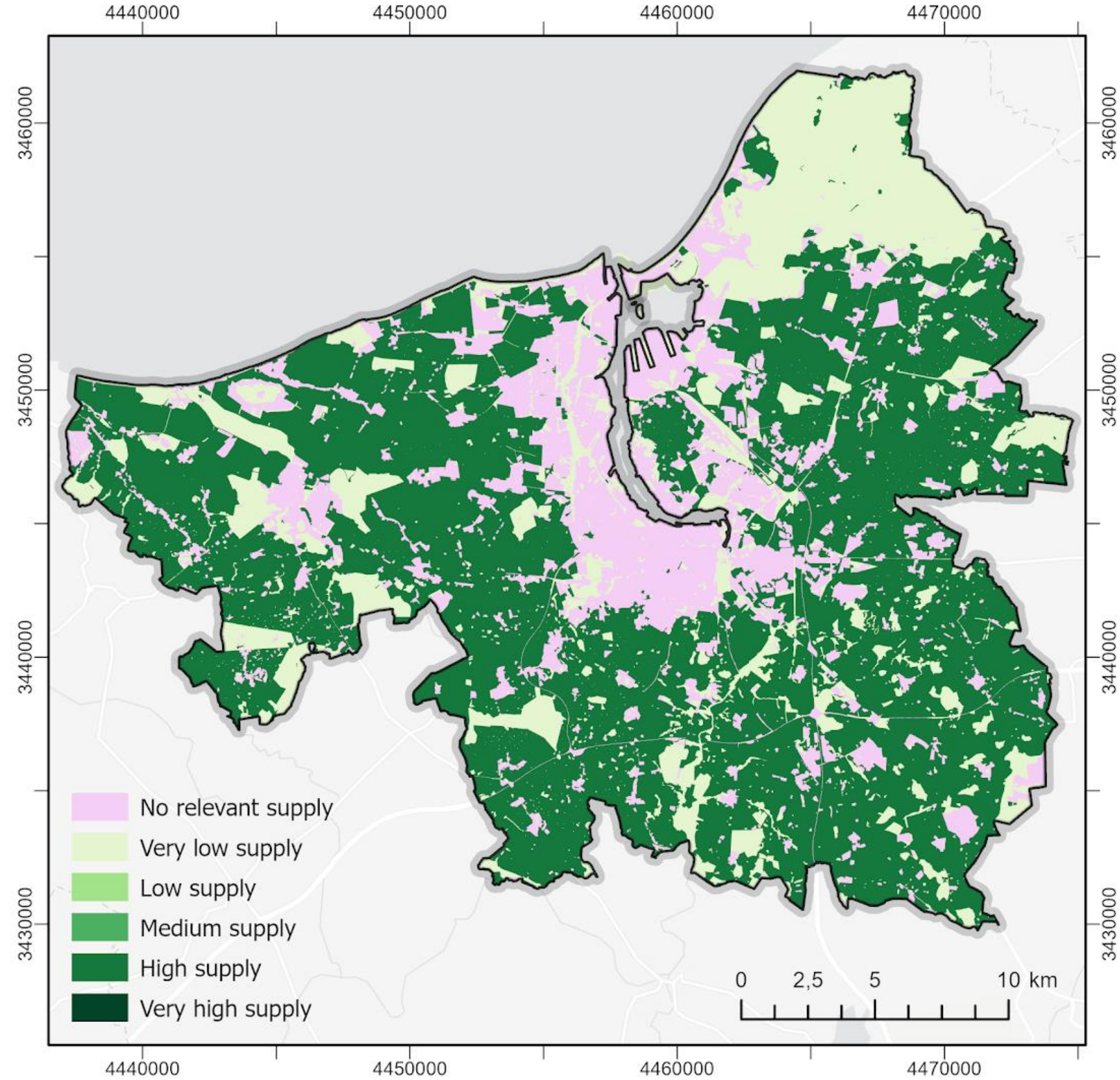
Table S19. Similarity values of the map comparison between the maps from expert estimates (expert-based ES matrix approach) and the indicator *f-ETP-Index* (literature data) in the urban region of Munich. 0 indicates no similarity. and 1 very high similarity between the compared maps.

LULC	Mean	Std. dev.
Residential area	0.89	0.09
Industrial and commercial areas	0.82	0.09
Urban green areas	0.68	0.17
Water bodies	0.65	0.13
Agricultural areas	0.96	0.10
Forests	0.91	0.10
Open vegetation	0.86	0.17
Wetlands	0.86	0.09
Infrastructure	0.90	0.12

Table S20. Similarity values of the map comparison between the maps from expert estimates (expert-based ES matrix approach) and the indicator *heat mitigation index* (InVEST model *Urban cooling*) in the urban region of Munich. 0 indicates no similarity. and 1 very high similarity between the compared maps.

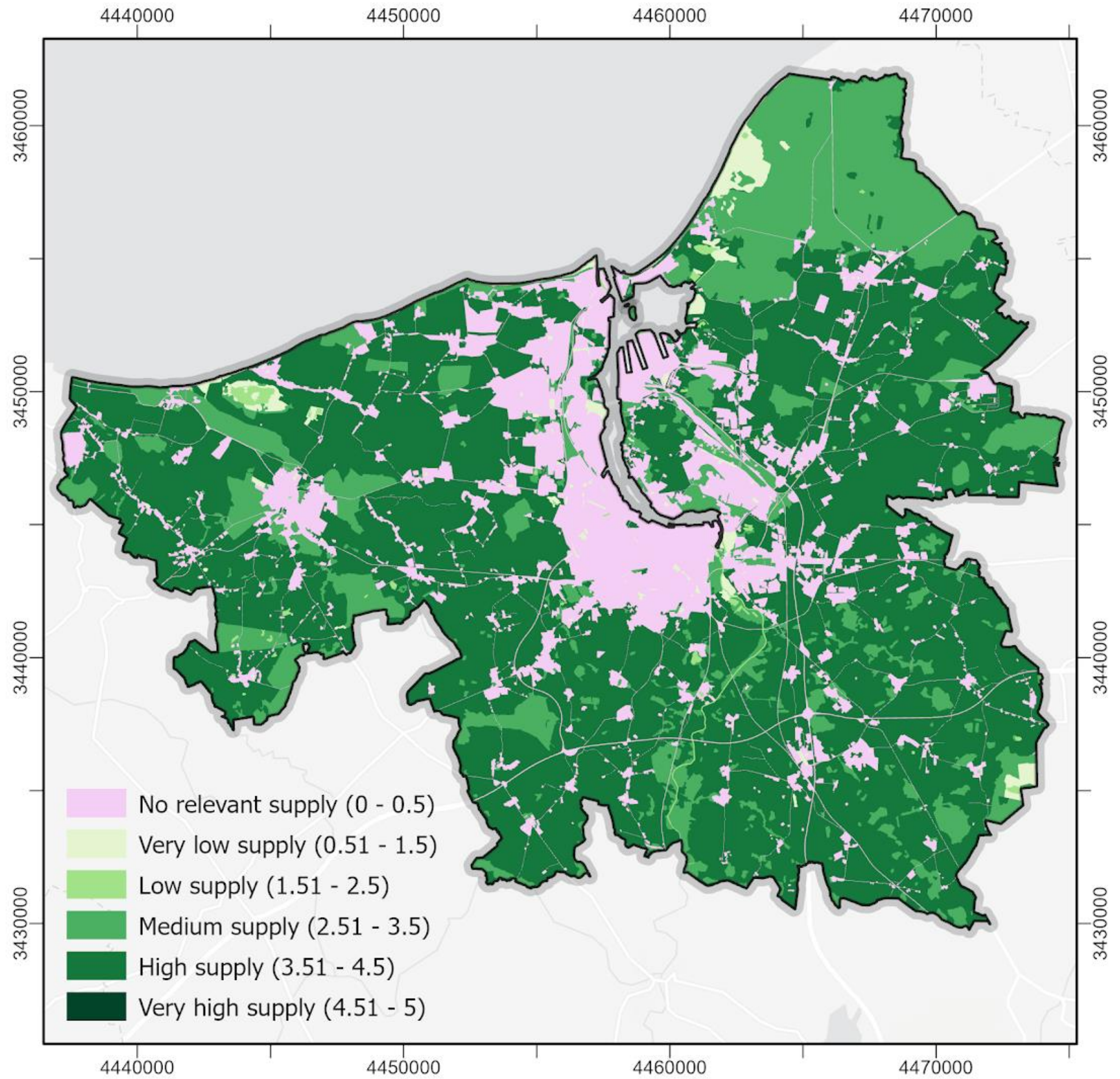
LULC	Mean	Std. dev.
Residential area	0.84	0.22
Industrial and commercial areas	0.86	0.26
Urban green areas	0.76	0.15
Water bodies	0.66	0.10
Agricultural areas	0.58	0.10
Forests	0.75	0.06
Open vegetation	0.64	0.11
Wetlands	0.66	0.02
Infrastructure	0.70	0.30

Figure S2. Expert estimates of ES supply of food (from cultivated terrestrial plants). Urban region of Rostock.



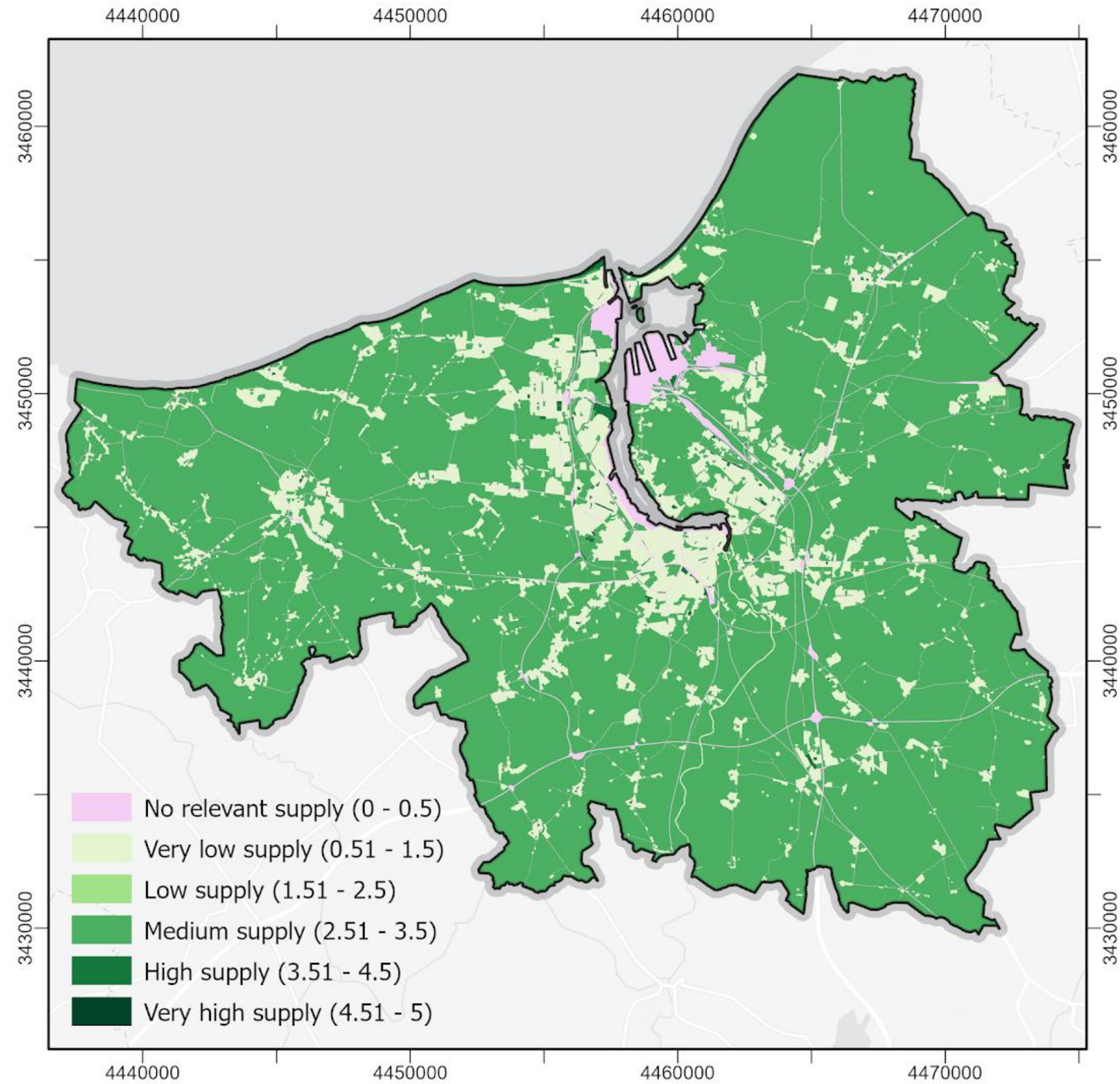
Data: Expert-based ES supply assessment, n=15; ATKIS © GeoBasis-DE/M-V 2017; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S3. Expert estimates of ES supply of raw materials (from cultivated terrestrial plants). Urban region of Rostock.



