Anita Poturalska is an environmental geographer whose research uses geoinformatics-based approaches to integrate aspects of human and physical geography in the study of ecosystem services. Her dissertation emphasizes the value of a geographical perspective when assessing critical ecosystem services, combining spatial analysis with statistical methods.

She seeks to understand the dynamics of the supply, demand and potential of chosen ecosystem services at different scales. Her thesis synthesizes theoretical frameworks for assessing ecosystem services and demonstrates the application of these frameworks through three individual research examples: she maps the supply, demand and potential of services across scales, incorporates ecosystem service flows into supply-demand mismatch evaluations, and highlights the importance of subjective human needs and perceptions as essential components of ecosystem service demand.

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Assessing ecosystem services across scales: Potential, supply, and demand of provisioning and cultural services

Anita Poturalska

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Contents

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Abstract

Ecosystems provide us with countless benefits, such as material resources, regulation of environmental processes, and opportunities for recreation. These benefits, known as ecosystem services (ES), support our daily welfare and well-being. ES arise from ecological, sociocultural, and economic interactions, and are influenced by both ecosystems' capacity to provide services and society's demand for them. ES are unevenly distributed across space, and their supply and demand change over time. Understanding the patterns of ES provision and consumption facilitates the evaluation of their sustainable use. Therefore, comprehensive assessments of ES production and consumption across spatial and temporal scales are essential to deepen our understanding of the ES concept and its role in natural resource management.

In this thesis, I exemplify the use of the ES framework by assessing the spatial and temporal patterns of ES potential, supply, and demand. Overall, I demonstrate how to select and interpret indicators of ES potential, supply, and demand and address them using spatial and statistical methods. I study the provisioning services of forests (wood resources) and the cultural services provided by urban and peri-urban areas through three separate case studies. Each article examines ES aspects across distinct scales, ranging from continental to local. Two articles are at the European level, one of which also includes a temporal scale, and one is at the urban level.

The results regarding wood ES show that the potential, supply, and demand for wood have all increased across Europe. Compared to demand, Europe has a substantial supply surplus, and the analysis of mismatches between the supply and demand indicates that, on average, Europeans have good spatial accessibility to wood resources. However, the growing trend of exploiting wood ES might affect the state of forest ecosystems and their capacity to provide high-quality ES other than wood. The findings regarding cultural ES suggest that subjective spatial characteristics of green spaces, such as perceived accessibility, play a bigger role in more frequent interactions with nature than the biophysical features of these spaces or the consumption of cultural ES itself. This indicates that urban residents demand better access to green spaces in order to fully enjoy and recognize the capacity of urban ecosystems to deliver high-quality cultural ES within close proximity to their homes.

My thesis exemplifies the application of the ES framework in ES mapping, incorporates ES spatial flow into supply and demand mismatch evaluation, and highlights the importance of subjective human needs and perceptions regarding ES demand as vital parts of the ES framework. The evaluation of the distribution and trends in the potential, supply, and demand of the provisioning ES of wood, alongside the produced maps, supports resource monitoring of European forests. The same applies to the maps of wood ES supply–demand mismatches, which integrate the ES spatial flow through spatial accessibility analysis. These results can inform European forest management strategies, providing spatial insights into wood potential, supply, and demand, and their mismatches. Furthermore, the evaluation of the characteristics of green spaces' use patterns emphasizes the importance of spatial perceptions in interactions with urban and peri-urban nature. This information can be communicated to decision-makers in the studied cities and used to enhance access to green spaces that provide vital cultural ES for urban populations.

Keywords: ecosystem services (ES), multiscale ES assessment, Geographical Information Systems (GIS), ES potential, ES supply and demand, provisioning ES, cultural ES

List of original publications and author contributions

This thesis is based on the listed articles, which are referred to in the text by their Roman numerals:

I Poturalska A, Alahuhta J, Kangas K & Ala-Hulkko T (2024) Mapping ecosystem service temporal trends: A case study of European wood potential, supply and demand between 2008 and 2018. *One Ecosystem* 9: e118263. https://doi.org/10.3897/oneeco.9.e118263

II Poturalska A, Kotavaara O & Ala-Hulkko T (2025) A spatial accessibility framework for mapping the mismatch between wood supply and demand across Europe. *Ecological Indicators* 170: 113116. https://doi.org/10.1016/j.ecolind.2025.113116

III Poturalska A, Ala-Hulkko T, Artell J, Juutinen A & Kangas K (in press) Exploring the subjective and objective characteristics affecting the frequency of human–nature interactions in urban green spaces: A case study from Finland. *Urban Ecosystems.*

The original publications and manuscript are available in the appendices of the printed version of this thesis. Article I and Article II are reprinted under CC BY 4.0 Creative Common license. Article III is included as the author's accepted manuscript.

Author contributions for publications I–III are specified below:

I Anita Poturalska: writing – original draft, visualization, investigation, methodology, data curation, conceptualization. Terhi Ala-Hulkko: writing – review & editing, validation, supervision, conceptualization. Other authors: writing: review & editing.

II Anita Poturalska: writing – original draft, visualization, investigation, data curation, conceptualization. Ossi Kotavaara: writing – review & editing, software, methodology, conceptualization. Terhi Ala-Hulkko: writing – review & editing, visualization, validation, supervision, formal analysis, conceptualization.

III Anita Poturalska: writing – original draft, visualization, investigation, conceptualization, formal analysis. Terhi Ala-Hulkko: writing – review & editing, supervision, conceptualization. Janne Artell: writing – review & editing, methodology, conceptualization, data curation. Artti Juutinen: data curation, conceptualization. Katja Kangas: writing – review & editing, supervision, conceptualization, data curation

I have not used generative AI in the planning and writing of my dissertation. I take full responsibility for the content of this dissertation.

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Thank you. Kiitos. Dziękuję.

List of abbreviations

CICES....................Common International Classification of Ecosystem Services
CLC........................Corine Land Cover
ES...........................Ecosystem Service(s)
GIS.........................Geographic Information Systems
IPBES....................International Panel for Biodiversity and Ecosystem Services
IRR.........................Incidence Rate Ratio
LAU........................Local Administrative Units
MEA.......................Millenium Ecosystem Assessment
NCP........................Nature's Contributions to People
NUTS.....................Nomenclature of Territorial Units for Statistics
O-D cost matrix...Origin-Destination cost matrix
PGLM....................Panel Generalized Linear Model(ing)
PPGIS....................Public Participatory Geographic Information Systems
SBA.........................Service Benefiting Area
SCA........................Service Connecting Area
SDA........................Service Demanding Area
SPA.........................Service Providing Area
TEEB.....................The Economics of Ecosystems and Biodiversity

1 Introduction

Our civilization has always depended on the availability and use of services provided by ecosystems (Daily 1997; MEA 2005). Earth's ecosystems not only deliver material resources like wood, food, or clean water, which are essential in our daily lives. They also protect us from natural hazards, such as flooding and soil erosion, and enhance our well-being by offering opportunities for recreation and interactions with nature (Potschin & Haines-Young 2011). Sustaining human well-being and welfare relies on the provision of these goods, called *ecosystem services* (*ES*), and the natural capital that underpins them (Costanza et al. 1997). However, in the current era of polycrisis, filled with interconnected environmental, economic, geopolitical, and societal problems, ecosystems are becoming increasingly fragile. Therefore, it is important to assess the state of ecosystems and the services they provide from biophysical production and human consumption perspectives at multiple spatial and temporal scales (Daily 1997; IPBES 2019).

The ES framework is predominantly anthropocentric, as the value of services provided by the biosphere depends on human beneficiaries' needs to consume these services, both directly and indirectly (Goldenberg et al. 2017; Potschin-Young et al. 2018). All ES are exposed to sudden changes, being produced and consumed within a given space and time frame (Burkhard et al. 2012; Rau et al. 2020). Patterns of ES consumption revolve around ecological, sociocultural, and economic realms, shaped by ecosystem processes and human demands (Martínez-Harms & Balvanera 2012; Spangenberg et al. 2014). These processes and demands are influenced by multiple factors, including the biophysical characteristics of ecosystems (service providers) and the sociocultural evaluations of needs by beneficiaries. Because ES distribution patterns are complex and vary across time and space, their availability for consumption is uneven among groups of people, societies, and countries, and across borders (Ala-Hulkko 2019; MEA 2005). This complexity is compounded by the dynamic nature of ES characteristics and differences in their quantification across scales, which remain major challenges for ES researchers (Burkhard et al. 2012; Wallace et al. 2007). Comprehensive assessments of ES production and consumption patterns are essential to strengthen the understanding of the ES concept and its application to the sustainable management of natural resources (Burkhard et al. 2012; Kienast et al. 2009).

1.1 Thesis aims and objectives

In this thesis, I explore the potential, supply, and demand of provisioning and cultural ES at multiple spatial and temporal scales to advance the understanding of ES assessments (Articles I–III). I use the ES cascade model as the conceptual framework and the basis for selecting the indicators and characteristics of the studied ES. In Article I and Article II, I focus on the provisioning material ES of forests (wood resources), while in Article III, I study the non-material cultural ES of urban ecosystems.

Forests are one of the crucial ES providers worldwide (Thorsen et al. 2014). Even though some progress in studying forest ES has recently been made (see Maes et al. 2020), the need for further research remains, particularly considering issues such as insufficient data on ES supply and demand, evaluation of supply and demand mismatches, assessment of ES temporal trends, or more detailed spatial scale analysis. I tackle these research gaps for the ES of wood, which is one of the most critical services provided by forests (FAO 2022). Urban ecosystems, on the other hand, are the closest providers of ES in large population concentrations, and because of urban sprawl, the demand for their services is rapidly growing (Gerstenberg et al. 2020). Studying the patterns of human–nature interactions in urban spaces and the role of ES in those areas is a key point to understanding the needs of the people who are living in and using urban ecosystems on a daily basis. Moreover, both subjective user-specific factors, such as the demand for ES or perceptions of ecosystems, and objective characteristics of green spaces, including the availability of infrastructure or biodiverse forest cover, influence their frequent use. However, these aspects are rarely assessed together. This thesis addresses this gap by examining how both groups of characteristics affect visitation frequency in the studied green spaces and, consequently, how they shape more frequent interactions with urban and peri-urban ecosystems.

Article I analyzes the spatiotemporal patterns of wood ES supply and demand in relation to ES potential across Europe, at the continental, national, and regional scales, to identify areas with increasing and decreasing supply and demand levels between 2008 and 2018. Article II explores spatial mismatches between wood ES supply and demand across the European continent by applying the concept of ES spatial flow through a spatial accessibility-based methodology. Article III assesses the role of the demand for cultural ES in the frequency of human–nature interactions in green spaces surrounding the Finnish cities of Espoo, Kuopio, and Jyväskylä, considering also characteristics of spatial perceptions and biophysical and infrastructure features of these spaces. In these articles, I use geographic information systems (GIS) tools and statistical analysis methods. The detailed research objectives (Table 1, O1–O3) are divided based on the original research papers and the research questions (RQ1–RQ6) addressed in each article.

Table 1. List of research objectives (O1–O3) and research questions (RQ1–RQ6) of this thesis, organized by article (ES = ecosystem service(s)).

<table>
<tr><th></th><th>Objective</th><th>Research questions</th></tr>
<tr><td rowspan="2">Article I</td><td rowspan="2">O1: Explore the distribution and spatiotemporal trends of wood ES potential, supply, and demand across multiple spatial scales in Europe.</td><td>RQ1: How does the distribution of ES potential, supply, and demand vary at different spatial scales (continental, national, regional) across Europe between 2008 and 2018?</td></tr>
<tr><td>RQ2: What are the recent spatiotemporal trends in wood ES potential, supply, and demand within the analyzed spatial scales across Europe?</td></tr>
<tr><td rowspan="2">Article II</td><td rowspan="2">O2: Explore the supply–demand mismatches of European wood ES at different transportation distances.</td><td>RQ3: How well can the wood ES supply of European regions satisfy demand when interregional spatial flows are not considered?</td></tr>
<tr><td>RQ4: Considering spatial flows through spatial accessibility, what transport distances are required to satisfy the overall demand for wood ES in different parts of Europe?</td></tr>
<tr><td rowspan="2">Article III</td><td rowspan="2">O3: Assess the role of cultural ES demand in the frequency of human–nature interactions in urban and peri-urban green spaces, considering also other subjective and objective characteristics of these spaces.</td><td>RQ5: What is the role of subjective (demand for cultural ES, sociodemographic background, perceived accessibility) in the frequency of visits to green urban and peri-urban spaces in Finnish cities?</td></tr>
<tr><td>RQ6: What is the role of objective characteristics (biophysical and infrastructure features) in the frequency of visits to green urban and peri-urban spaces in Finnish cities?</td></tr>
</table>

Based on the previous research and mentioned research gaps, I hypothesize the following: 1) the choice of spatial scale will influence the assessment of wood ES potential, supply and demand patterns (Article I); 2) applying a spatial accessibility approach will provide more accurate representation of wood ES supply and demand mismatches compared to commonly used overlay analysis (Article II); and 3) subjective perceptions and objective characteristics of green spaces jointly influence the frequency of human–nature interactions in urban and peri-urban areas (Article III).

2 Ecosystem services

The discussion about the importance of goods provided by nature and their overexploitation has a long history. However, the ES framework was not widely conceptualized or acknowledged in policy and development strategies until the late 20th century. The concept of ES began to gain prominence in scientific discussions in the 1980s, a period marked by growing concerns about the overuse of natural resources and environmental degradation (e.g., Costanza et al. 1997; Daily 1997; Ehrlich & Ehrlich 1981). In the late 1990s, the book *Nature's Services: Societal Dependence on Natural Ecosystems* (Daily 1997) laid the foundational groundwork for the modern ES concept. This publication, along with subsequent work (such as Costanza et al. 1997), played a key role in raising awareness about ecosystem use and demonstrating how human well-being is closely tied to healthy, sustainably managed ecosystems.

Daily (1997) catalyzed the development of a scientific basis for the ES framework, shifting the way in which policymaking and environmental conservation strategies consider sustainable natural resource management. The ES concept underlines that environmental protection and sustainable use of ecosystem goods and services directly support human welfare and well-being. From then on, many initiatives aimed to evaluate the consequences of rapidly changing ecosystems for human well-being. The Millennium Ecosystem Assessment (MEA) in 2005 was one of the first major attempts to examine global ecosystems, their condition, and the services they provide (Everard 2017; Haines-Young & Potschin 2010; MEA 2005).

The MEA (2005) set the foundation for studying the ability of global ecosystems to provide services and understanding how they support human welfare and well-being. The MEA (2005) defines ES as "*the benefits that people obtain from ecosystems*" and identifies four major service types: provisioning, regulating, cultural, and supporting. Provisioning services represent the material natural resources that can be directly extracted from nature, such as food, wood, or drinking water. Cultural services, on the other hand, encompass all non-material benefits related to interactions with nature, such as recreation, aesthetics, and spiritual experiences offered by ecosystems to support human well-being. Regulating services include benefits from the regulation of ecosystem processes, such as climate regulation, pollination, and water quality. Supporting services represent the processes that enable the provision of other services and include, for instance, nutrient cycling and soil formation.

The MEA (2005) indeed popularized the ES concept; however, debates arose soon after its publication regarding the vague definition of ES categories (Everard 2017; Raffaelli & White 2013). Challenges stemmed from the difficulty of applying the ES concept in practical contexts, inconsistencies in how different fields interpreted ES definitions, and the fact that it conflated service provision processes with services themselves (Everard 2017; Fisher et al. 2009; Potschin & Young 2010; Wallace 2007).

This has led to the development of alternative ES definitions and classification systems throughout the years (Potschin & Haines-Young 2017).

For example, *The Economics of Ecosystems and Biodiversity* (TEEB 2010) focuses on the economic side of ES and excludes the supporting services from the main service types. However, TEEB's emphasis on economic and monetary ES valuation has been criticized, as it undermines other values, such as the social, cultural, and spiritual values of nature (Spangenberg & Settele 2010). Unlike TEEB, the *Common International Classification of Ecosystem Services* (CICES) was specifically designed to "*measure, account and assess ES*" (Haines-Young 2023). CICES aims to resolve the issues of the comparability of definitions for ES assessments. It is continuously updated to create a refined classification that accurately represents the key challenges in the conceptualization of ES, as recognized in the literature (Haines-Young 2023). More recently, the International Panel for Biodiversity and Ecosystem Services (IPBES) introduced the term "*Nature's Contributions to People*" (NCP), which builds upon the ES concept, but prioritizes the role of culture in defining connections between the natural environment and human well-being (Díaz et al. 2018).

ES represent the interdisciplinary, dynamic, and context-dependent connections between people's needs and nature's capacity to provide desired benefits (Potschin-Young et al. 2018). The mentioned evolution of the ES concept reflects an ongoing effort to bridge ecological, economic, and sociocultural perspectives regarding service provision and consumption, but also explains why ES definitions remain diverse and context-dependent today (de Groot et al. 2010; Everard 2017; Fisher et al. 2009; Potschin & Haines-Young 2017; Spangenberg et al. 2014). In order to apply ES in practical settings and support sustainable management policies, context-specific ES assessments are needed (Martín-López et al. 2012). For these assessments to remain credible and comparable they need to follow established conceptual frameworks (Jacobs et al. 2016).

I followed the MEA and CICES classifications for defining the ES studied (Table 2). The ES assessed include the provisioning ES of wood, delivered by forest ecosystems (Articles I and Article II); and the cultural ES of urban and peri-urban green spaces, such as recreation, hunting, fishing, berry and mushroom picking, beautiful scenery, and cultural heritage (Article III).

2.1 Ecosystem service assessment approaches

Despite efforts to improve definitions and conceptualize ES, their multidimensional character and the complex links they represent between people and nature have made them difficult to assess and communicate consistently (Haines-Young & Potschin 2010; Spangenberg et al. 2014). The diverse conceptual and classification systems (like MEA, TEEB, NCP, and CICES) and approaches towards definitions of ES aspects (even for the same ES) create challenges for comparing ES patterns and their practical application (Bitoun et al. 2022; Burkhard & Maes 2017; Burkhard et al. 2012; Paetholz et al. 2010). Early ES studies struggled with vague boundaries between ecosystem functions, services, and benefits, which led to conceptual inconsistencies (Burkhard & Maes 2017; de Groot et al. 2010; Haines-Young & Potschin 2010; Wallace 2007). However, despite these challenges, moving from the conceptualization phase to ES assessments and their practical application was essential in demonstrating the ES concept as a useful tool for managing nature's services (Burkhard et al. 2010; Burkhard et al. 2012; Kienast et al. 2009; Villamagna et al. 2013).

Table 2. Ecosystem services considered in this thesis, alongside their Common International Classification of Ecosystem Services class numbers and definitions (Haines-Young 2023).

Article	ES type	Service provider	ES considered	CICES service definition	CICES class
Article I & Article II	Provisioning	Forest ecosystems	Wood ES	*Fibers and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials)*	1.1.1.2.
Article III	Cultural	Urban ecosystems	Recreation	*Elements of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions*	3.1.1.1.
			Hunting		
			Fishing		
			Berry and mushroom picking		
			Peaceful and quiet environment	*Elements of living systems that have symbolic meaning, capture the distinctiveness of settings or their sense of place*	3.4.1.1
			Beautiful scenery and landscape	*Elements of living systems that enable aesthetic experiences*	3.2.1.4
			Cultural history	*Elements of living systems that are resonant in terms of culture or heritage*	3.2.1.3
			Other cultural ES	*Other characteristics of living systems that have cultural significance*	3.5.X.X

Researchers recognized that one of the first steps toward effective ES assessments was to create a theoretical framework to understand and define the mechanisms linking ecological structures and human well-being (Ash et al. 2010; Potschin-Young et al. 2018). Addressing the challenges of ES assessment for practical application required consistent terminology to define all elements of service provision from nature, including flows and societal demands (Burkhard et al. 2012; Paetzold et al. 2010; Villamagna et al. 2013). Moreover, it was quickly recognized that all ES are produced and consumed within specific spatial and temporal contexts. Therefore, spatially explicit mapping approaches and spatial analysis were identified early on as promising tools for ES assessments (Burkhard et al. 2012; Haines-Young & Potschin 2010; Maes et al. 2012). There was a need to determine where services are generated and where they are consumed, as well as the spatial relationships between these units (Haines-Young & Potschin 2010; Syrbe & Walz 2012). Ecological structures vary geographically, and spatial context influences societal demands and needs, making geographical perspectives essential in ES assessment (Haines-Young & Potschin 2010). Understanding these complex aspects theoretically was crucial for establishing a consistent basis for ES delivery, flows, and consumption patterns, thereby laying the groundwork for ES assessment.

2.2 The ecosystem service cascade model

The flow of services from biophysical structures to society is generally acknowledged to be a stepwise process, well-presented through the conceptual framework of the ES cascade model (Haines-Young et al. 2010; Heink & Jax 2019). First introduced by Haines-Young and Potschin (2010), the cascade model's principal task was to separate and clarify the elements that link ecological structures and functions, the services they provide, and the benefits people receive, as well as the relationships between these elements (Haines-Young & Potschin 2010; Hein & Jax 2019).

Following the cascade model (Figure 1), the process of ES generation starts within the biosphere. It originates from biophysical structures and depends on their properties and processes (de Groot et al. 2010; Haines-Young & Potschin 2010). Once the value of these structures for human beneficiaries is recognized, the ecosystem's functional capacity to provide services, known as service potentials, is established (de Groot et al. 2010; Potschin & Haines-Young 2011). After recognition of service potentials, the actual service is mobilized from the ecosystem, being transferred from the biosphere to the direction of the anthroposphere, where the needs of the beneficiaries are concentrated (Bastian et al. 2013; Potschin & Haines-Young 2011). Within the anthroposphere, the value of delivered ES is determined by the worth that society places on these benefits, which can be expressed in, for example, monetary, social, cultural, spiritual, or health-related terms (Braat and De Groot 2012; de Groot et al. 2010; Spangenberg et al. 2014). The elements of the ES cascade are not static, and disruptions in any of its elements can result in changes to the rest of the cascade chain (Ala-Hulkko 2020; Haines-Young & Potschin 2010).