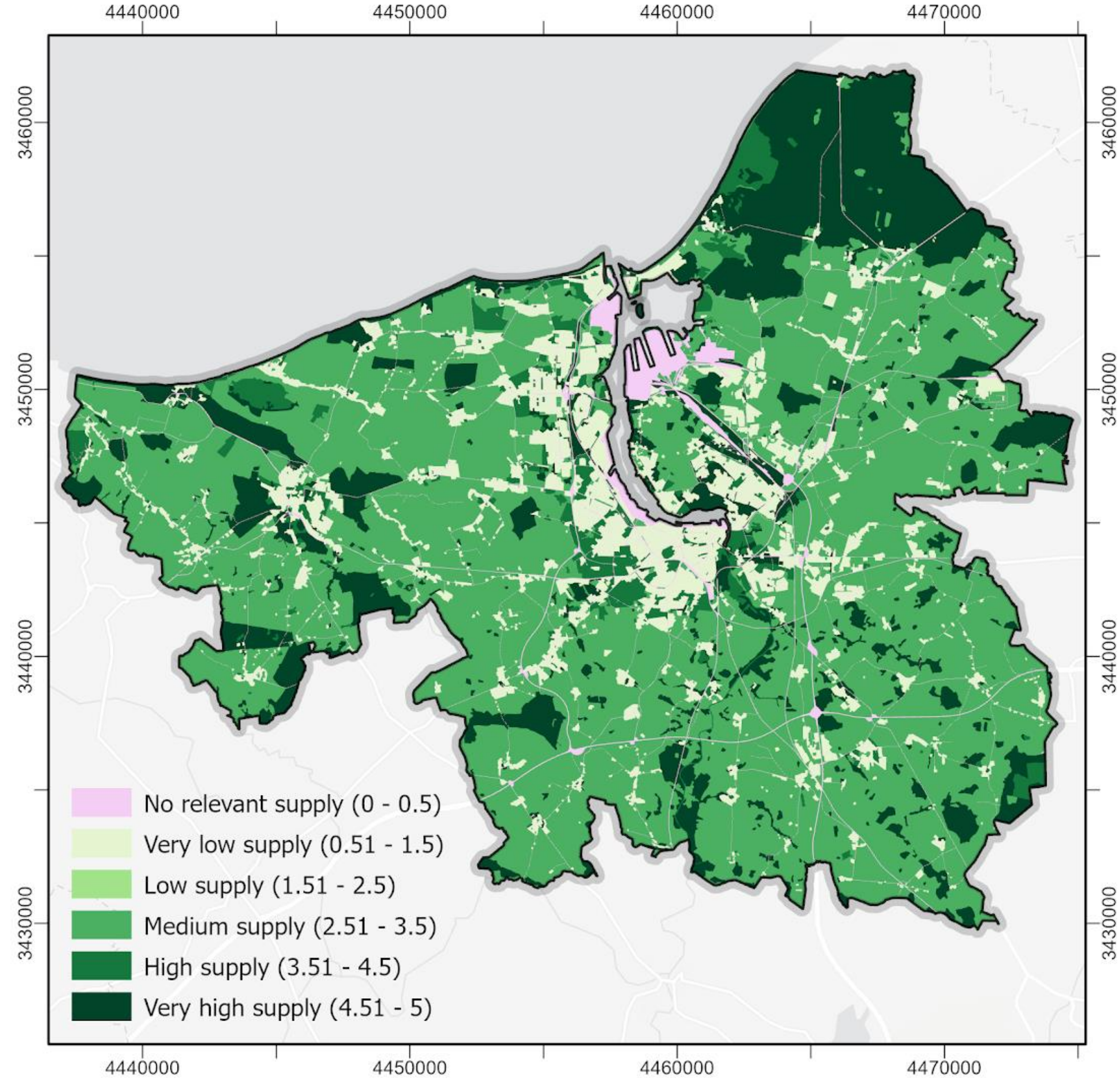
Data: Expert-based ES supply assessment, n=15; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S4. Expert estimates of ES supply of pollination. Urban region of Rostock.



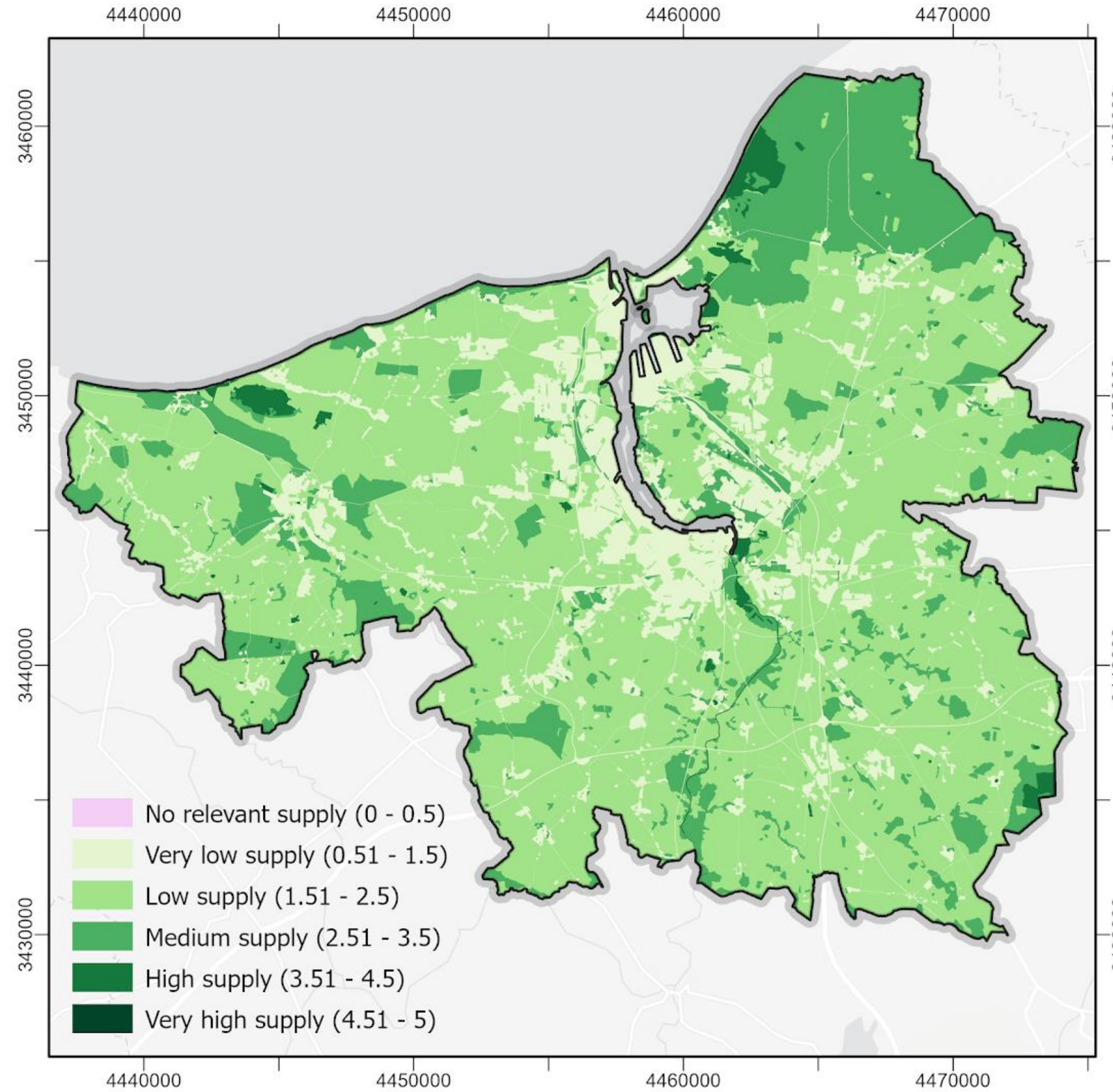
Data: Expert-based ES supply assessment, n=15; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S5. Expert estimates of ES supply of local climate regulation. Urban region of Rostock.



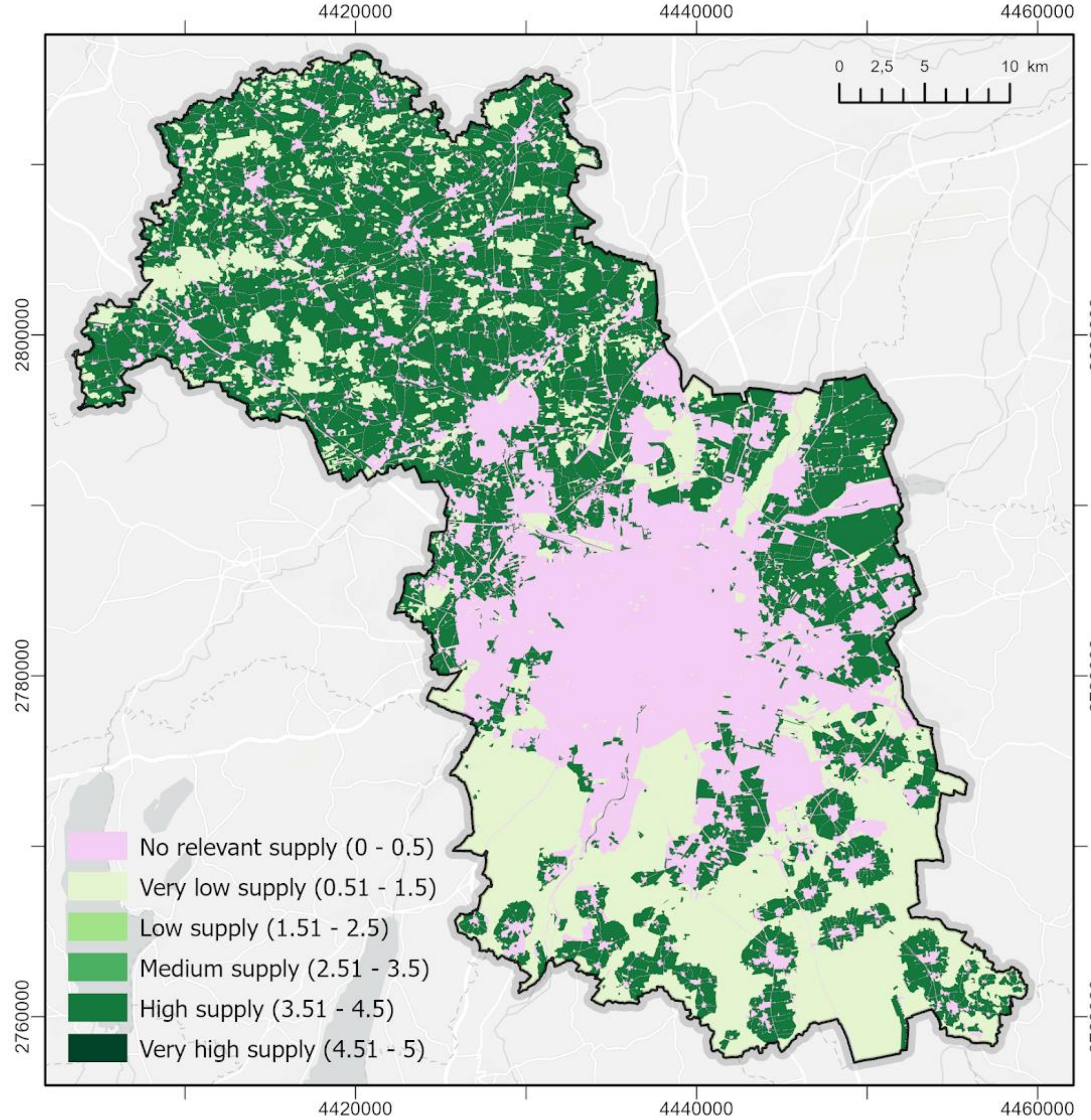
Data: Expert-based ES supply assessment, n=15; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S6. Expert estimates of ES supply of flood and coastal protection. Urban region of Rostock.