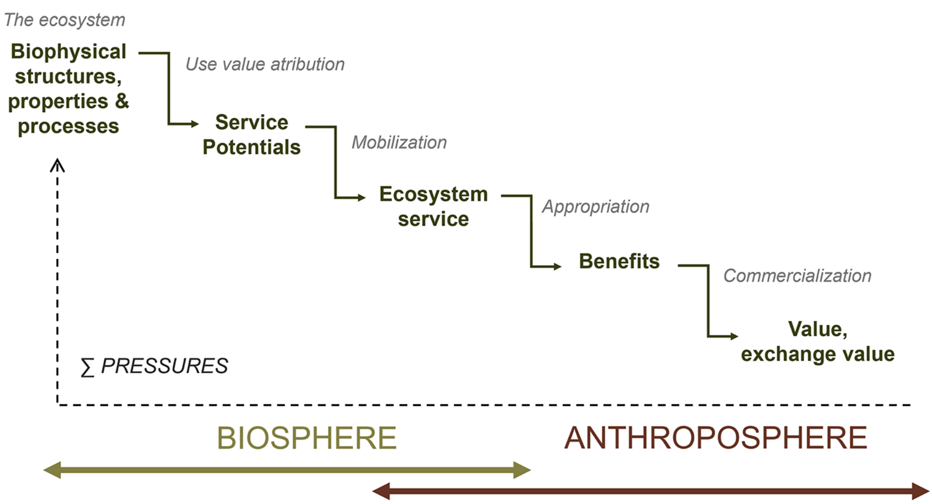

Figure 1. Adaptation of the ecosystem services cascade model, which illustrates the flow of services from the biosphere (green arrow) to the anthroposphere (red arrow), after Potschin and Haines-Young (2010, 2011), Spangenberg et al. (2014), and Potschin-Young et al. (2018). The dashed arrow directed from the anthroposphere illustrates the summarized pressures of human needs towards ecosystems. Compared to the original model, service potentials replace functions to more clearly represent the recognition of an ecosystem's capacity to provide the services demanded by human beneficiaries (Spangenberg et al. 2014).

The ES cascade model was not intended to strictly represent the complete ES paradigm but rather to highlight the key ES components from the bio- and anthroposphere, which can be refined depending on the type of service assessed (Potschin-Young et al. 2018). The five parts of the cascade help clarify the distinction between services and benefits and illustrate how certain ecosystem functions create services, while other, more general features of nature support those functions in the background (Potschin-Young et al. 2018). Despite some criticism regarding the model's practical applications, such as oversimplifying complex socio-ecological interactions (Costanza et al. 2017; Heink & Jax 2019), the cascade has been widely used (Potschin-Young et al. 2018). For example, it has been applied to assess the availability and applicability of spatial data in ES mapping (Tolvanen et al. 2016) or as an analytical tool in ES studies (Baró et al. 2016; Bürgi et al. 2015; Geijzendorffer et al. 2015; Hansen & Pauleit 2014; Martín-López et al. 2012), as well as for reframing related ES concepts (Spangenberg et al. 2014). I use the cascade model as a theoretical basis for selecting the data indicators and variables for assessing aspects of ES potential, supply, and demand.

2.3 Ecosystem service potential, supply, and demand

The elements of the cascade model can be translated into measurable aspects of ES potential, ES supply, and ES demand (Langemayer et al. 2016; Paetzold et al. 2010). The biosphere-dependent left side of the cascade relates to aspects of ES potential, which represents the condition and capacity of an ecosystem to provide services (Burkhard et al. 2012; Langemayer et al. 2016; Paetzold et al. 2010; Schröter et al. 2014). The middle of the cascade is related to service provision and the flow of goods from the biosphere to the anthroposphere and is represented by the ES supply, bridging the social and ecological domains (Ala-Hulkko 2020; Vaz et al. 2017). The anthroposphere-dependent right side of the model corresponds to societal demand for ES and is related to the benefits and values received from ecosystems (Burkhard et al. 2012; Langemayer et al. 2016; Paetzold et al. 2010). Consistent with the cascade model, ES potential, supply, and demand are independent aspects of the ES framework; however, they are closely interrelated with each other (Dworczyk & Burkhard 2021; Potschin & Haines-Young 2011).

ES potential represents the hypothetical maximum capacity of the ecosystem to provide a service, based on the current state of its conditions and properties (Burkhard & Maes 2017; Dworczyk & Burkhard 2021; Maes et al. 2020). ES potential is useful in demonstrating the ecosystem's ability to provide given services. However, it does not measure the actual use of a service but rather informs that the condition to provide a service exists (Potschin-Young et al. 2018). ES supply and demand differ from the stocks of potential services.

ES supply can be defined as the amount of mobilized service within the ecosystem capable of providing it (Burkhard et al. 2012; Dworczyk & Burkhard 2021; Villamagna et al. 2013). It represents the realized flow of ES, which is intended to be available for human consumption in a given time and space (Dworczyk and Burkhard 2021). ES supply is steered by ES demand, as without the need to use the service, there is no need to supply it (Burkhard & Maes 2017). Even if the service is mobilized from the ecosystem, it is not always consumed in the same areas and in the same amount as extracted (Dworczyk & Burkhard).

ES demand represents the need for ES consumption by the end users (Bastian et al. 2013; Burkhard et al. 2012; Haines-Young & Potschin 2010) and serves as socially focused pressure on the ecological structure. ES demand reflects the human needs and preferences regarding ES use in a given place and time and can vary greatly depending on the social, cultural, political, and economic context (Dworczyk & Burkhard 2021; Potschin-Young et al. 2018). The demand for these services is a fundamental part of the ES paradigm, as a service is only recognized if the human beneficiaries see its benefit value (Potschin & Haines-Young 2011).

The aspects of ES potential, supply, and demand can be quantified, evaluated, or modeled, both spatially and temporally, using various service-specific indicators (Dworczyk & Burkhard 2021; Potschin & Haines-Young 2011; Rau et al. 2020; Syrbe & Grunewald 2017). Using indicators for estimating ES supply and demand enables the simplification and quantification of information about complex ecological and social processes for both scientific and policy applications (Ala-Hulkko 2020; Kandziora et al. 2013). The selection of the indicators can vary depending on the context, perspective, and purpose of the ES assessment (Ala-Hulkko 2020; Fisher et al. 2009; Kandziora et al. 2013; Müller & Burkhard 2012).

Many studies have focused on quantifying the potential and supply sides through metrics related to ecosystem condition, function, or capacity (Brown et al. 2014; Maes et al. 2016), such as landscape or statistical indicators. For example, I use the metrics of forest available for wood supply across Europe as a proxy for the ES potential of the provisioning ES of wood, while wood ES supply is represented by the amount of harvested (mobilized) wood. However, a comprehensive understanding of ES requires consideration of both supply and demand dynamics (Burkhard et al. 2012; Syrbe & Walz 2012) in relation to the service potentials. Nevertheless, the ES demand is more challenging to assess, because it is much more dynamic than potential or supply and shifts suddenly, depending on changing human needs, economic markets, or societal shock events such as wars and epidemics (Ala-Hulkko 2020; Wolff et al. 2015). Additionally, ES demand has many definitions (Dworczyk & Burkhard 2021), which affects the comparability of ES assessments.

All types of ES require different assessment perspectives to acknowledge the distinct factors that shape their consumption patterns (De Vreese et al. 2016). For provisioning services, ES demand can be represented by specific goods and their quantities. For instance, I use the indicator of wood ES consumption statistics per capita as a proxy to estimate the demand for this provisioning service across Europe. However, finding indicators to estimate the demand for other ES categories can be much more complex, especially considering cultural ES, which encompass non-material benefits derived from nature through human–environment interactions (MEA 2005; Xia et al. 2025).

Cultural services are usually more challenging to measure, quantify, or categorize because the demand for them is highly sensitive to the subjectivity of human needs and perceptions of nature in maintaining their well-being (De Vreese et al. 2016; Xia et al. 2025). More specifically, these needs are shaped not only by the available services and the characteristics of the ecosystem landscapes where consumption occurs, but also by various other factors related to the sociodemographic background of ES users (Gottwald et al. 2022; Nowak-Olejnik et al. 2024; Romelli et al. 2025) and their perceptions of the environment, which largely affect their spatial behavior (Philips et al. 2021; Soga & Gatson 2020).

When evaluating ES that are difficult to assess with statistical or land-use indicators, such as non-material cultural ES, it is crucial to consider the subjective preferences of human beneficiaries (Kabisch et al. 2015). Integrating information on how people subjectively experience ES provision can reveal more detailed consumption patterns of

ES across time and space. Data about perceptions of the environment, and consequently, patterns of ES demand, can be collected via public participatory geographic information systems (PPGIS) surveys (De Vreese et al. 2016; Fagerholm et al. 2021).

PPGIS is a well-established tool for collecting data on spatial behavior and perceptions and enhances understanding of how individuals or societal groups subjectively value nature (Fagerholm et al. 2021; Scholte et al. 2015). I use PPGIS survey data, in which respondents marked green spaces they visit in the cities of Espoo, Kuopio, and Jyväskylä, and the frequency of their visits (Article III). The respondents provided information about the cultural ES they are consuming (ES demand) during their visits to marked spaces, as well as shared their spatial perceptions regarding marked locations (e.g., considering perceived accessibility). In this PPGIS survey, respondents could acknowledge one or more services consumed in a marked location, together with other characteristics of visited green spaces.

Common methods of PPGIS data analysis related to the exploration of ES patterns include, for instance, spatial pattern analysis, such as hotspot or cluster analysis, or statistical modeling methods, including, for example, regression models (Bagstad et al. 2014; Fagerholm et al. 2021). I apply the panel generalized linear modeling (PGLM) approach to examine the role of cultural ES demand and other subjective and objective variables of green spaces in the frequency of human–nature interactions on the local urban scale. PGLM is particularly suitable for this data analysis because it accounts for variability within the dataset and controls for unobservable respondent-level factors, such as personal values, preferred visitation patterns, and the influence of others' choices, that may affect an individual's decision to visit a particular location (Wooldridge 2010).

2.4 Spatial characteristics of ecosystem services

ES mapping approaches can reveal where ecosystems have the biophysical capacity to generate services (potential), where services are actually being delivered or extracted (supply), and where human beneficiaries need and consume these services (demand; Burkhard et al. 2012; Nedkov & Burkhard 2012). Mapping methods are proven to be one of the most effective ways to visualize and analyze ES indicators across landscapes (Potschin & Haines-Young 2011). ES maps enable geographic interpretation of ES supply and demand as well as the balance in space and time, allowing more informed decisions in land-use planning, conservation, and resource management and thus better policy support (Burkhard et al. 2012; Daily & Matson 2008). Therefore, ES mapping is one of the most effective tools for the practical application of the ES concept (Burkhard et al. 2012; Maes et al. 2012).

ES mapping approaches serve as tools for the identification, quantification, and visualization of not only ES potentials but also supply and demand as separate units. They can also be insightful for analyzing the synergies and trade-offs between ES, ES monetary valuation, or ES congruence with biodiversity (Maes et al. 2012). Additionally, since the aspects of supply and demand are rarely distributed evenly in space, mismatches between where services are generated and where they are needed can strongly influence how people benefit from them (Burkhard et al. 2012). Maps can be used to assess the spatial and temporal mismatches between service supply and demand (Ala-Hulkko et al. 2019; Baró et al. 2015; Dworczyk & Burkhard 2021), highlighting surplus and deficit areas as well as tensions between them across the geographical landscapes (Burkhard et al. 2012; Paetzold et al. 2010).

To map the spatial relationships between ES potential, supply, and demand, it's necessary to understand the theoretical foundations that describe how ES are produced, delivered, and consumed across space (Ala-Hulkko 2020; Bastian et al. 2012; Crossman et al. 2013; Fisher et al. 2009). The spatial characteristics of ES were first categorized by Costanza (2008) into five types: global non-proximal, local proximal, directional flow-related, in situ, and user movement-related. This laid the groundwork for more structure-dependent indicators later refined by Fisher (2009) and formalized by Syrbe and Walz (2012), who introduced the concepts of *service providing areas* (SPAs), *service benefiting areas* (SBAs), and *service connecting areas* (SCAs).

SPAs represent spatial units within the biosphere, where an ecosystem has the capacity to generate a particular service (ES potential), as well as where the service is actually provided (ES supply). These units contain partial or entire ecosystems and their properties and conditions, which serve as a basis for ES provision (Ala-Hulkko 2020; Burkhard et al. 2014; Dworczyk & Burkhard 2021; Potschin-Young et al. 2018). For example, in the case of the provisioning ES of wood, which I mapped in this thesis, the SPA represents the areas capable of wood production (ES potential) and areas of actual service provision (ES supply). In contrast, **SBAs** refer to the areas within the anthroposphere where people or communities actually receive, consume, or experience the benefits of the service provision (Ala-Hulkko 2020; Ala-Hulkko et al. 2019; Syrbe & Walz 2012). Dworczyk and Burkhard (2021) further enriched the conceptual understanding of SBA, elaborating its definition to the spatial unit where people benefit from ES both knowingly and unknowingly. Additionally, they proposed the term "*service demanding area*" (**SDA**), which refers to the spatial location of beneficiaries (locations where people live, e.g., buildings, neighborhoods, or land-use types, where the benefits are demanded). The SDA therefore represents the area of service demand but not an area of direct consumption of services. I refer to the SBA in general as a unit representing the location of service beneficiaries.

SBAs are complementary to SPAs, but for many ES, these areas might not be identical or overlapping (Ala-Hulkko 2020; Syrbe & Walz 2012). In those cases, the **SCA** must be considered to define and visualize the specific ways in which the service is delivered from provisioning to benefiting locations (Ala-Hulkko 2020; Syrbe & Walz 2012). The SCA describes the links between providing and benefiting areas, which may be represented by natural elements, such as rivers, streams, air currents, or human-made elements, including transportation networks and built infrastructure (Ala-Hulkko 2020; Dworczyk & Burkhard 2021; Syrbe & Walz 2012). The properties of the connecting space (SCA) can influence ES delivery (ES spatial flows) from distant provision sites (Ala-Hulkko 2020; Ala-Hulkko et al. 2019; Dworczyk & Burkhard 2021; Syrbe & Walz 2012). It must be acknowledged that the term "*ES spatial flow*" differs from ES flow, which is commonly used as a synonym of ES supply (Ala-Hulkko 2020; Bagstad et al. 2013; Villamagna et al. 2014). I use ES spatial flow separately from ES flow as a way to identify the spatial connections between SPAs and SBAs.

The distinction between SPAs, SBAs, and SCAs shows that the spatial relationship between ES supply and demand varies depending on the specific service being assessed and the geographic location of service provision and beneficiaries. There are three main categories of spatial connections between SPAs and SBAs with the varying roles of SCAs (Dworczyk & Burkhard 2021; Syrbe & Walz 2012; Walz et al. 2017). ES can be provided and consumed in the same location, for example, in a situation when a settlement uses the groundwater from the same area (in situ, Figure 2a). However, for many ES, the spatial relationship between SPAs and SBAs is captured through directional (e.g., urban residents travel to visit parks and other green spaces (Article III) and benefit from the supply of cultural ES therein) or non-directional connections (e.g., benefiting from a service, like wood (Article I and Article II), provided in a distant geographical location and transported for consumption to or near the settlement) and requires the recognition of SCAs. ES spatial connections can coexist, particularly for services, such as cultural ES, where people's presence in provisioning areas ensures service consumption (Ala-Hulkko 2020; Paracchini et al. 2014; Schirpke et al. 2019). In that case, individuals must first reach the overlapping areas of SPAs and SBAs by moving there via SCAs from the areas of their settlements (SDAs; Ala-Hulkko 2020). Examples of ES spatial relationships are visualized in Figure 2.

Distinguishing among SPAs, SBAs, SDAs, and SCAs is critical for ES assessments, highlighting that the presence of a high ES potential or supply does not automatically ensure that humans benefit from it unless there is an effective connection

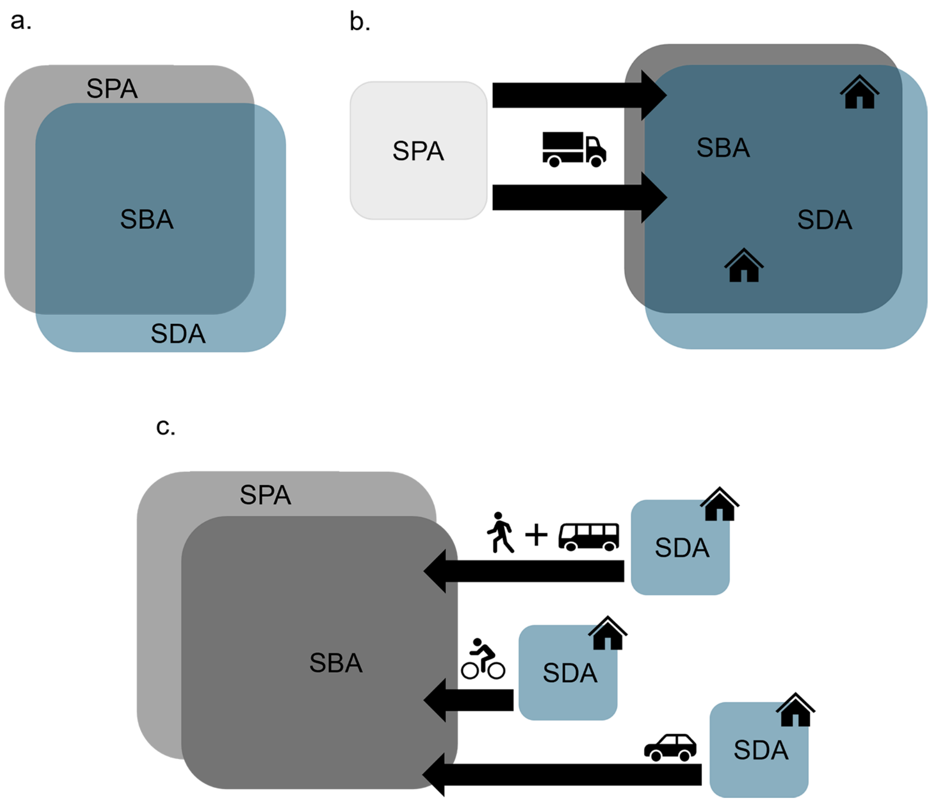

Figure 2. Examples of spatial relationships between service provisioning areas (SPAs), service benefiting areas (SBAs) and service demanding areas (SDAs) and the role of service connecting areas (SCAs, visualized as arrows) in connecting them: (a) *in situ relationship*, where SPA, SBA, and SDA overlap, for example, the regulating ES of water purification by wetlands; (b) *non-directional relationship* involving transportation, e.g., the movement of commodities such as wood ES (service studied in Article I and Article II); (c) *directional with predominant use direction* where people travel to an SBA (via a chosen transportation mode) to consume services provided by a spatially overlapping SPA, e.g., cultural ecosystem services like recreation in distant landscapes (services studied in Article III). Visualizations are adapted from Syrbe and Walz (2012), Walz et al. (2017), Ala-Hulkko (2020), and Dworczyk and Burkhard (2021).

(Potschin-Young et al. 2018; Spangenberg et al. 2014; Walz et al. 2017). Spatial ES assessment improves the understanding of whether and how services reach or are reached by the intended beneficiaries and helps detect supply and demand mismatches (Burkhard et al. 2012; Syrbe & Grunewald 2017). Visualizing and mapping these mismatches enable the detection of ES potential overconsumption, supply surpluses, and the unsustainable use of services across spaces and can be directly applied to policy- and decision-making (Crossman et al. 2013; Dworczyk & Burkhard 2021; Syrbe & Grunewald 2017; Villamagna et al. 2013).

Mapping ES supply and demand spatial mismatches is one of the major challenges for ES assessment (Syrbe & Grunewald 2017). Although supply and demand balance analyses have gained popularity in recent years, the ES spatial flow and the transfer of services from provisioning to benefiting areas are still often overlooked. Until now, the most common approach for mapping these mismatches was overlay analysis of supply and demand (e.g., Burkhard et al. 2012; Martínez-Lopez et al. 2019). Overlay of supply and demand can lead to a misleading understanding of mismatches, especially in cases where service consumption depends on the transportation or movement of services from provisioning to benefiting areas (Bagstad et al. 2014; Syrbe & Grunewald 2017). Applying methods that account for the ES spatial flow between SPAs and SBAs, such as distance-based approaches like spatial accessibility analysis (e.g., Ala-Hulkko et al. 2019), can provide more precise information regarding the supply and demand balance across different scales. This is especially important for provisioning ES, which often relies on the movement of an extracted service from an SPA to an SBA.

Spatial accessibility consists of proximity and availability components and is often used as a tool to evaluate the opportunities to reach services through a transportation network (McGrail & Humphreys 2009; Páez et al. 2012). It can be explored through different measures of reaching services, such as time or distance (Páez et al. 2012). In ES studies, spatial accessibility methods, such as floating catchment models, have been used to map mismatches between grain ES supply and demand across Europe (Ala-Hulkko et al. 2019). However, other accessibility methodologies can also be beneficial for ES mapping. To explore the spatial mismatches between supply and demand of the provisioning ES of wood, I use the spatial accessibility-based supply and demand balance analysis (Article II). In this case, the road and ferry transportation network serves as a proxy for SCA. This method allows testing the opportunities for the populations of European regions to consume the services provided in Europe across different transportation distances. To assess the effect of incorporating spatial flow into the analysis of ES mismatches, I compare the accessibility results with an overlay analysis of the supply and demand of the studied provisioning service. Applying spatial accessibility-based methods has the potential to enhance our understanding of how to map the spatial characteristics of ES, particularly in relation to integrating spatial flow into the evaluation of supply and demand balance.

2.5 The effect of spatial and temporal scales on ecosystem service assessment

Already, the MEA (2005) highlighted that one of the main challenges in advancing ES evaluation is identifying ES patterns, trade-offs, and synergies across different scales (MEA 2005; Potschin & Haines-Young 2011; Raudsepp-Hearne et al. 2016). Scale is therefore a fundamental component of any ES assessment, shaping both its analytical design and its outcomes. ES can be assessed with a variety of spatial (local, regional, national, continental, and global) and temporal (hourly, daily, monthly, and annual) scales (Burkhard et al. 2014).

Following Burkhard et al. (2014), consideration of both spatial and temporal scales in ES assessment is equally important. Mapping ES at different spatial and temporal scales can provide a better understanding of their patterns and offer more detailed insights into management issues (Rau et al. 2020; Renard et al. 2015). However, ES are unevenly distributed across space and change over time due to, e.g., seasonal changes, climate variability, and land use interventions (Burkhard et al. 2009; Burkhard et al. 2012; De Groot et al. 2010; Potschin & Haines-Young 2011; Rau et al. 2020). Thus, the spatial and temporal scales in each assessment must be adjusted to the specific type of service (Berkes et al. 2006; Potschin & Haines-Young 2011). Selecting the appropriate scale is vital for ES assessments because it influences not only the results of the mapping, but also the applicability of these assessments to context-specific objectives (Ala-Hulkko 2020; Burkhard et al. 2014; Martínez-Harms & Balvanera 2012; Raudsepp-Hearne & Peterson 2016).