Data: Expert-based ES supply assessment, n=15; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

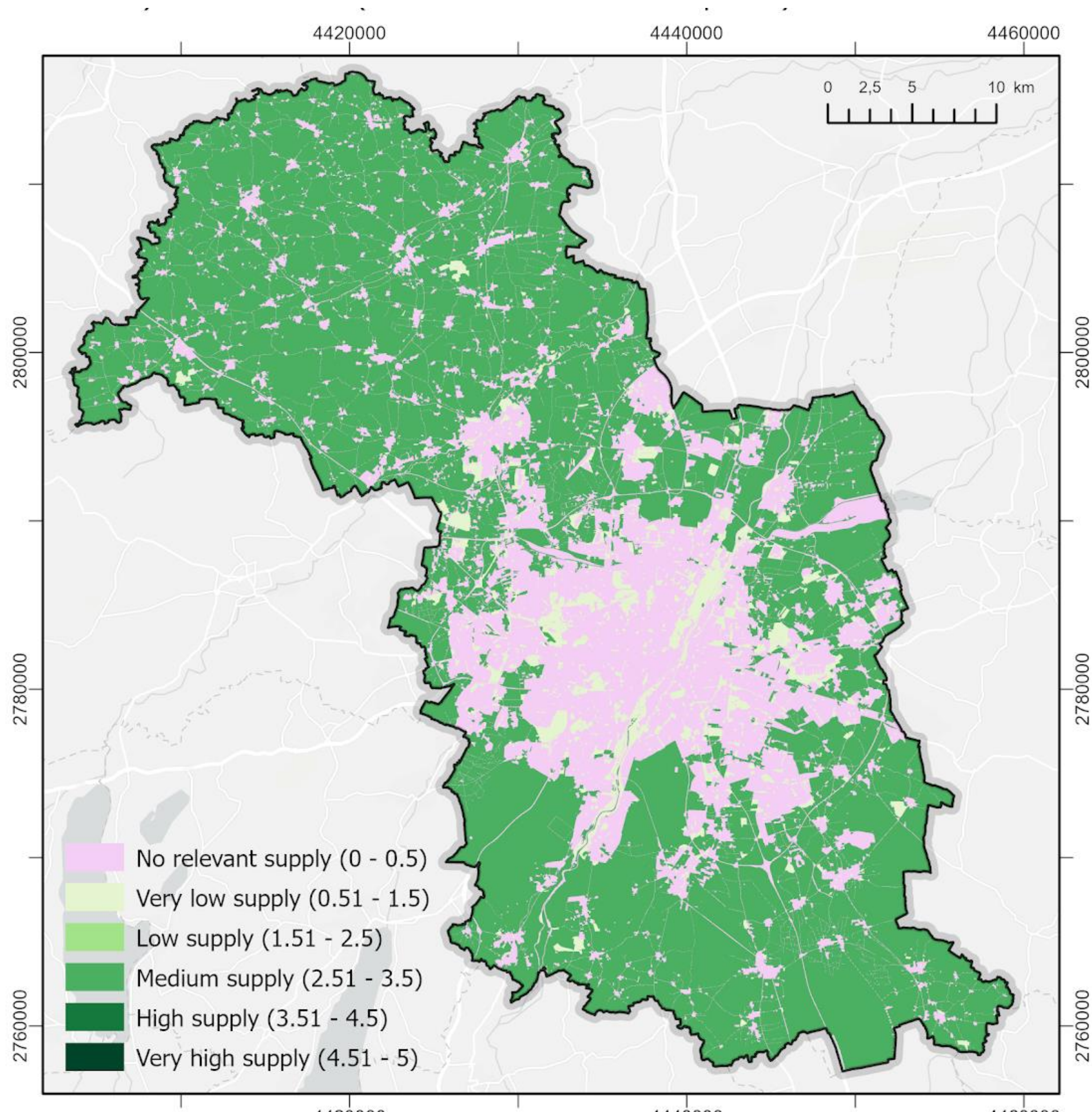
Figure S7. Expert estimates of ES supply of food (from cultivated terrestrial plants). Urban region of Munich



Data: Expert-based ES supply assessment, n=12; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).

Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

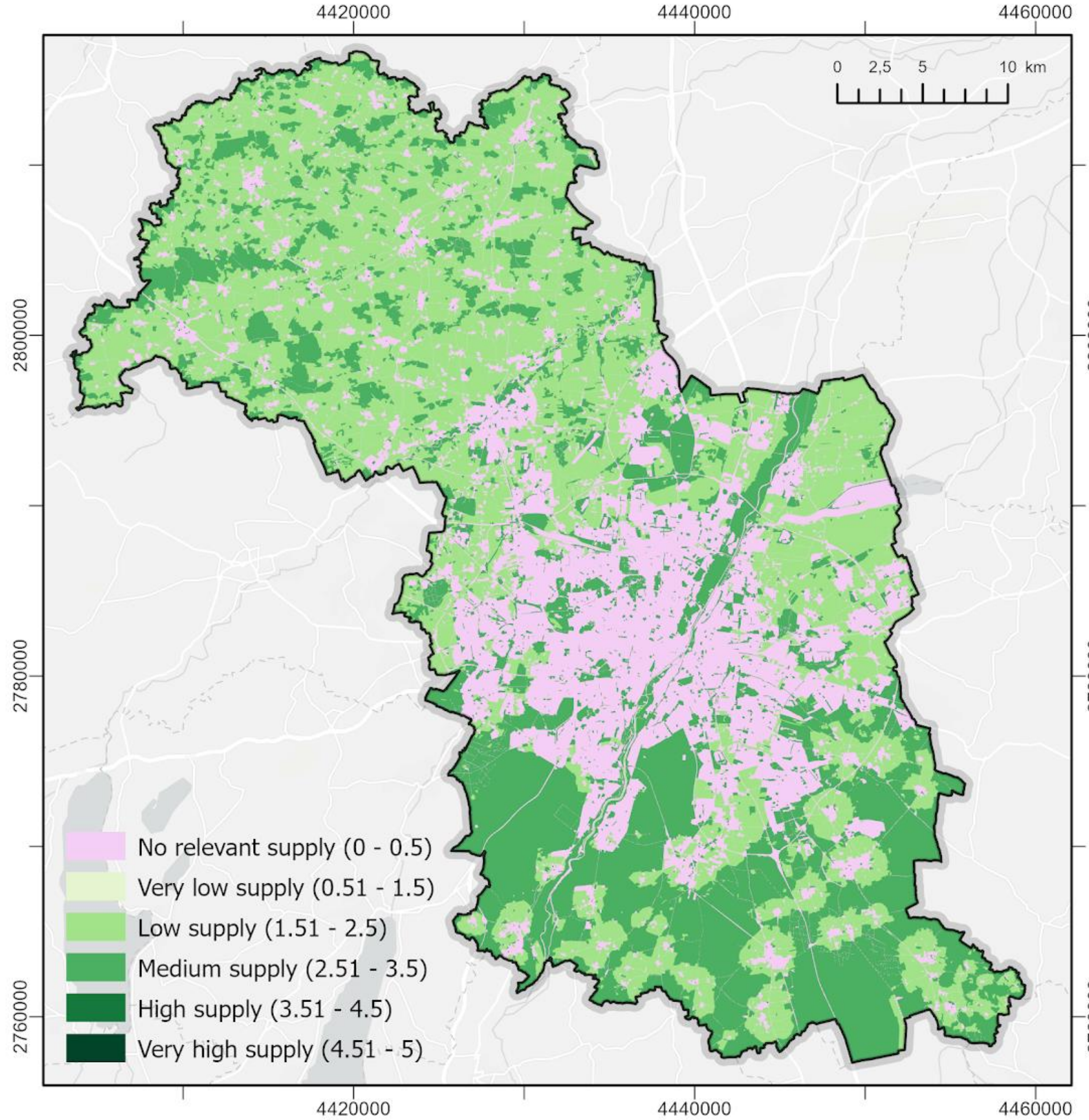
Figure S8. Expert estimates of ES supply of raw materials (from cultivated terrestrial plants). Urban region of Munich.



Data: Expert-based ES supply assessment, n=12; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).

Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

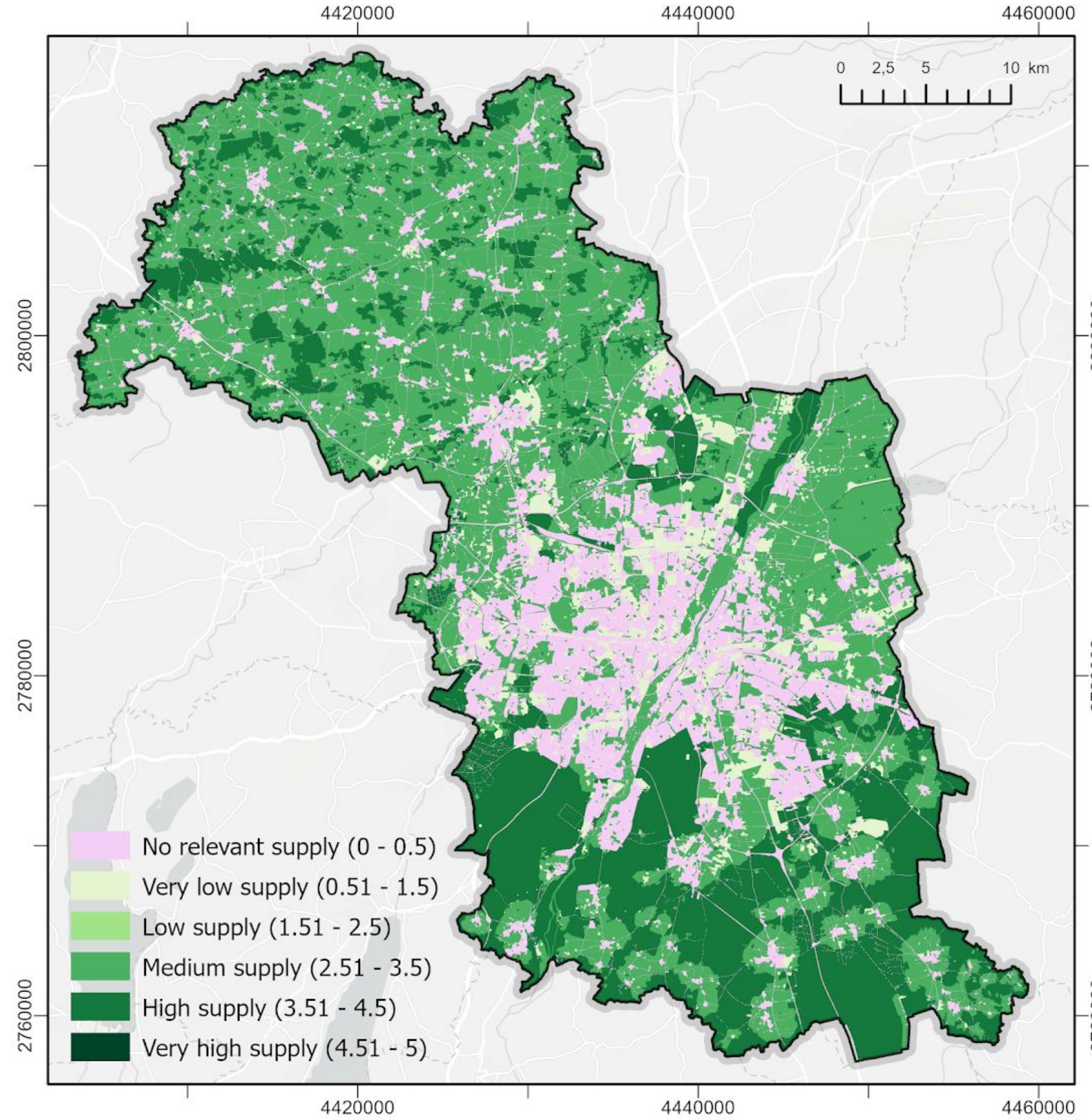
Figure S9. Expert estimates of ES supply of pollination. Urban region of Munich.



Data: Expert-based ES supply assessment, n=12; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).

Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

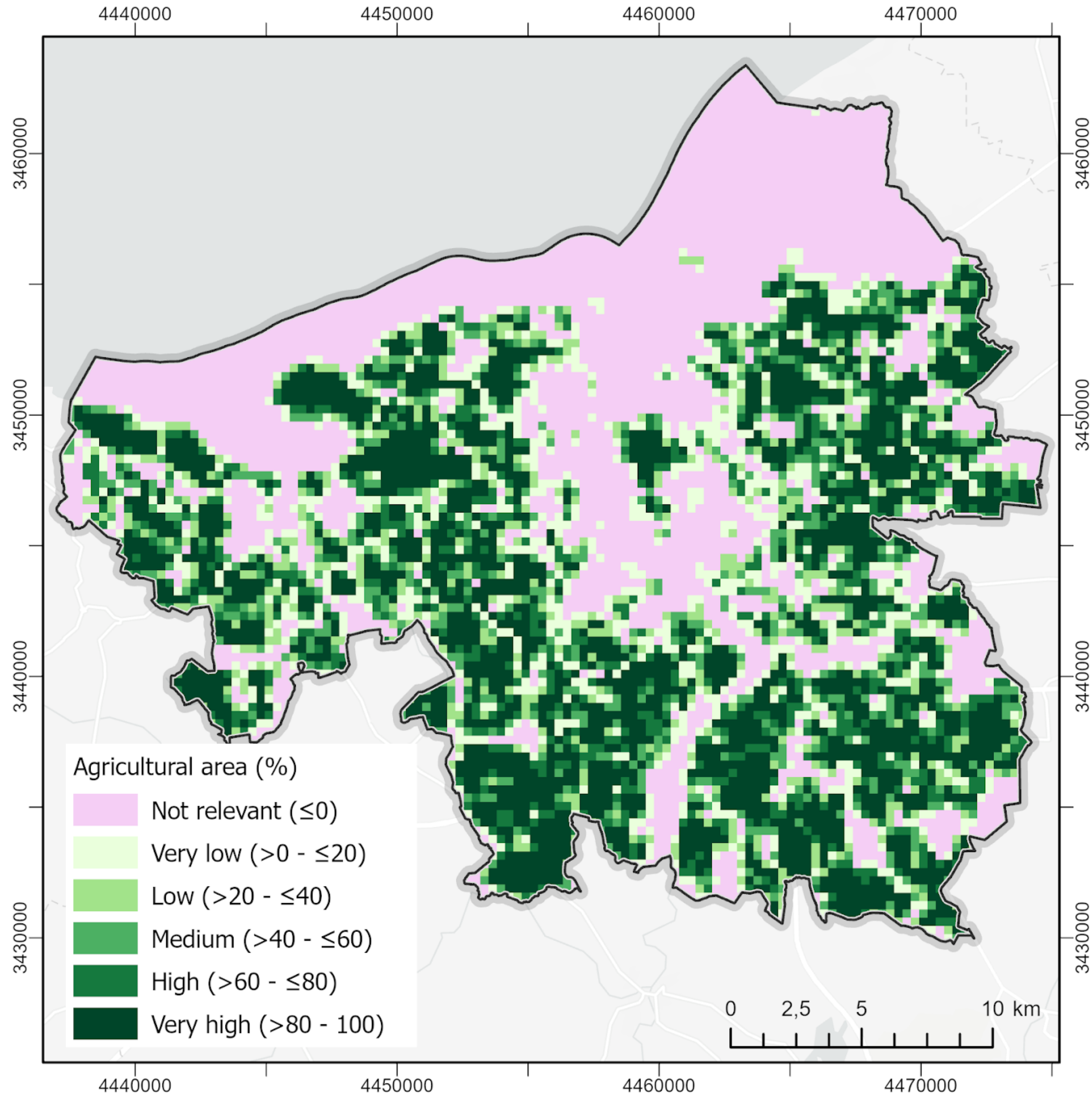
Figure S10. Expert estimates of local climate regulation. Urban region of Munich.



Data: Expert-based ES supply assessment, n=12; Urban Atlas © EEA 2016; © EuroGeographics for the administrative boundaries (2020).

Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

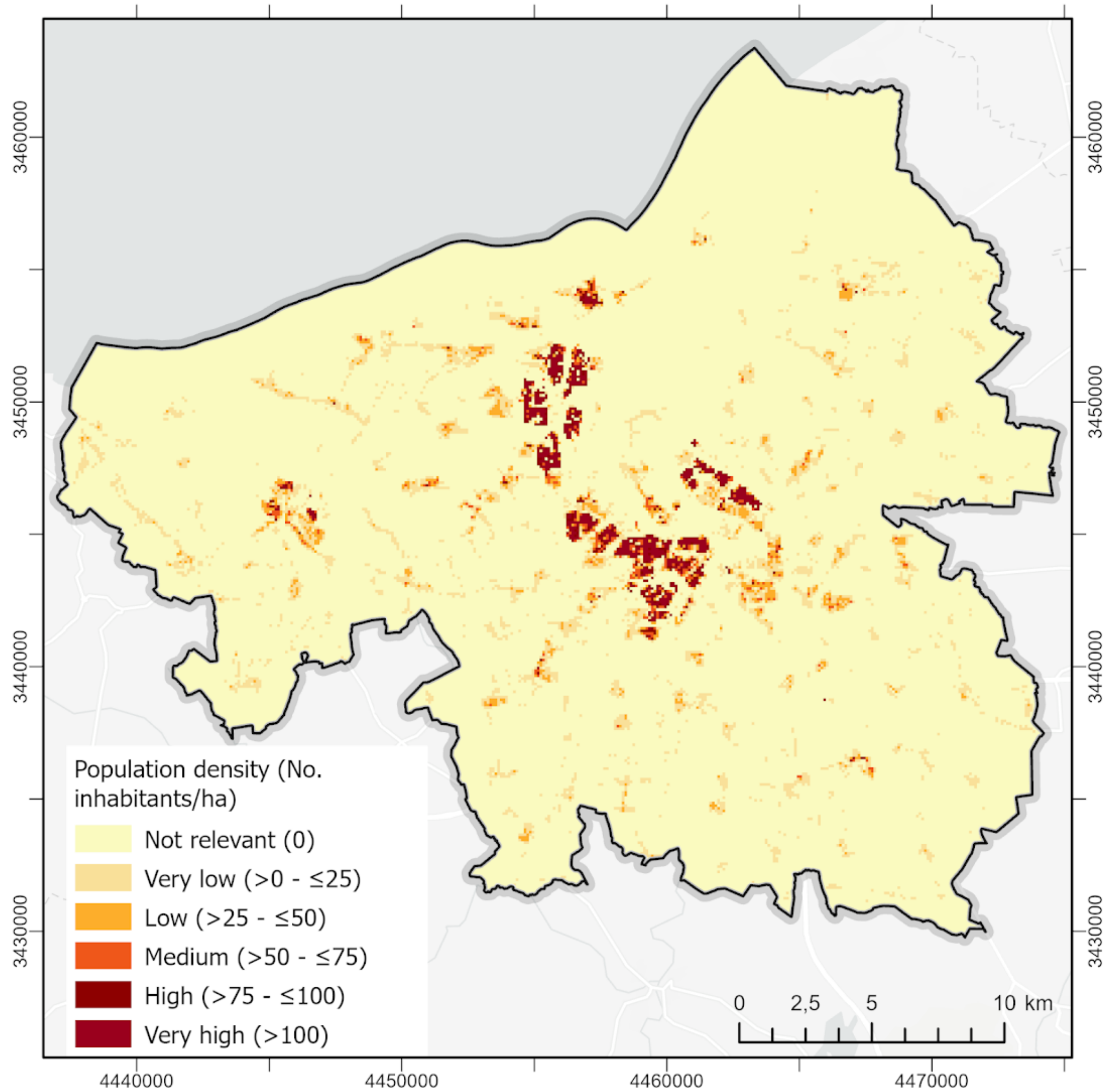
Figure S11. Food (from cultivated terrestrial plants). Indicator: Agricultural area (%). Urban region of Rostock.



Data: Urban Atlas © EEA 2016: © EuroGeographics for the administrative boundaries (2020).

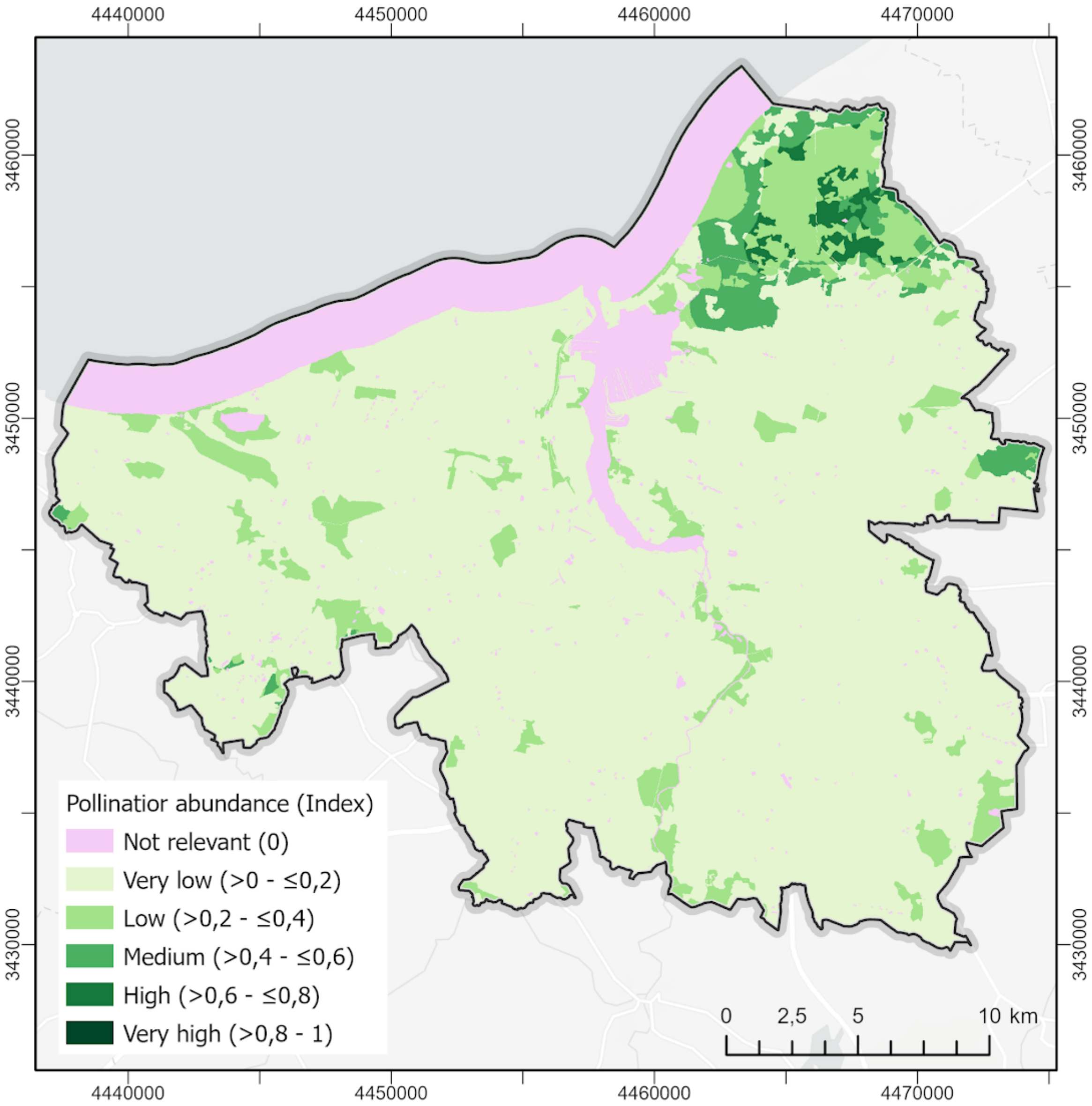
Basemap: ESRI. HERE. Garmin. FAO. METI/NASA. USGS

Figure S12. Food (from cultivated terrestrial plants). Indicator: Population density (Inhabitants ha^{-1}). Urban region of Rostock.



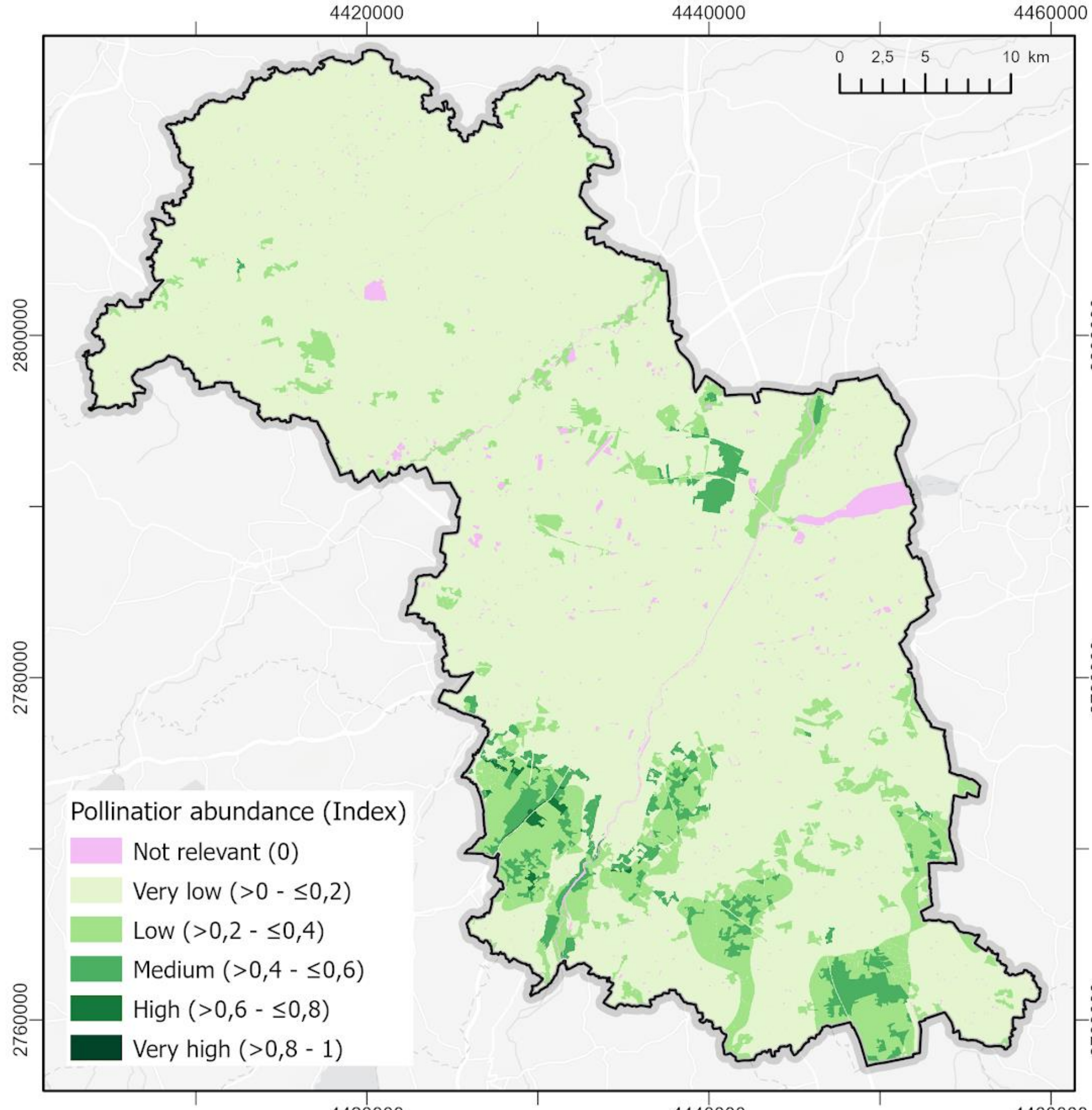
Data: Population density: Statistisches Bundesamt (2015); BKG 2020; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S13. Pollination. Indicator: Pollinator Abundance (Index 0 to 1). Urban region of Rostock.



Data: Urban Atlas © EEA 2016; Corine Land Cover © EEA 2019; © EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S14. Pollination. Indicator: Pollinator Abundance (Index 0 to 1). Urban region of Munich.



Data: Urban Atlas © EEA 2016; Corine Land Cover © EEA 2019; EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S15. Coastal protection. Indicator: Human health at risk of coastal flooding. Urban region of Rostock.

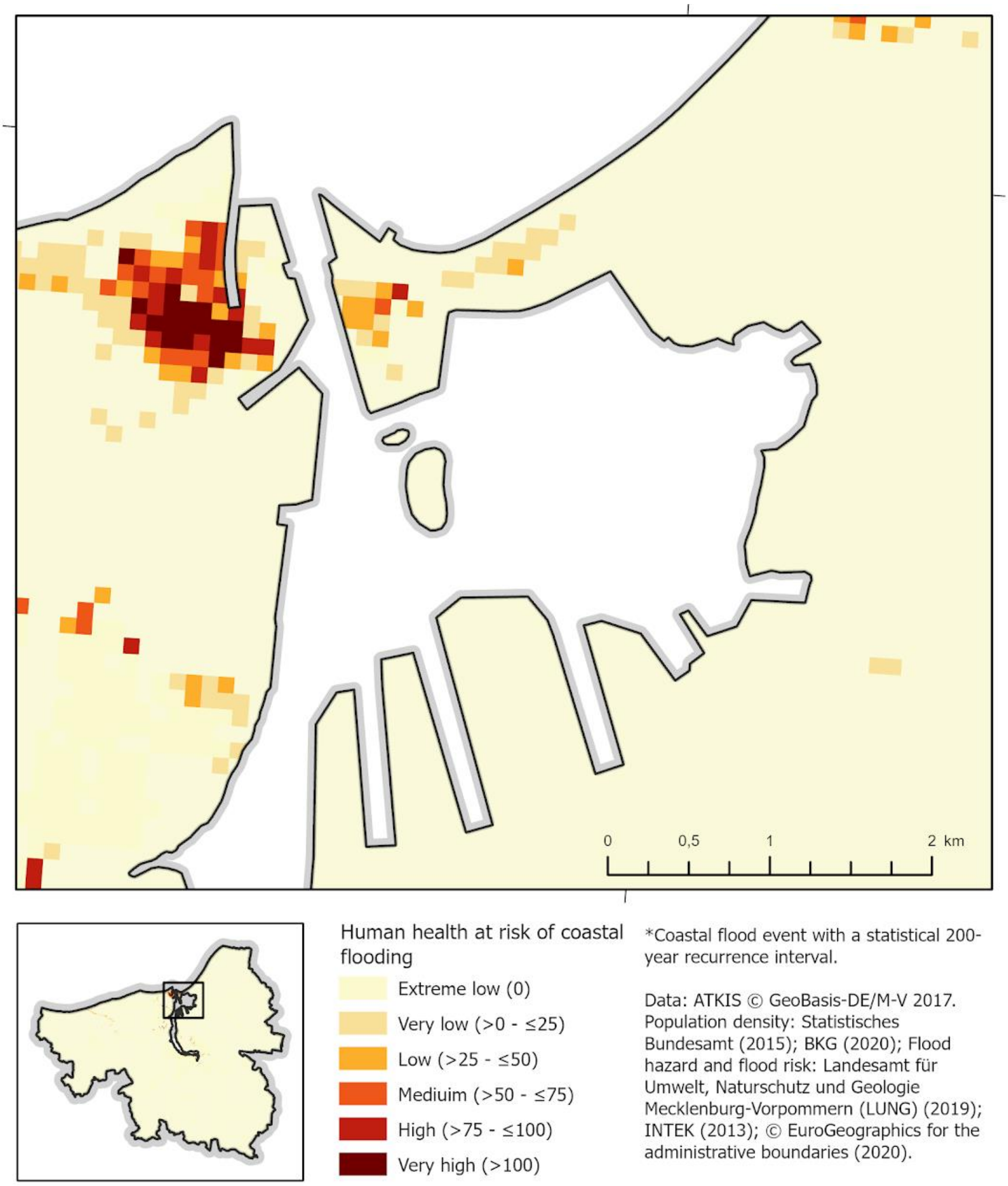


Figure S16. Coastal protection. Indicator: Infrastructure at risk of coastal flooding. Urban region of Rostock.

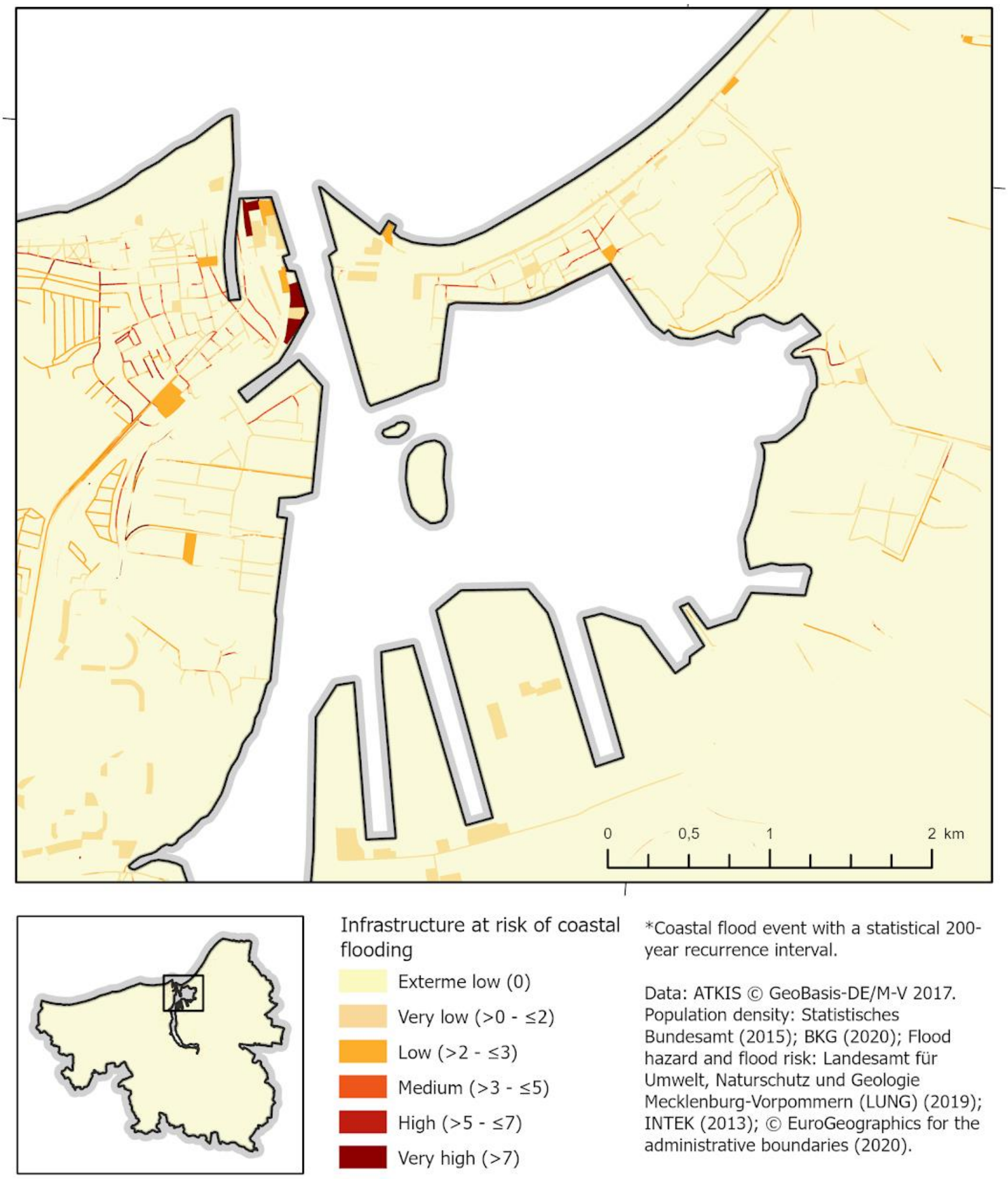


Figure S17. Coastal protection. Indicator: Environment (biotopes) at risk of coastal flooding. Urban region of Rostock.

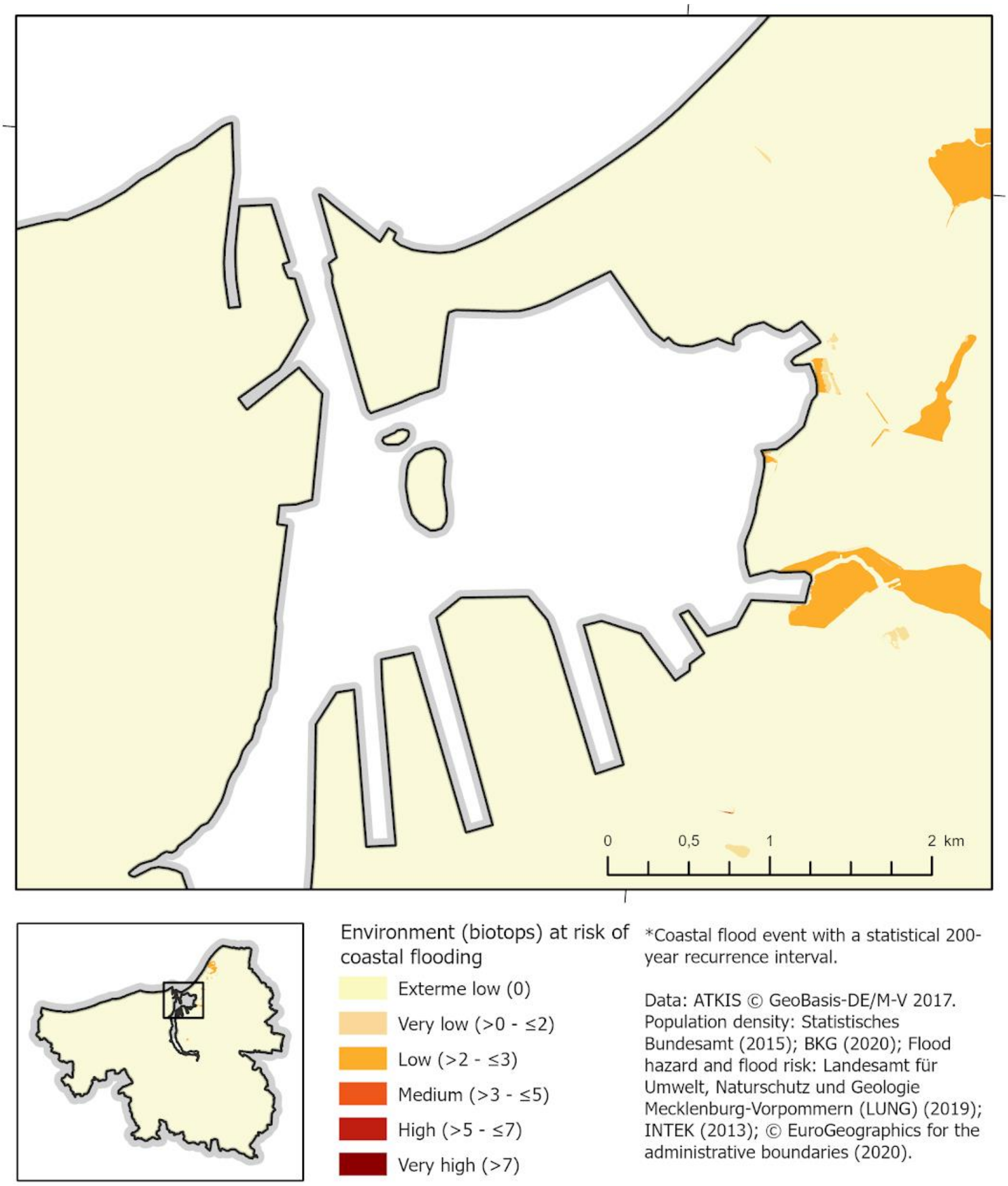


Figure S18. Coastal protection. Indicator: Human economic activities at risk of coastal flooding. Urban region of Rostock.