Despite the clear need for comprehensive assessments of ES across spatiotemporal scales, several challenges arise in implementing such research. One of the main limitations is related to data availability. Although ES supply and demand data are increasingly being collected, acquiring temporal datasets is time-consuming, and the exploration of their spatiotemporal dynamics remains limited (Rau et al. 2020). Additionally, the ES supply and demand datasets may have diverging spatial or temporal resolutions, making it difficult to study them simultaneously and ensure comparability, which greatly affects the results of the assessments. Coarse-scale data, for example, can mask important fine-scale heterogeneity, leading to the underestimation or overestimation of ES hotspots or trade-offs (Burkhard et al. 2014; Eigenbrod et al. 2010). Therefore, it is beneficial to collect data at the highest possible resolution, compare results across different scales, and ensure that the evaluated ecosystem service components remain comparable at each scale. Nevertheless, even coarser resolutions can be efficient for ES assessment if they are useful for answering the assessment's addressed research question and objective.

There are several tools for analyzing spatiotemporal ES data, including GIS-based evaluations such as hotspot and trend analysis, as well as statistical modeling approaches like geographically weighted regression with a temporal dimension (e.g., Guo et al. 2023; Ming et al. 2022). I use the GIS-based space-time cube to assess the distribution and temporal trends of the provisioning ES of wood across Europe between 2008 and 2018 (Article I). The space-time cube serves both as a visualization tool for the spatial patterns of ES potential, supply, and demand, and as an analytical tool for exploring the temporal trends (using the Mann–Kendall trend test) of these components. It provides an effective means of visualizing and analyzing the temporal trends of the assessed ES components.

3. Materials and methods

3.1 Study areas

I selected **Europe** as the study area of Articles I and II due to the availability of data for mapping wood ES, but also because wood ES plays a significant role in supporting the welfare of Europeans. Although forest areas across the continent have expanded over the past century, European forests and the forest industry face growing economic, technological, societal, and environmental pressures (Kauppi et al. 2018; Oberle et al. 2019; Palmero-Iniesta et al. 2021). Collecting more data regarding wood ES production and consumption and exploring its spatial flow can support policymaking and the implementation of forest strategies such as the European Green Deal (2019) and the EU Forest Strategy for 2030 (2020).

Article I covered 24 European Union countries and Switzerland, for which comparable data on ES potential, supply, and demand were available between 2008 and 2018. The study considered the continental, national, and regional scales (Figure 3a). On the continental scale, Europe was analyzed as a single region. The national scale was based on country borders (Eurostat 2016), and the regional scale refers to the nomenclature of territorial units for statistics (NUTS 3; *n* = 1061) and local administrative units (LAUs; *n* = 957) division. Due to the great variation in the geographical size of NUTS regions across Europe, it was combined with the LAU division for Sweden, Denmark, Finland, Estonia, Lithuania, and Latvia. Incorporating LAUs into the analysis instead of large NUTS regions makes the ES assessment more comparable, as the regions have more similar areal coverage. The regional borders were based on the Eurostat NUTS and LAU region information from 2016 (Eurostat 2016).

In Article II, the study area covered 25 European Union countries, the United Kingdom, Switzerland, and Norway, as well as Balkan states, including Albania, Croatia,

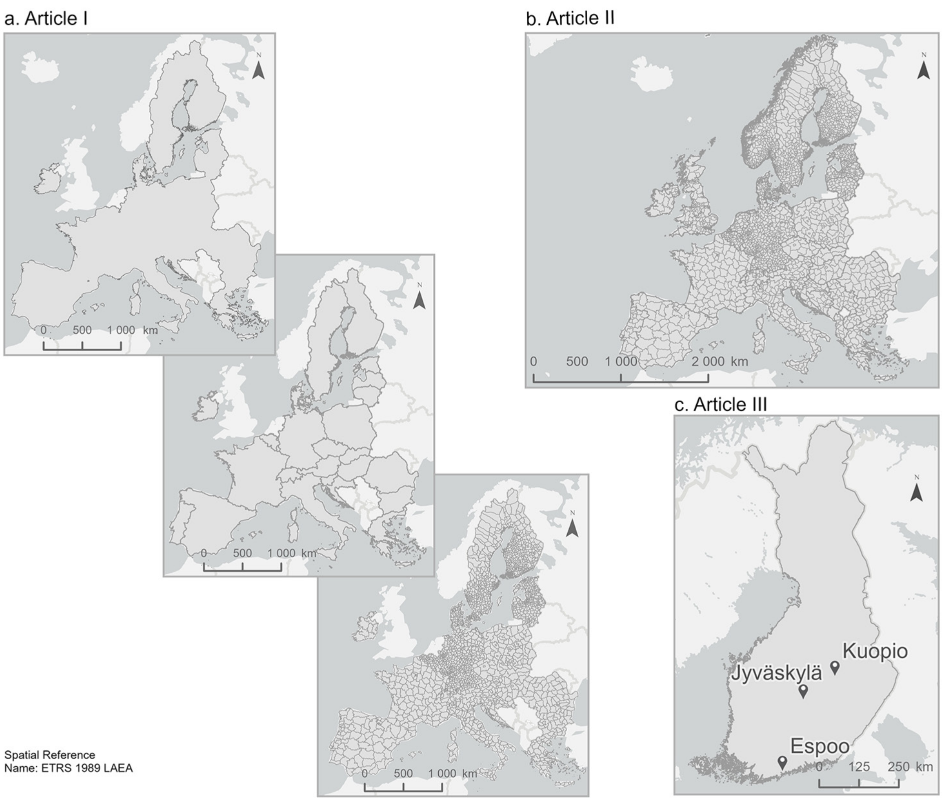

Figure 3. Visual representation of the spatial resolution applied in (a) Article I, (b) Article II, and (c) locations of cities studied in Article III.

Macedonia, Serbia, Montenegro, and Bosnia and Herzegovina (Figure 3b). Similar to Article I, the resolution of this study is based on the NUTS and LAU regional division of Europe (Eurostat 2016). However, more regions were included in this study due to better data availability (NUTS 3 n = 1326, LAU n = 1313). In addition, Bosnian regional division units (n = 18) were included in the study.

I selected **Finland** as the study area of Article III, focusing on three cities: Kuopio, Jyväskylä, and Espoo (Figure 3c). Out of these three cities, Espoo is the biggest by population (over 300,000 inhabitants), followed by Jyväskylä (approximately 150,000 inhabitants) and Kuopio (125,000 inhabitants, Statistics Finland 2025). The studied cities are characterized by good availability of green spaces that support the provision of cultural ES. In Finnish cities, the average green space coverage can reach up to 40%, which is one of the highest rates in Europe (Copernicus Land Monitoring Service 2021; European Environmental Agency 2022; Hautamäki 2021). However, these cities are experiencing rapid urbanization pressures, and their population density is growing rapidly (Statistics Finland 2025). As a result, the availability of green spaces for urban residents may become increasingly constrained, posing challenges for maintaining cultural ES benefits in the future. Article III covered both urban and peri-urban green spaces of the studied cities.

3.2 Data

I used geospatial data to map and evaluate case-specific aspects of the studied ES. The term "*indicator*" describes the quantitative proxies used to map the potential, supply, and demand, as well as the spatial flow of the provisioning ES in Articles I and II. The term "*variable*" refers to the characteristics of green urban and peri-urban spaces, whose roles in the intensity of human–nature interactions were explored in Article III.

3.2.1 Indicators for mapping provisioning ecosystem service of wood

In Articles I and II, I used indicators to map the potential, supply, and demand of the provisioning ES of wood across Europe. Data collection adhered to the principles of the ES cascade framework (Figure 1) tailored specifically to wood ES. In Article II, I used the same regional wood ES supply and demand indicators to explore spatial mismatches between these two aspects across European regions, taking into consideration ES spatial flow.

To estimate the European **wood ES potential**, I used the national-level information on *forest available for wood supply* for the period between 2008 and 2018 as a proxy indicator (Eurostat & European Forest Accounts 2023). Forest available for wood supply is defined as

> "[…] *forests where there are no restrictions (social, environmental or economic) that would have an impact on current or potential supply of wood*" (Alberdi et al. 2020; Eurostat & European Forests Accounts 2023).

The ES potential serves as background information on the ecosystem's (in this case, the forest ecosystem's) capability to provide the service in comparison to ES supply and demand levels. The data cover the same period (annual ES potential between 2008 and 2018) and the same areas (at the national level) and are measured in the same units (cubic meters, m^3), making them comparable to wood ES supply and demand.

I estimated **wood ES supply** based on annual wood production statistics (cubic meters, m^3), between 2008 and 2018, for NUTS or LAU regions, collected from the studied countries' statistical databases (NUTS & LAU regional division). In cases where regional data were unavailable, I supplemented missing information with the country-level Eurostat Wood Production Database (Eurostat 2021). Then, to obtain a proxy for regional supply, I shared the national amount of wood production between country regions using the extent of forest cover therein. These data were based on Corine Land Cover (CLC; European Environmental Agency 2006, 2012 and 2018; CLC 2006 as the basis of forest cover for 2008, CLC 2012 as the basis of forest cover for 2009–2014, and CLC 2018 as the basis of the forest cover between 2015-2018) and included all forest classes (coniferous, broadleaved, and mixed forest types). Due to the broad scale of the analysis, I could not consider many harvest restrictions. However, I excluded protected forest areas, based on the World Database on Protected Areas (WDPA, IUCN & UNEP-WCMC 2022), from the spatial coverage of forest cover. These included areas in which wood should not be harvested because of the conservation status, such as strict natural reserves, wilderness areas, national parks, and nature reserves (see details in Supplementary Materials of Article I).

I estimated **wood ES demand** using the per-capita wood consumption data from the United Nations Economic Commission for Europe (UNECE 2022). Similar to the supply data, demand was originally compiled in cubic meters (m^3) for the years between 2008 and 2018. The data are based on the Joint Forest Sector Questionnaire (JFSQ), which was initiated by the Food and Agriculture Organization of the United Nations (FAO), the International Tropical Timber Organization (ITTO), the United Nations Economic Commission for Europe (UNECE), and Eurostat to gather statistics related to global timber consumption (Eurostat 2023a). The data represent the capability of the country's wood processing industry to provide the demanded goods, defined as

> "*The sum of wood logs from all sources plus wood that is imported, minus wood that has been exported* […] *measured under bark*" (UNECE 2022).

Since this information is provided at the country level per capita, I used the annual data on population density from Eurostat (2022) of each administrative region as a surrogate for wood ES consumed within each region in a given year.

I analyzed the wood ES aspects in Article I, using relative values, dividing the total supply and demand of each region (m^3) by the region's area (ha) to ensure spatial and visual comparability of mapped indicators. Due to the methodology requirements, in Article II, I used the absolute values of supply and demand instead.

3.2.2 Transportation network

The delivery of many provisioning ES, including wood, depends on the transfer of the service and its spatial flow from provisioning to benefiting locations (Syrbe & Walz 2012). In Article II, to explore the spatial mismatches between the supply and demand of wood ES, a theoretical representation of an area connecting service providers and beneficiaries was necessary. Therefore, I used the transportation network as a representation of this connecting area (SCA) and the spatial flow of wood ES. The network consisted of road and ferry connections across the European continent. I used the EuroGlobalMap (2016) dataset, which includes roads and ferry networks at a scale of 1:1 million as the basis for the network and covers most of the countries studied. However, since this dataset did not contain information about transportation networks in some Balkan states, which were included in the study (Bosnia and Herzegovina, Montenegro), I acquired complementary information regarding road and ferry connections therein from the Open Street Map (OSM 2016). All topology and connection errors were corrected manually (Ala-Hulkko 2020; Ala-Hulkko et al. 2019).