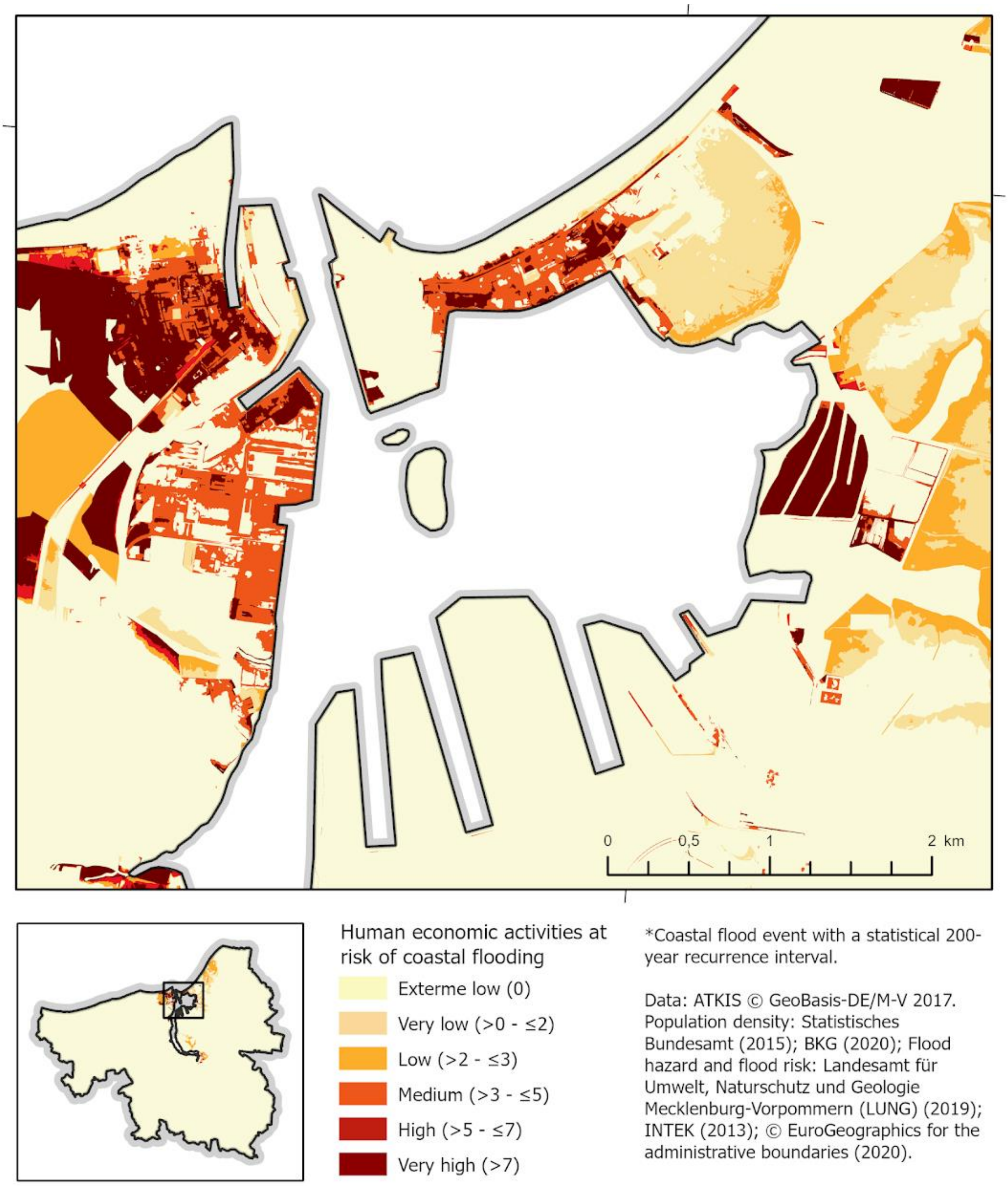
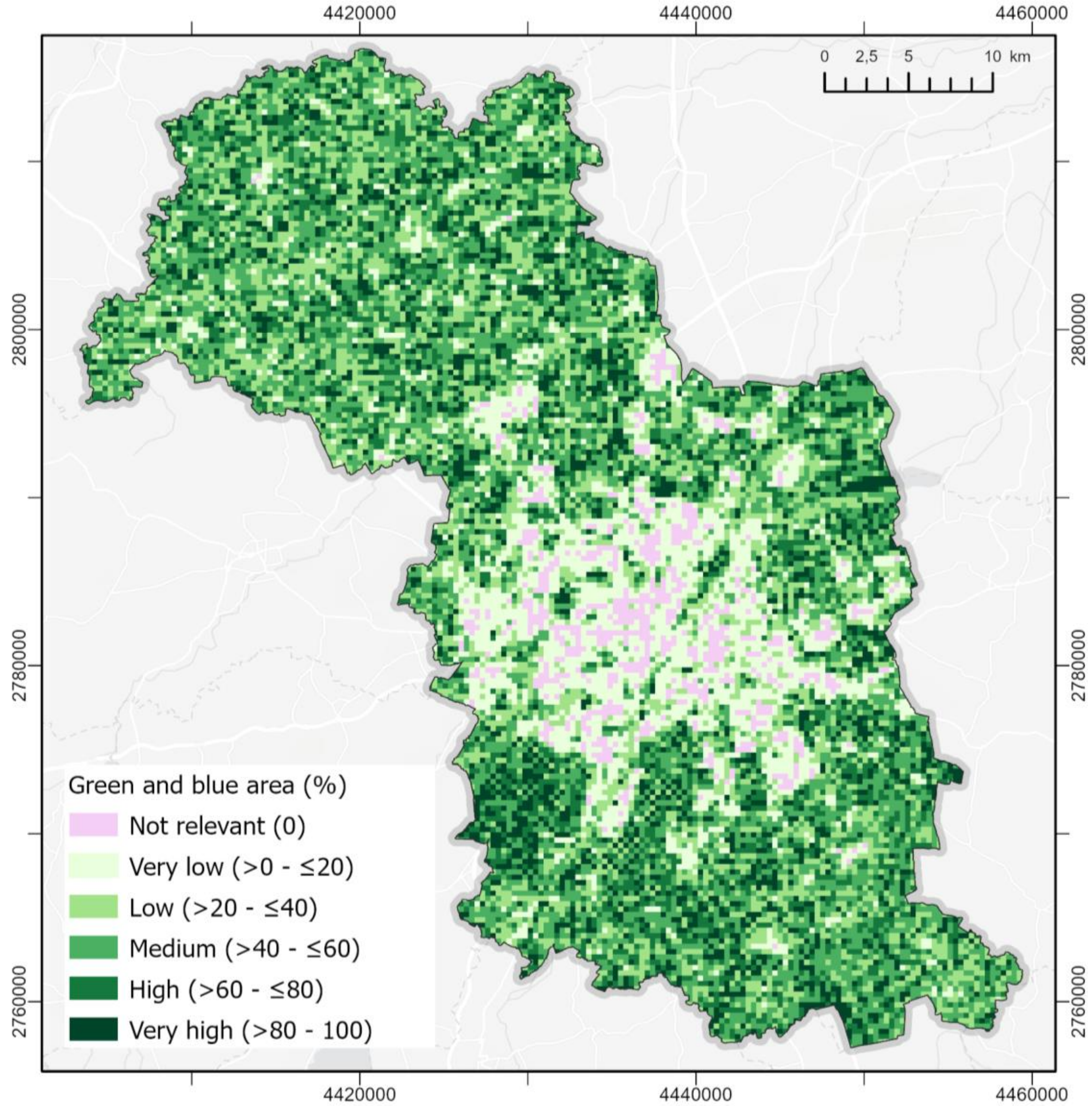
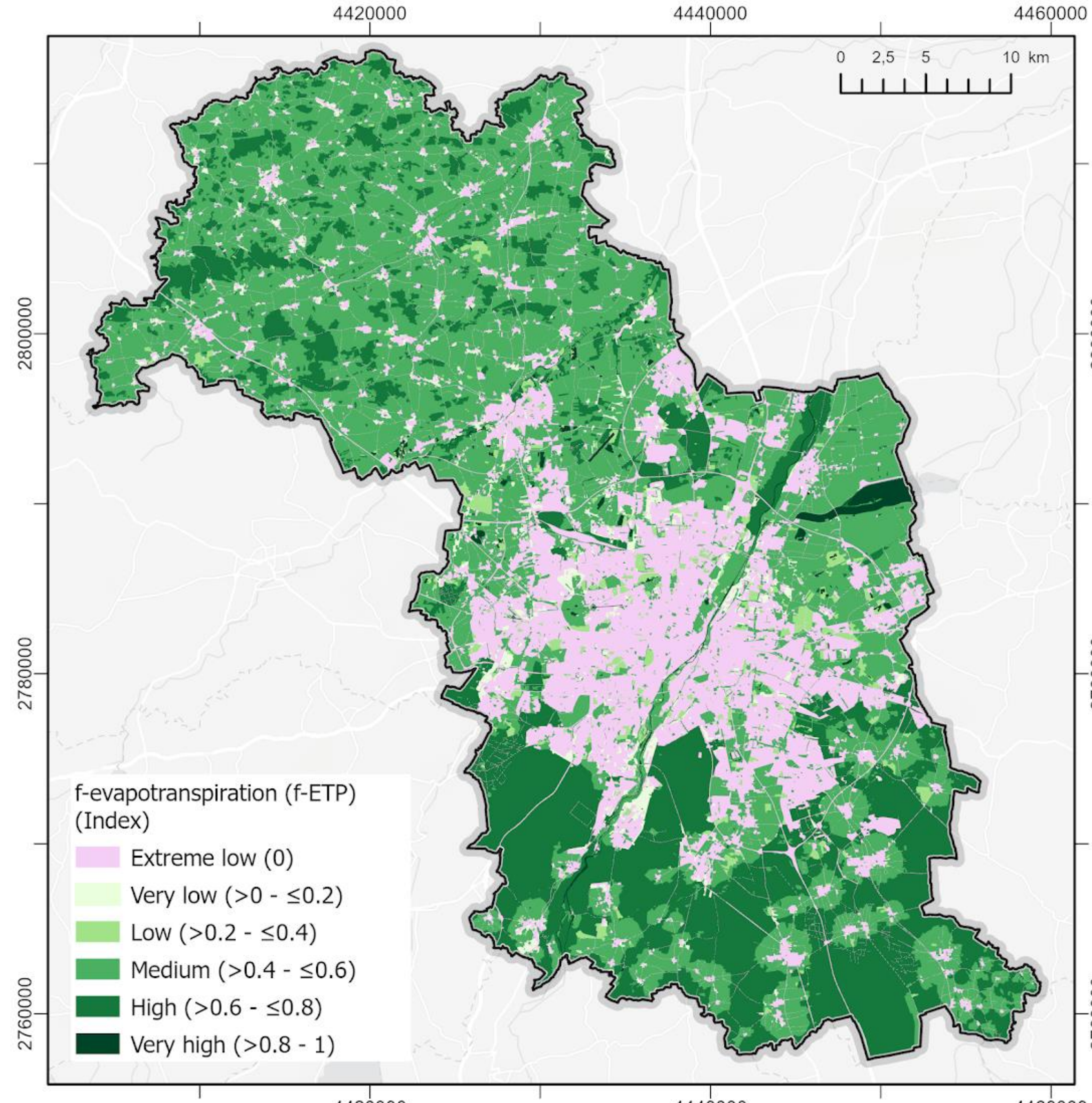


Figure S19: Local climate regulation. Indicator: Green and blue area (%). Urban region of Munich.



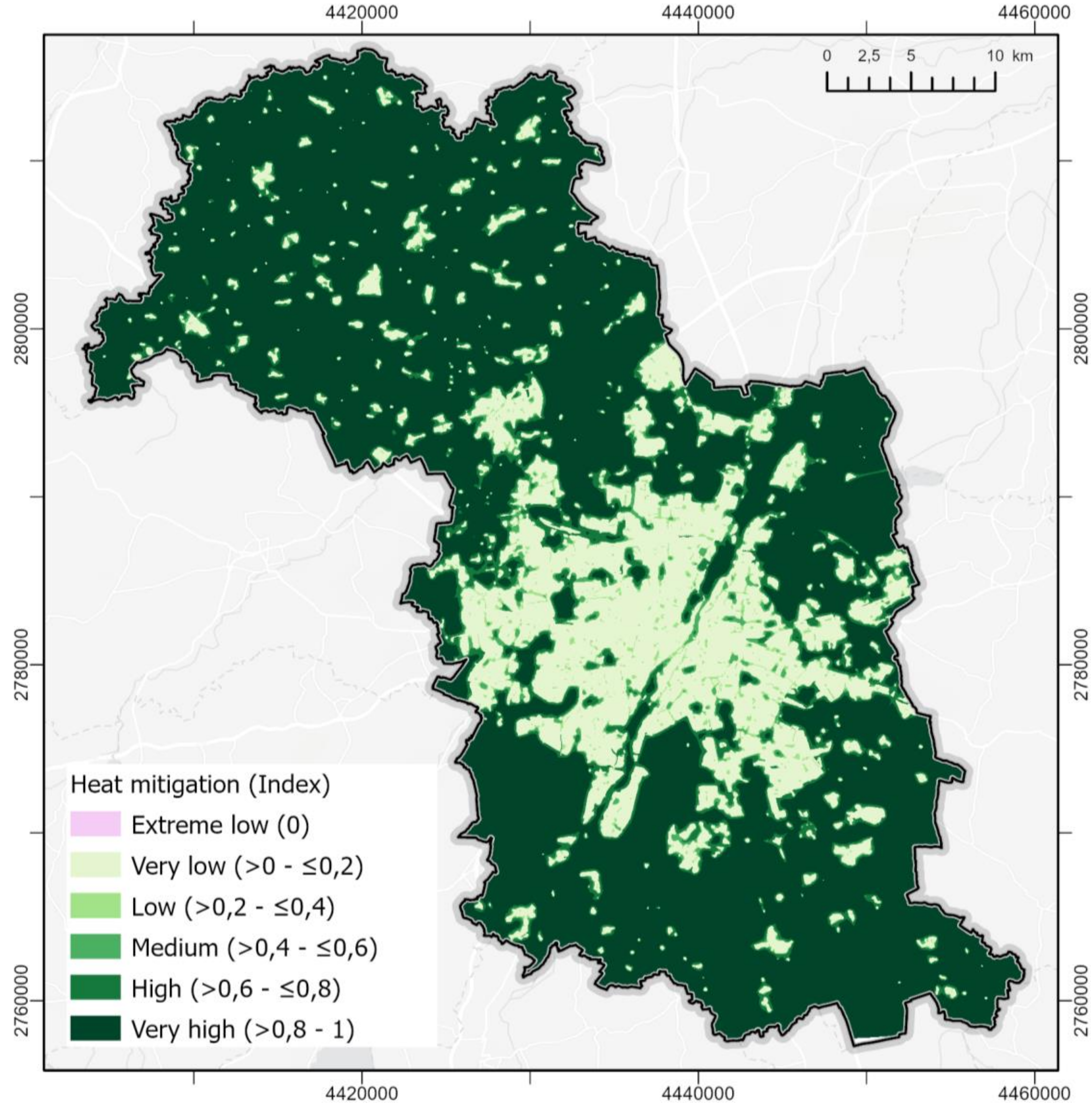
Data: Urban Atlas © EEA 2016: © EuroGeographics for the administrative boundaries (2020).
Basemap: ESRI. HERE. Garmin. FAO. METI/NASA. USGS

Figure S20. Local climate regulation. Indicator: *f*-evapotranspiration (*f*-ETP) (Index 0 to 1). Urban region of Munich.



Data: Urban Atlas © EEA 2016; Corine Land Cover © EEA 2019; EuroGeographics for the administrative boundaries (2020).
Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Figure S21. Local climate regulation. Indicator: Heat mitigation (Index 0 to 1). Urban region of Munich.



Data: Urban Atlas © EEA 2016; Corine Land Cover © CDC 2018a; © CDC 2019; © CDC 2020; Yale University 2019; Nistor 2016; Stewart and Oke 2012; © EuroGeographics for the administrative boundaries (2020).

Basemap: Esri, HERE, Garmin, FAO, METI/NASA, USGS.

Supplementary information for Chapter 5

Appendix A. Grunewald et al. (2020)

Thematic analysis of stakeholder interviews

Question 1. "What do you think about the ES concept in general? Is it necessary for political/administrative actors of the city administration?"

The four components revealed by PCA (eigenvalue > 1) accounted for 80% of the total variance in practitioner's perception/attitude of the ES concept. The first component PC1 (explaining 36% of the total variance) was characterised by a high positive loading with three main categories: awareness of ES concepts, planning and cooperation (Table 1). These categories were positively correlated to the axis PC1. Other categories including decision-making/legislation, communication tool and willingness to use ES concept also contributed to a lesser extent to the first component with communication tool (negative loading) located at the opposite end of the axis. The second component PC2 (explaining 19% of the total variance) was characterised by monetarisation (positively correlated to PC2) and implementation (negative loading) followed by public pressure and willingness (negative loading) located in the opposite direction (Table 1).

Table 1. Results from the principal component analysis (PCA) showing the four principal components. Associations between categories were analysed across the 14 interviews. Categories with factor loadings below a cut-off value of −0.50 and above a value of 0.50 are shown in bold and further referred to as components of the PCs.

	PC1	**PC2**	**PC3**	**PC4**
Monetarisation	-0.06171	**0.838625**	-0.27277	0.260492
Communication tool	**-0.62232**	0.214788	-0.29251	0.465713
Planning	**0.886667**	0.023514	-0.22929	-0.12049
Decision-making	**0.669362**	-0.02298	0.461759	-0.07388
Cooperation	**0.78656**	0.327528	-0.12468	-0.11552
Implementation	-0.39078	**-0.74786**	-0.26287	0.182931
Public pressure	-0.36635	**0.594476**	0.564397	0.135854
Evidence	-0.46295	-0.08784	0.481614	-0.59788
Willingness	**0.537284**	**-0.53045**	0.138899	0.417626
Innovative	0.074389	-0.1075	0.628871	0.637419
Awareness	**0.946393**	0.105881	-0.00104	0.132834

Question 2. What requirements/requests do you have with regard to ES/biodiversity (nature in the city)? In which concrete instruments do you see possible applications?)

The four components revealed by PCA (eigenvalue > 1) accounted for 79% of the total variance in the data that characterised the identification of starting points/structures of daily work, which can be enriched/supported by the ES concept. The first component PCA (explaining 31% of the total variance) was characterised by two main categories monetarisation and implementation which are located opposite from each other (Table 2). Cooperation, communication tool and evidence were also contributing to a lesser extent to the horizontal axis PC1.The second component PC2 (explaining 19% of the total variance) was characterised by willingness to use ES concept and to a lesser extent by the categories planning and evidence (positive loadings) (Table 2).

Table 2. Results from the principal component analysis (PCA) showing the four principal components. Associations between categories were analysed across the 14 interviews. Categories with factor loadings below a cut-off value of −0.50 and above a value of 0.50 are shown in bold and further referred to as components of the PCs.

	PC1	**PC2**	**PC3**	**PC4**
Monetarisation	**0.810643**	0.372198	0.024273	-0.3787
Communication tool	**0.63844**	-0.19915	-0.14677	-0.09509
Planning	-0.25952	**0.691929**	-0.03074	-0.58402
Decision-making	-0.41237	-0.36775	0.38541	-0.29631
Cooperation	**0.692178**	0.180992	**0.538981**	0.36922
Implementation	**-0.85989**	-0.24475	-0.0031	0.273158
Public involvement	-0.03025	0.081257	**0.870659**	-0.19145
Evidence	**-0.5218**	**0.517244**	0.458914	0.288577
Knowledge and training	0.425081	0.191051	-0.0123	**0.670372**
Willingness	-0.35413	**0.822451**	-0.33963	0.18894

Question 3 To what extent are the outcomes/results of ES-assessments relevant (added value) for environmental agencies/authorities and other sectors?

The four components revealed by PCA (eigenvalue > 1) accounted for 89% of the total variance in the data that characterised the relevance of the outcome of scientific case studies/projects. The first component PC1 (explaining 26% of the total variance) was characterised by communication tool, implementation and monetarisation (positive loadings). The second component PC2 (explaining 22% of the total variance) was predominantly characterised by the category knowledge and training (positive loading). Evidence (positive loading) to a lesser extent also contributed to PC2 (Table 3).

Table 3. Results from the principal component analysis (PCA) showing the four principal components. Associations between categories were analysed across the 14 interviews. Categories with factor loadings below a cut-off value of −0.50 and above a value of 0.50 are shown in bold and further referred to as components of the PCs.

	PC1	PC2	PC3	PC4
Monetarisation	**0.865023**	-0.3734	0.034216	-0.07925
Communication tool	**0.629563**	0.095846	0.208482	**0.637653**
Cooperation	0.003967	**0.566542**	-**0.56169**	0.019998
Implementation	**0.581507**	**0.60032**	0.295521	0.075371
Evidence	-0.1374	0.010048	**0.842501**	0.143188
Knowledge and training	-**0.689**	**0.589067**	0.071215	0.368875
Willingness	0.061164	0.446087	0.407317	-0.75466
Decision making	**0.750659**	0.388033	-0.25386	-0.07569

Question 4:

A) Which inhibitory factors do you see? What suggestions do you have regarding fields of application?

The three components revealed by PCA (eigenvalue > 1) accounted for 77% of the total variance in the data that characterised the inhibitory factors of ES. The first component PC1 (explaining 34% of the total variance) was characterised by the difficulties to implement, limited capacity and unwillingness to apply ES concept (all positive loadings). Abstract concept also contributed slightly to the PC1.The second component PC2 (explaining 27% of the total variance) was characterised by limited evidence/standardised methods, the lack of legislation and to a lesser extent limited public involvement, unwillingness to apply ES concept and limited knowledge (all positive loadings) (Table 4).

Table 4. Results from the principal component analysis (PCA) showing the three principal components. Associations between categories were analysed across the 14 interviews. Categories with factor loadings below a cut-off value of −0.50 and above a value of 0.50 are shown in bold and further referred to as components of the PCs.

	PC1	PC2	PC3
No legislation	-0.12049	**0.702782**	-0.48808
Hard to implement	**0.912594**	0.356454	-3.18E-05
Limited public	-0.37247	**0.587552**	**0.51434**
Limited evidence	-0.35402	**0.759679**	-0.25373
Limited knowledge	-0.1863	**0.553947**	0.483028
Unwillingness	**0.800064**	**0.565874**	-0.05791
Limited capacity	**0.79936**	-0.07085	**0.516579**
Abstract	**0.549555**	-0.08321	-0.42515

B) Which promoting factors do you see? What suggestions do you have regarding fields of application?

The three components revealed by PCA (eigenvalue > 1) accounted for 71% of the total variance in the data that characterised the inhibitory factors of ES. The first component PC1 (explaining 31% of the total variance) was characterised by public pressure, monetarisation and willingness to implement ES. Public involvement, case studies (and standardised methods) and legislation also contributed to a lesser extend to the axis PC1. The second component PCA2 (explaining 23% of the total variance) was characterised by communication and to a lesser extent legislation, public involvement, knowledge and training, and case studies (Table 5).

Table 5. Results from the principal component analysis (PCA) showing the three principal components. Associations between categories were analysed across the 14 interviews. Categories with factor loadings below a cut-off value of −0.50 and above a value of 0.50 are shown in bold and further referred to as components of the PCs.

	PC1	PC2	PC3
Knowledge and training	0.359424	**-0.59372**	**-0.53898**
Case studies and standardised methods	**0.583818**	0.510741	-0.01342

Legislation, regulation, reform	-0.58046	**0.630142**	-0.18856
Monetarisation	**0.692646**	-0.24899	0.291875
Communication	0.463912	**0.725922**	0.372823
Cooperation	0.341464	0.115836	**-0.74943**
Public involvement	**0.620506**	**0.612945**	0.039491
Public pressure	**0.695217**	-0.16808	-0.04415
Willingness	**-0.66383**	-0.0309	0.451636
Awareness	0.422511	-0.48958	**0.66007**

Table 6. Higher-level themes for each question. The 115 phrases across the four questions were grouped under higher-level themes.