3.2.3 Public participatory GIS survey and environmental and infrastructure variables

I used the PPGIS data as the basis for exploring the subjective, user-specific variables impacting the frequency of human–nature interactions in green urban and peri-urban areas (Article III; Table 3). The data were collected by the Natural Resources Institute Finland between November 2020 and February 2021 through the Maptionnaire tool (Maptionnaire 2021). The survey was distributed in two ways: by invitation (random sample, $n = 1500$ invited by the city) and through an open-ended web survey advertised online (Juutinen et al. 2023). The representativeness of this sample with respect to the general population was determined in a previous study that utilized these data (see Juutinen et al. 2023). The answers from the open survey showed greater variation between cities. Females and respondents aged 30–39 were overrepresented, and participants were more likely to hold academic degrees.

Table 3. Sociodemographic characteristics of Public Participatory Geographic Information Systems survey respondents and sample overview.

Sociodemographic variable		**Number of responses, *n* (%) or descriptive statistics**
Survey type	Open	140 (28.1%)
	Invited	359 (71.9%)
Municipality	Kuopio	174 (34.9%)
	Espoo	175 (35.1%)
	Jyväskylä	150 (30%)
Gender	Male	236 (47.3%)
	Female	260 (52.1%)
	Other	3 (0.6%)
Education	Elementary school	11 (2.2%)
	Upper secondary school	44 (8.8%)
	High school	48 (9.6%)
	Professional degree	54 (10.8%)
	Bachelor's degree	125 (25.1%)
	Master's or higher degree	217 (43.5%)
	Other education	10 (2.0%)
Housing	Apartment building, more than 3 floors	175 (35.1%)
	Small apartment building, less than 3 floors	53 (10.6%)
	Row or twin house	107 (21.4%)
	Detached house	164 (32.9%)
Age		*minimum age*=19, *maximum age*=81, *median age*=45, *mean age*=45.7

The main task for survey respondents was to mark personally important green urban and peri-urban spaces, as well as the annual number of visits and estimated distance from home to these spaces. Additionally, they were asked to provide information about their sociodemographic background, including gender, education level, type of housing, municipality of residence, and age (Table 3).

After marking the location of an important green space and estimating the frequency of visits, respondents were asked to select all the cultural ES consumed in the marked locations from a list of options (Table 4). These included benefits obtained from ecosystems, such as recreation (e.g., walking, hiking, biking), hunting, fishing, berry picking, cultural history, a peaceful and quiet environment, a beautiful landscape, and the perception of biodiversity to support the quality of cultural ES. In addition to cultural ES, the list of preselected reasons included perceived accessibility and self-evaluated availability of useful infrastructure (Table 5). I preprocessed the data by filtering out the missing information with no responses. I limited the number of visits to a maximum of 2 per day (730 trips per year) and set the distance to a maximum of 100 km, to exclude planned overnight trips. After preprocessing, the final dataset contained 1721 locations marked by 499 respondents (Kuopio: n = 174; Espoo: n = 175; Jyväskylä: n = 150).

In addition to the PPGIS data, I calculated variables regarding the objective environmental and infrastructure characteristics of the locations that were important for

Table 4. List of cultural ecosystem services and the number of times (%) of their selection by survey respondents. Multiple services consumed could be selected at a single location.

Cultural ES consumed in green spaces	Number of locations marked (%)
Recreation	887 (13.8%)
Hunting	25 (0.4%)
Fishing	94 (1.5%)
Berry picking	376 (5.9%)
Biodiversity	513 (8.0%)
Peaceful and quiet environment	889 (13.8%)
Beautiful scenery	1087 (16.9%)
Cultural history	191 (3.0%)
Other	147 (2.3%)

Table 5. Perceived spatial and infrastructure characteristics of green spaces as identified by Public Participatory Geographic Information Systems survey respondents. Similar to the cultural ES, multiple characteristics could be selected for a single location.

Perceived spatial characteristics of green spaces	Variable type	Number of locations marked (%) or descriptive statistics
Accessible	Binary: yes (1) or no (0)	994 (15.5%)
Easy terrain		395 (6.1%)
Facilities		826 (12.9%)
Self-reported distance (km) from home	Continuous	*minimum* = 0.1, *maximum* = 100, *median* = 3, *mean* = 7.7

human–nature interactions in the studied cities. For the calculations, I used a circular buffer with a 500-meter radius surrounding the marked places. This buffer is commonly used in literature to explain landscape patterns in PPGIS-mapped locations (e.g., Brown & Hausner 2017; Ridding et al. 2018).

I retained six of the nine initially considered objective environmental and infrastructure variables in the final analysis; the others were excluded due to high multicollinearity (Spearman's $r \geq 0.6$). The variables regarding the marked locations' environmental characteristics included 1) mean tree volume, indicating the quantity of forest (Natural Resources Institute Finland 2021); 2) highly biodiverse forests (top 10% of biodiverse forests), indicating the quality of forests (Mikkonen et al. 2018); 3) built green urban areas including parks and sport and leisure areas (European Environmental Agency 2018); and 4) distance to nearest water bodies, indicating the proximity to blue spaces (European Environmental Agency 2018). The considered infrastructure characteristics included 1) recreational roads' availability (University of Jyväskylä 2024) and 2) walking roads' availability (Finnish Transport Infrastructure Agency 2023).

3.3 Assessment methods

The methods I applied in the assessment of the studied ES include GIS and statistical modeling tools (Table 6). Article I analyzes the distribution and spatiotemporal trends of wood ES potential, supply, and demand across Europe using a GIS-based space-time cube. Article II assesses spatial mismatches between wood ES supply and demand using overlay analysis and a GIS spatial accessibility-based supply and demand balance analysis, exemplified by three different transport distances. Article III examines the role of subjective and objective variables (including, e.g., cultural ES consumption) of visited locations in the frequency of human–nature interactions using the PGLM approach. Additionally, several supporting methods were used in each assessment (e.g., correlation, variation analysis, or model fit statistics).

Table 6. Summary of main methods and tools used for ecosystem services data analysis in each thesis article and the scale considered in each assessment.

	Data	Main analysis method	Scales applied
Article I	• Wood ES potential • Wood ES supply • Wood ES demand	Trend analysis (performed with space-time cube tool)	Spatial (continental, national, and regional) and temporal
Article II	• Wood ES supply • Wood ES demand • Road and ferry transportation network	Spatial accessibility-based supply and demand balance analysis	Spatial (regional)
Article III	• PPGIS survey data (cultural ES demand, perceived accessibility and infrastructure and sociodemographic background of survey respondents) • Spatial data (biophysical features and recreational infrastructure)	Panel generalized linear model	Spatial (local, urban and peri-urban areas)

3.3.1 Space-time cube

In Article I, I analyzed the spatiotemporal trends of potential, supply, and demand data of wood ES, using the space-time cube tool from Esri's ArcGIS Pro 3.0.3 software. The space-time cube incorporates basic statistical analysis and spatial visualization of the trends within the data studied (see Article I). It supports the exploration of spatiotemporal patterns or changes within the studied areas and as clusters. The tool analyzes the trends with the Mann–Kendall trend test (Esri 2023; Kendall & Gibbons 1990; Mann 1945), which is a nonparametric test for monotonic trend detection in time series (Ringard et al. 2019). It identifies the statistically significant trends within polygons by comparing the sums with an expected sum (zero). Besides identifying the trend, the analysis provides the value of its direction (positive means increasing trend, negative means decreasing trend) and its *p*-value, which describes the trend's statistical significance ($p < 0.01$ = 99% significant; $p < 0.05$ = 95% significant; $p < 0.1$ = 90% significant).

I constructed the space-time cube at the national level ($n = 25$), and then at the regional level ($n = 2018$) across Europe for the temporal coverage between 2008 and 2018. I used the tool to detect the trends (up trends or down trends) in the wood ES supply, demand, and potential at national and regional levels within independent individual polygons of first nations and then regions. In addition to the space-time cube trend analysis, I have calculated basic summary statistics (i.e., mean, standard deviation) for all studied indicators. Additionally, I have calculated the coefficient of variation to examine the basic variation of the potential, supply, and demand data.

3.3.2 Spatial accessibility-based supply and demand balance analysis

In Article II, I used the GIS-based spatial accessibility methodology to explore the balance between wood ES supply and demand across European regions. This method allowed me to consider the spatial flow of the service from provisioning to benefiting areas. To evaluate the impact of accessibility analysis on mapping the supply–demand balance, I also performed an overlay analysis of supply and demand. This examined the effect of not including ES spatial flow in the mismatch assessment. The overlay analysis revealed the supply–demand balance within the studied region, while spatial accessibility enabled evaluation of this balance when the service was transported elsewhere. I calculated the overlay by subtracting the demand from the available supply in each studied region.

Spatial accessibility allows estimating the potential for delivering supply to demand areas within a specified transportation distance. The method utilizes an origin-destination (O-D) cost matrix built with Python 3 for ArcGIS Pro 3.0.3, which accounts for supply surpluses and unmet demand across three different transportation distances. The transportation distances (in kilometers) serve as the transport cost of an ES from provisioning to benefiting locations. The thresholds were selected after examining the average transport distances of wood ES across studied countries and by different transport modes (Eurostat 2023b; Strandström 2022). I chose the following distances for accessibility analysis: 150 km (local distance), 300 km (domestic transport), and 600 km (possibly crossing national borders). The distances represent how far a service is transported within the road network. The longer the distance, the farther the service is delivered. This demonstrates both the regional and international spatial flow of the ES studied.

The spatial accessibility method relates supply and demand to each other within a given transportation distance. It applies stepwise iteration from smallest to highest cost, in this case, distance. In each of the steps, supply is subtracted from demand, and demand is subtracted from supply for each connecting location within a given cost distance. The supply (*S*) can be expressed as a row vector in the O-D cost matrix,

$$S = [s_1 \quad \cdots \quad s_i] \qquad (1)$$

while demand (*D*) as a column vector.

$$D = \begin{bmatrix} d_1 \\ \vdots \\ d_j \end{bmatrix} \qquad (2)$$

Least cost path-based O-D matrix (*T*), that connects supply and demand locations can be defined as a *i*×*j* matrix.

$$T = \begin{bmatrix} t_{11} & \cdots & t_{i1} \\ \vdots & \ddots & \vdots \\ t_{1j} & \cdots & t_{ij} \end{bmatrix} \qquad (3)$$

Following that, supply s_l in location *l* (where *l* can be $1 \leq i$), demand d_m in location *m* (where *m* can be $1 \leq j$), and the least cost path between elements s_l and d_l can be expressed as t_{lk}. Next, the O-D cost matrix *T* is sorted, allocating supply to the closest demand,

$$T_n = min\{t_{11,\cdots,}t_{ij}\} \qquad (4)$$

If supply is larger than or as large as the demand $s_l \geq d_k$, negative change for supply and demand equal available demand:

$$\Delta s_l = \Delta d_k = -d_k \qquad (5)$$

Or if the demand is larger than or as large as the supply:

$$\Delta s_l = \Delta d_k = -s_k \qquad (6)$$

Then, the distribution of the remaining supply to demand continues within the next closest distance (least cost path t_{kl}), under the defined distance threshold *c*.

$$t_{lk} < c \qquad (7)$$

The vectors *S* and *D* thus represent the supply surplus or unsatisfied demand within the defined transportation distance *c*.