Question	Higher-level themes	Phrases
1	Communication tool (help in valuation and inter-connectedness of nature)	Complex and abstract Too theoretical, need examples/ evidence of physical benefits ES concept not widely used / known ES useful as communication tool High potential if emphasise in physical benefits Nature is valuable for people/ enriching (benefits for public) Valuation of ES useful and important e.g. wellbeing ES = useful in valuation of nature
	Cooperation	ES facilitates cooperation across different actors ES concept links nature to other sectors ES concept is applicable/ can be used at multi levels (municipal, regional and national) ES has international support ES = useful for political/administrative actors of the city administration ES = important / essential / crucial

	Decision-making and legislation	Lack/outdated of ES concept in official planning document ES not incorporated into legislation Es concept not central to decision making ES helps in justification for decision making ES approach leads to even/equalise the demand-supply region (e.g. rural v. city)
	Planning	ES concept supports planning High potential of using ES for urban planning authorities Applicable/ ES concept has a role in planning
	Awareness	ES concept has been previously applied/ implemented ES concept, some people are aware of it
	ES implementation	Limitation/ valuation and practices not transferable Awareness of how to implement ES is low/ uncertain on how to implement ES ES concept not working Enlightened politician/community leader is important for implementation of ES into planning
	Evidence and methods	Standardised methods and criteria to value nature needed
	Innovative concept	Not a new concept ES concept used but not named (vague) ES = Innovative, novel concept ES= New better approach to assess natural environment
	Monetarisation	Sceptical about monetarisation of nature Monetarisation of nature has some accessory benefit but not the driving force for policy or administration Nature cannot be exchanged Valuation of ES useful and/or important e.g. monetarisation
	Public pressure	Strength of public pressure to consider ES (existence of public awareness of nature value) Weight of public opinion in politics matters
	Willingness to adopt ES	Using ES when it suits the individual/ opportunistic Unwillingness to adopt ES Willingness to implement ES concept

2	Communication tool (help in valuation and inter-connectedness of nature)	Terminology issues e.g. language barrier Terminology issues e.g. need standardise clarification as too abstract/ complex, vague, no legal terms) ES useful as communication tool ES concept improves communication Promote various usage of nature/ multi-functionality High potential if emphasise in physical benefits exists
	Decision-making and legislation	Valuable for negotiating/ discussion Change the way actors think ES helps in Justification for decision making ES central to policies Integration of ES into legislation needed Reform planning needed ES Implementation across all levels needed Inforce legislation Government needs to "buy-in" into the ES concept/ inforce Targets for resources conservation needed
	Planning	Need to Prioritise eco-sensitive land use policies (Green infrastructure / nature based solution) ES helps understand urban planning Inclusion of ES into spatial planning High potential of using ES for urban planning authorities
	ES implementation	Co-funding by key economic players can help to implement ES Challenge to fund new ES project Limited capacity (lack of resources, time and high cost) New ES approach can be challenging to use (hard to change plans) Progress v. preservation (competing interests)
	Knowledge/training of ES	Need to increase understanding/ knowledge/ training of ES

	Evidence and methods	Stronger scientific arguments / evidenced needed Standardised methods and criteria to value nature needed Case study - example (proof of concept) needed Baseline data, information needed
	Cooperation	Need for Cooperation across different actors Collaboration between scientists and non-scientists needed Need to link nature to other sectors
	Public involvement	More citizen involvement needed Reaching new audiences needed (public outreach) Strong opportunities for citizen involvement Citizen involvement is a strength
	Monetarisation	Need to value ES e.g. monetary Valuation of ES useful and/or important e.g. monetarisation
	Willingness to adopt ES	Using ES when it suits the individual/ opportunistic
3	Communication tool	Output of scientific case studies useful for communication Hard to understand scientific output
	Cooperation	Strength of collaborative projects (share workload, expand knowledge) ES project links nature to other sectors
	Decision-making	Output of scientific case studies useful for decision-making
	ES implementation	Gap between science research and real world implementation (e.g. administration, consultancy) Limited capacity (lack of resources, time and high cost) Difficult to implement scientific study New ES approach can be challenging to use (hard to change plans)
	Knowledge/training of ES	More ES education needed Importance of prior knowledge to understand scientific case study

	Evidence and methods	Case study - example (proof of concept) are important/needed More capability in tools to transfer ES concept across sectors Reputation of the source (e.g. scientific) can affect the influence of the study Outcomes of scientific project useful/ applicable Output of scientific case studies generate evidence and knowledge
	Monetarisation	Valuation of ES useful and/or important e.g. monetarisation
	Willingness to adopt ES	Sceptical about the outputs of public opinion survey Mixed feelings on the added value of scientific project
4a	Abstract	Terminology issues e.g. language barrier Terminology issues e.g. need standardise clarification as too abstract/ complex, vague, no legal terms) Gap between science research and real world implementation (e.g. administration, consultancy) Challenging to relate benefits/services of nature to individual level Lack of direct measure of nature Hard to understand scientific output ES concept is complex and abstract Research output not enough to reach public, need for attractive and effective ways to disseminate ES message
	No legislation	ES not incorporated into legislation Lack/outdated of ES concept in official planning document
	Limited capacity	Profit-driven decision, not long term Limited capacity (lack of resources, time and high cost) Challenge to fund new ES project Mismatch between timing of plan development and funding opportunities

	Hard to implement ES	Difficult to decided when contrasting aspects in planning Challenge to focus on more than one system (required multi) Lack of evaluation of impacts of decision-making (lack of case studies) New ES approach can be challenging to use (hard to change plans) Timing mismatch with ES assessment (research output) given after planning stage Difficult to implement ES concept Change in financial-economic mechanism of planning, how can ES be translated into city revenue opportunity
	Limited knowledge/training of ES	Lack of knowledge/training/ experience
	Limited evidence	Lack of standardised methods and criteria to value nature
	Limited public involvement	Reaching new audiences can be challenging (public outreach) More citizen involvement needed Research output not enough to reach public, need for attractive and effective ways to disseminate ES message Require public pressure/interest
	Unwillingness	Unwillingness to adopt ES Sceptical about the outputs of public opinion survey Buy-in of ES concept/effectiveness of ES depends on individual perceptions Resistance to change Using ES when it suits the individual/ opportunistic
4b	Communication tool (help in valuation and inter-connectedness of nature)	Improve communication Nature/greenness = Popular topic -> help ES implementation Promote various usage of nature/ multi-functionality
	Legislation	Reform planning Integrate ES into legislation Inforce legislation from top-down If ES based-argument are well-evidenced, increase opportunity to influence decision-making/court ruling/planning

	Cooperation	Cooperation across different actors/ sectors help for ES implementation International support (Multi-actors meeting/ agreement) for ES concept Inspiration from other countries that use ES
	Awareness	Incorporation of ES informally into planning (ES concept already in use)
	Knowledge/training of ES needed	more understanding/ knowledge/ training about ES concept needed
	Evidence and methods	Case study - example (proof of concept) are important/needed Standardised method and criteria to value nature is important/needed (e.g. model)
	Monetarisation	Valuation of ES is useful and/or important e.g. monetarisation
	Public involvement	Citizen are more positive toward conservation => use this for pushing ES concept forward Strong opportunities for citizen involvement Citizen involvement is a strength
	Public pressure	Public pressure to consider ES (existence of public awareness of nature value) Weight of public opinion in politics matters (move toward conservation and nature)
	Willingness to adopt ES	Willingness to implement ES concept

Supplementary information for Chapter 6

Table 1 Used datasets

Data	Type	Application		Description	Source
		Model	ES		
Precipitation	Timeseries	x		1 min resolution	(DWD Climate Data Center (CDC) 2021b)
Temperature	Timeseries	x		10 min resolution Minimum and Maximum	(DWD Climate Data Center (CDC) 2019a)
Wind speed	Timeseries	x		10 min resolution	(DWD Climate Data Center (CDC) 2019b)
Solar radiation	Timeseries	x		10 min resolution	(DWD Climate Data Center (CDC) 2021a)
Relative humidity	Timeseries	x		10 min resolution	(DWD Climate Data Center (CDC) 2019c)
DEM	Geodata	x		1 m resolution	(Landesamt Mecklenburg-Vorpommern -)
Tree	Geodata	x		Used Attributes: Type, Diameter	(Hanse- und Universitätsstadt Rostock - Amt für Stadtgrün, Naturschutz und Friedhofswesen 2017)
Soil type	Geodata	x			(Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019a)
Land use	Geodata	x	x	Used Attributes: Land use types, Sealing	(Steinbeis-Transferzentrum Geoinformatik 2017)
Population density	Geodata		x	Unit: People/ha	(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt)
Land reference value	Geodata		x		(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt 2021)
Monuments	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Kultur, Denkmalpflege und Museen 2017)
Hospitals	Geodata		x		(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt 2017)
Fire stations	Geodata		x		(Hanse- und Universitätsstadt Rostock – Brandschutz- und Rettungsamt 2017)
Schools	Geodata		x		(Hanse- und Universitätsstadt Rostock – Schulverwaltungsamt 2017)

Care facilities	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Jugend, Soziales und Asyl 2017b)
Institutions for disabled	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Jugend, Soziales und Asyl 2017a)

Table 2 Indicators and explanation of used FRES terms. Further details and descriptions of supply, actual demand, and budget definitions can be found in Wübbelmann et al. (2022).

Term	Explanation	Indicator
Supply Change	The FRES supply is the provision of a service by an ecosystem (Burkhard und Maes 2017). In our study, FRES supply is provided by canopy interception and soil water storage.	Change of intercepted water depth [mm] Change of soil water depth [mm]
Hazard Change	Here, the FRES supply change in a particular ecosystem captures the supply increase or decrease through climatic (rainfall) or site-specific composition (NBS) changes.	Change of surface water depth [mm] Reduction of peak runoff [m^3/min]
Potential Demand	The flood hazard is defined by the model output surface flooding. The flood hazard change indicates the increasing or decreasing of surface water due to adaptation measures (NBS) or higher rainfall amounts by the difference between the scenario and the reference scenario. The potential demand describes the potential need for an ES by society or other stakeholders. The demand for FRES can be captured by the need for risk reduction, prevention and security increase. The potential demand is always existing irrespective of currently existing flooding and does not change in this study.	Population density [inhabitants/ha] Occurrence of monuments [-] Ground reference value [€] Occurrence of critical Infrastructure [-] (hospitals, fire brigade, schools, care facilities, disabled institutions) Occurrence of traffic infrastructure [-] (streets, railways, stations)
Actual Demand Change		Change of potential demanding area that is flooded [-]
Budget Change		Supply – Demand Budget Index [-]

14. Curriculum Vitae

Claudia Anna Dworczyk

22.11.1990, born in Fürth, Germany

EDUCATION

Since 2018	**Leibniz University Hanover, *Doctoral studies in geography*** **Doctoral thesis**: Conceptual and methodological challenges of ecosystem services mapping in urban regions
10.2013 - 07.2016	**Christian-Albrechts-Universität zu Kiel, *M.Sc. in Umweltgeographie und -management*** **Master thesis:** Bewertung und Kartierung von Ökosystemleistungen auf nationaler Ebene in Deutschland – Expertenbasierte Anwendung der Matrix-Methode
10.2010 - 07.2013	**Friedrich-Alexander-Universität Erlangen-Nürnberg, *B.A. in Kulturgeographie*** **Bachelor thesis:** Der städtebauliche Wandel einer mittelsizilianischen Agrostadt in den letzten vier Jahrzehnten.
2010	**Maximilian-Kolbe-Schule, Staatliche anerkannte Fachoberschule in Neumarkt i.d.OPf, *allgemeine Fachhochschulreife***

PROFESSIONAL BACKGROUND

Since 03.2016	**Research assistant** **Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, Germany**
08.2016 - 04.2017	**Research assistant** **Institute Landscape Ecology, University Vechta, Germany**
09.2015 - 02.2016	**Internship** Nationalpark Donau-Auen GmbH, Orth an der Donau, Austria
04 - 06. 2015	**Student assistant** Christian-Albrechts-Universität zu Kiel, Kiel, Germany
04. - 08. 2013	**Internship** Rehau AG + Co, Erlangen, Germany
2009 - 2016	**Student assistant** Regens-Wagner-Stiftung, Neumarkt i.d.OPf, Germany
06. - 08. 2009	**Internship** WHY – Forschung für Marken, Neumarkt i.d.OPf, Germany

Claudia Anna Dworczyk

Hanover, December 2022