I performed both overlay and accessibility analysis for the mean values of regional supply and demand data between 2008 and 2018. I repeated the analysis for the supply and demand values in the most recent year from the data (2018; see details in Supplementary Materials of Article II). Exploration of spatial mismatches in these two periods allowed me to determine whether there was a significant variation in spatial mismatches during the period in which the data were collected.

3.3.3 Panel generalized linear models

In Article III, I examined the roles of subjective (cultural ES consumption, sociodemographic background, and perceived accessibility and infrastructure) and objective (environmental and infrastructure measures features) variables in the frequency of human–nature interactions in urban and peri-urban areas, using PGLM (Croissant 2021; Croissant & Milo 2019). I pre-analyzed the data with correlation analysis prior to running the panel models. In addition, I evaluated the model fit before running the analysis, using diagnostics such as a log likelihood comparison between panel and non-panel models, an Akaike information criterion assessment (AIC), McFadden's pseudo-R-squared value assessment, and a likelihood-based test assessment.

PPGIS data consist of answers from multiple respondents, where each could mark more than one visited location. This creates the panel data structure, where multiple observations are nested within individual units. I chose PGLM as a method for evaluating the studied variables' roles in visit frequency in the marked spaces, because it accounts for the nested structure of the PPGIS data. PGLM accounts for the within-respondent variation in the data and controls the unobservable elements of respondent-level characteristics, including, e.g., personal values, preferred visitation patterns, and the impact of choices made by other individuals (Wooldridge 2010), which can impact the observed choices made by the survey respondents.

I applied a fixed-effects negative binomial model in the analysis. Fixed effects account for unobserved heterogeneity in the data structure (Croissant 2021; Hank et al. 2024), allowing the PPGIS survey respondents to have their own baseline tendency for choices of marking a location. The negative binomial regression, on the other hand, is used for overdispersed count data, e.g., event occurrence frequency, with variance greater than the mean frequency rate (Croissant 2021; Hastie L& Tay 2023; Wooldridge 2010). I conducted the PGLM model estimation using the *pglm*() function from the R package PGLM (Croissant 2021). Each survey respondent had an assigned ID number defined as the panel index in the analysis.

I constructed four separate models to evaluate the roles of studied groups of variables in the human–nature interactions across marked locations. Model 1 analyzed the roles of the respondents' sociodemographic backgrounds in the choices made. Model 2 evaluated the roles of cultural ES consumption in the visitation frequency. Model 3 included the roles of perceived accessibility and infrastructure variables in the choices, and Model 4 the impact on objectively measured environmental and infrastructure variables. The sociodemographic background of respondents from Model 1 was kept in all other models to control individual differences and provide a clearer interpretation of the roles of the studied groups of variables. The results of the models include regression coefficients (estimates), standard error values, *z*-scores, and *p*-values. The estimates, which represent the log-transformed effect of each variable analyzed, were exponentiated to incidence rate ratios (IRRs). The IRR shows the multiplicative change in visit frequency and allows for easier interpretation of the results. An IRR below 1 indicates that the variable is associated with lower visit frequency, an IRR equal to 1 indicates no difference in visit frequency, and an IRR above 1 indicates a higher visit frequency.

4 Results

In this chapter, the results are organized by the three objectives of the thesis (O1–O3; see Table 1), with each objective corresponding to one article of this thesis.

4.1 O1: Distribution and temporal trends of wood ecosystem service across Europe (2008–2018)

During the period studied (2008–2018), wood ES potential gradually increased at the continental level (Figure 4a). The biggest capacity to provide this service was concentrated in Central and Northern Europe (i.e., Austria, Switzerland, Germany, Finland, Sweden, and the Baltic States), where the mean potential values per country area were the highest in the period between 2008 and 2018 (Figure 5a). Due to the lack of appropriate and comparable data, it was impossible to assess the potential at the regional level.

The countries with high capacity for wood supply were also the biggest producers of this ES (Figure 5b), based on mean supply values at the country level. National wood ES demand was concentrated in the same countries, also being high in Belgium and

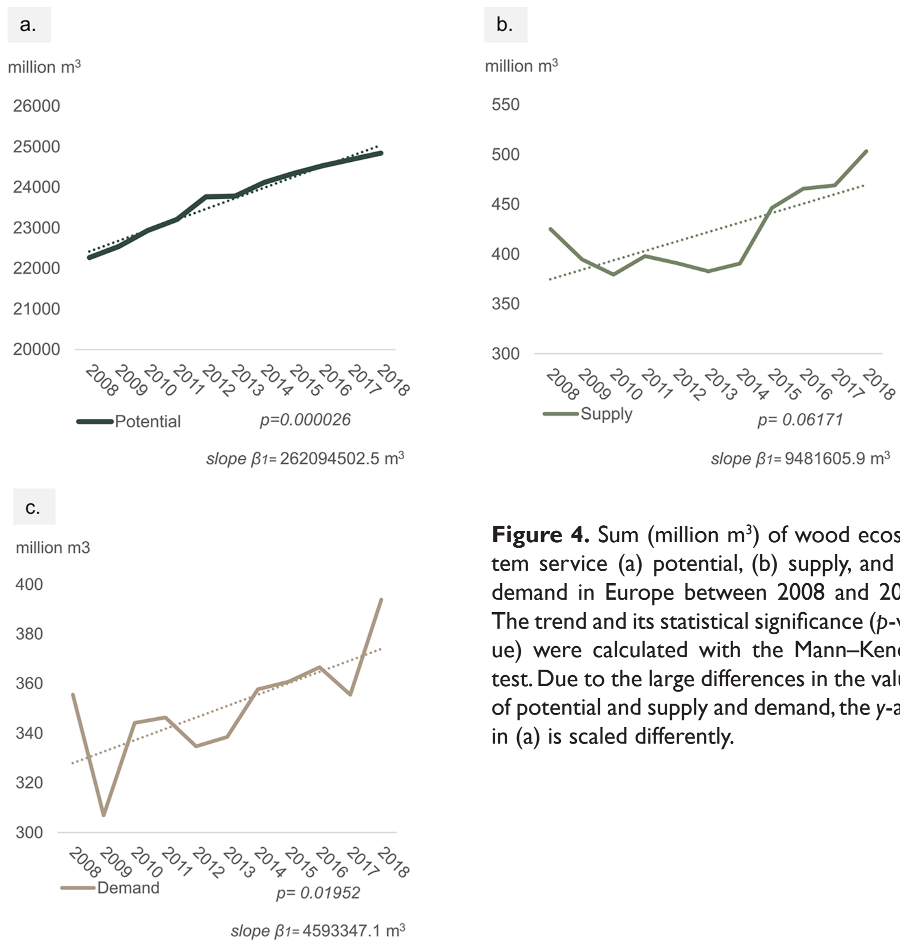

Figure 4. Sum (million m³) of wood ecosystem service (a) potential, (b) supply, and (c) demand in Europe between 2008 and 2018. The trend and its statistical significance (*p*-value) were calculated with the Mann–Kendall test. Due to the large differences in the values of potential and supply and demand, the *y*-axis in (a) is scaled differently.

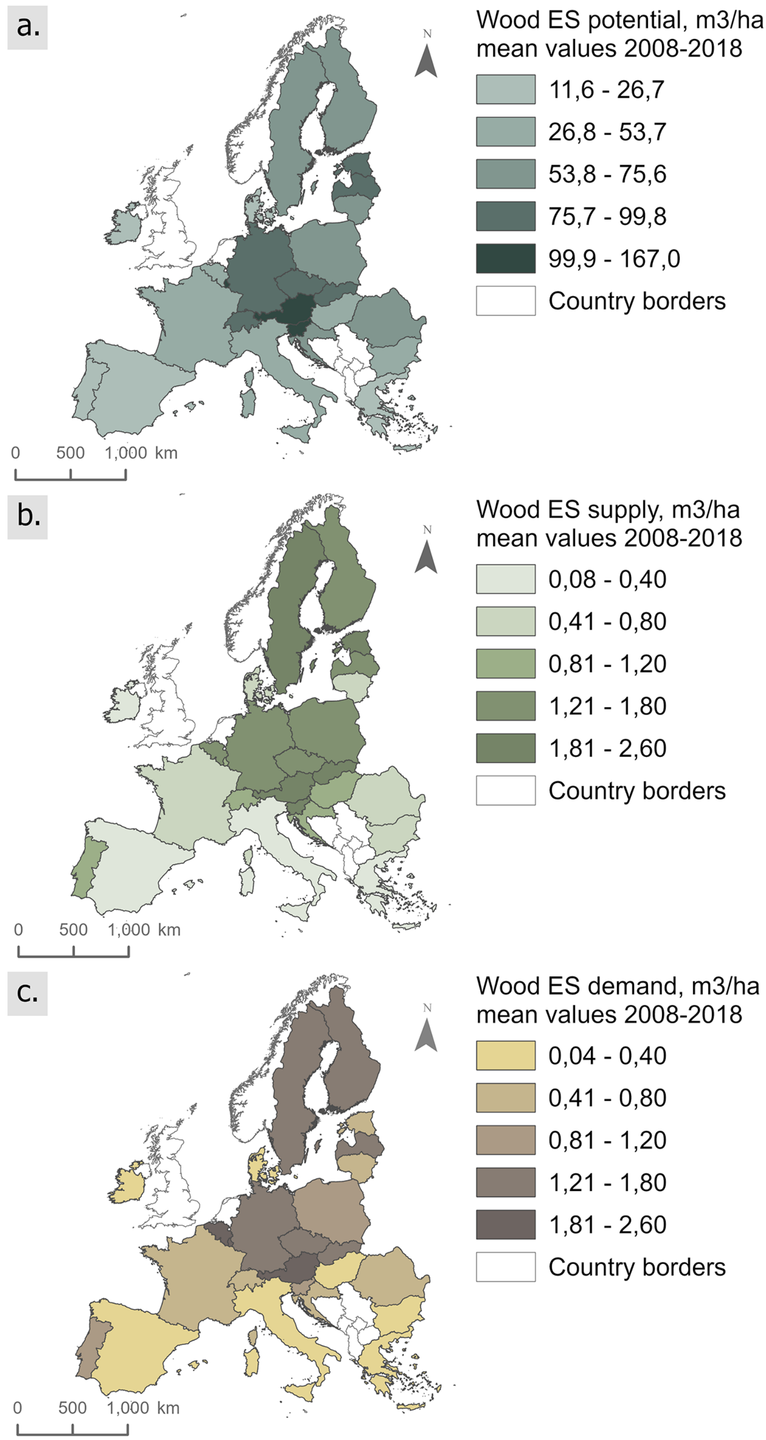

Figure 5. National-scale distribution of wood ecosystem service (a) potential, (b) supply, and (c) demand between 2008 and 2018, in m^3/ha.

Portugal (Figure 5c). Similar to the potential, wood ES supply and demand intensified on a continental scale in the period studied (Figure 4b and c). Wood ES supply increased more steadily than demand, with more dynamic growth starting around 2015. The growth of demand was more dynamic and often affected by shock events (e.g., economic crises). Overall, at the continental scale, supply exceeded demand and grew faster than demand (the supply growth rate between 2008 and 2018 was 16%, while demand grew by 10%). The country-level data for all mapped ES aspects were characterized by low variability (for more information, see Article I, Supplementary Materials, Figure S5).

Regional data provided more detailed information about the distribution of European wood ES supply and demand (Figure 6). From 2008 to 2018, mean supply levels were the highest across Northern Europe, particularly in the southern and southeastern

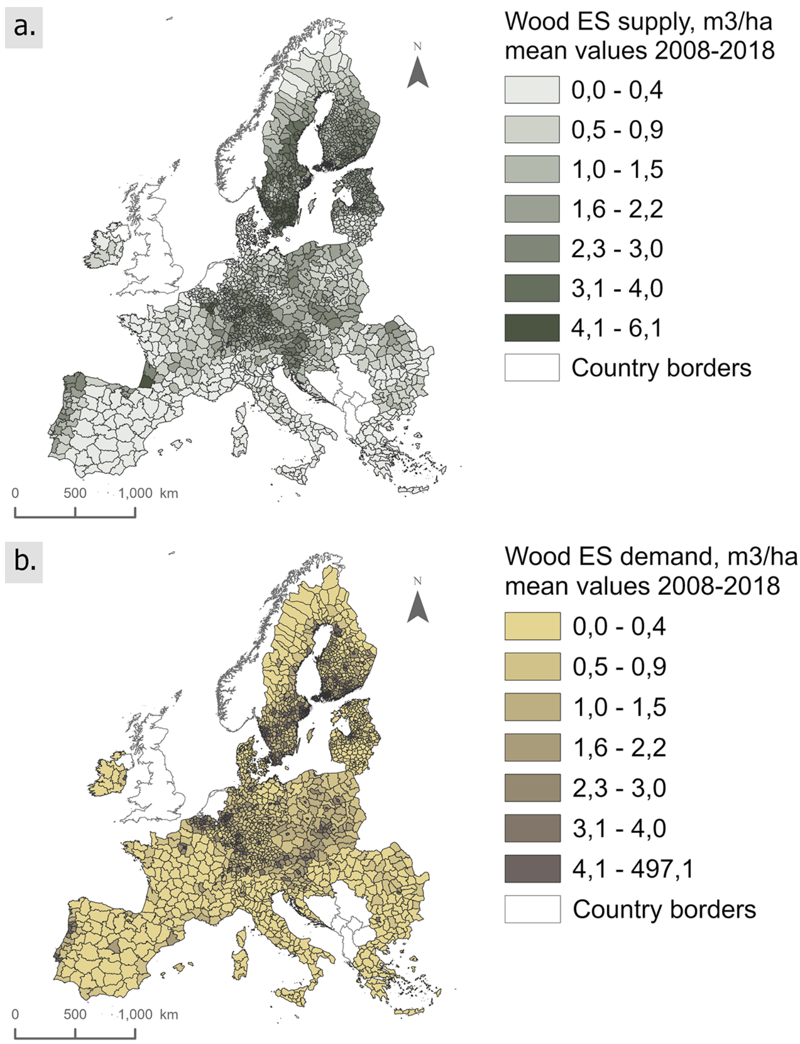

Figure 6. Regional-scale distribution of wood ecosystem service (a) supply and (b) demand between 2008 and 2018, in m^3/ha.

regions of Finland and Sweden (Figure 6a). Moderately high supply was observed in Central Europe, including regions in Germany, Austria, Slovenia, northern Portugal, and the French region of Aquitaine. On the other hand, the lowest supply was found across regions of Finnish and Swedish Lapland and across Southern Europe. Wood ES demand was concentrated in large cities and centers of wood ES distribution for the final consumers. The highest regional demand for wood ES during the period studied was located in the southern regions of Northern (Finland, Sweden) and Central Europe (Germany, Poland), and in the biggest capital cities of the studied countries (Figure 6b). The supply data at the regional scale showed greater variability across regions compared to country-level statistics; however, overall levels remained low. Similar to the regional supply data, the variation in regional demand was generally low (see information in Article I, Supplementary Materials Figure S6).

The national wood ES potential between 2008 and 2018 was characterized by an upward trend across most of the countries studied (Figure 7a). For supply and demand, the trend varied throughout the specific countries. A highly statistically significant upward

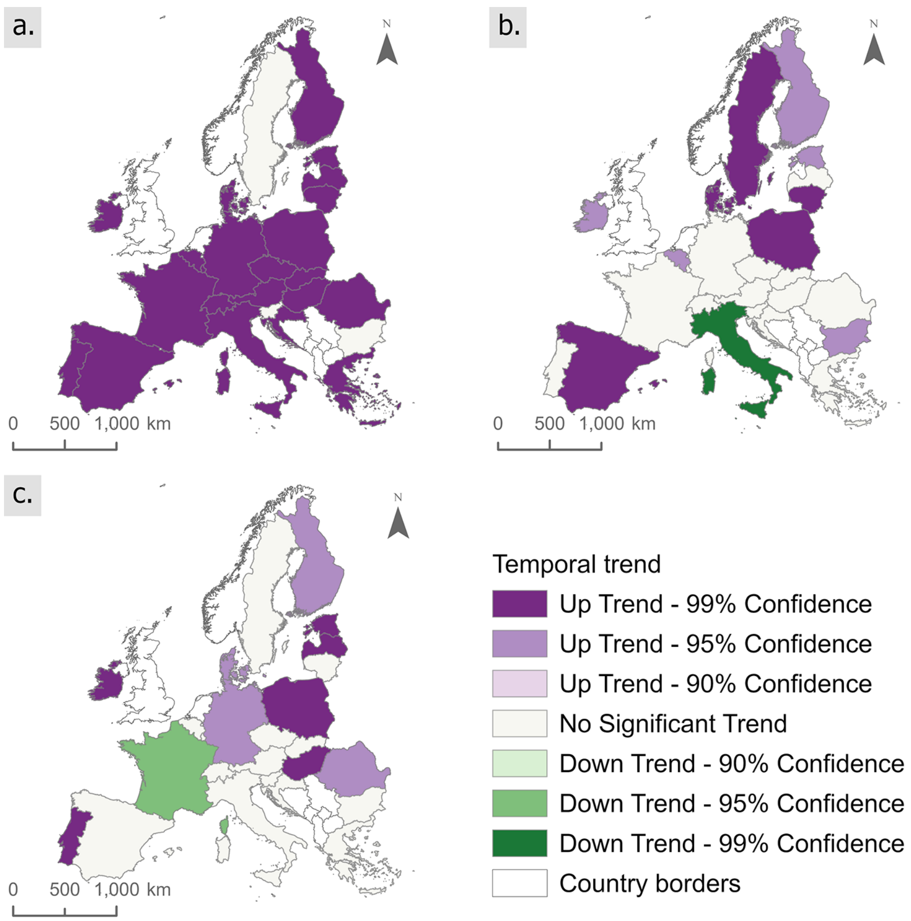

Figure 7. National-scale temporal trends of wood ecosystem service (a) potential, (b) supply, and (c) demand, with confidence intervals that indicate the statistical significance of a trend (99% confidence: $p < 0.01$; 95% confidence: $p < 0.05$; 90% confidence: $p < 0.1$).

trend of wood ES supply was observed in Sweden, Poland, Lithuania, Denmark, and Spain (Figure 7b), and for demand in Estonia, Latvia, Hungary, and Portugal (Figure 7c). A statistically significant downward trend was observed for supply in Italy and for demand in France.

At the regional level, upward trends of wood ES supply during the period studied (Figure 8a) were particularly recognizable in central and southern Sweden, Poland, Ireland, certain regions in France, and the north and west of Spain. Decreasing trends in supply were predominantly detected in southern Spain, northern Italy, southern Sweden, and a few regions in France, Germany, and Greece. The distribution and trends of regional wood ES demand demonstrated different spatial patterns across the studied areas (Figure 8b). The patterns of demand temporal trends in the period

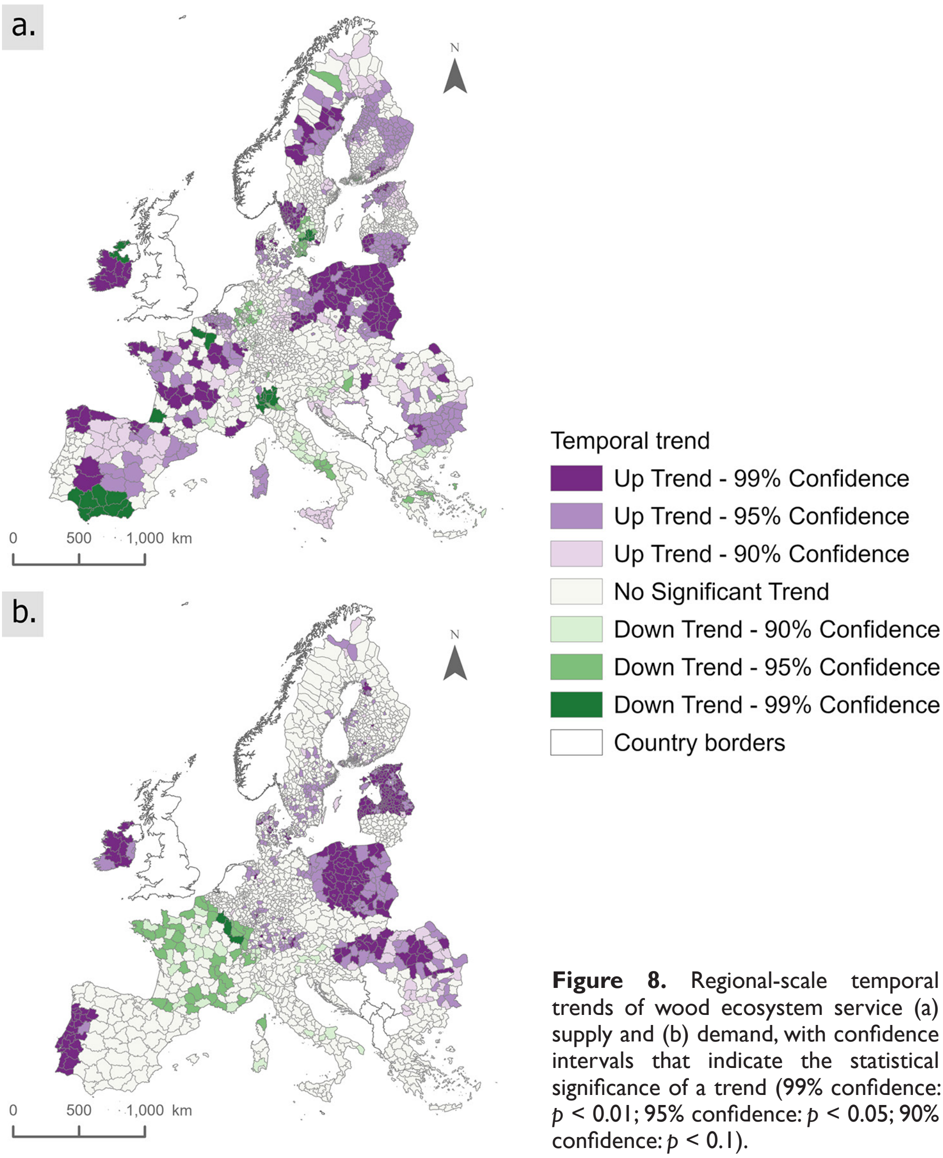

Figure 8. Regional-scale temporal trends of wood ecosystem service (a) supply and (b) demand, with confidence intervals that indicate the statistical significance of a trend (99% confidence: $p < 0.01$; 95% confidence: $p < 0.05$; 90% confidence: $p < 0.1$).

studied were highly intensifying but different from those of supply. An upward trend in wood ES demand was detected across regions of Estonia, Latvia, Poland, Romania, Bulgaria, Ireland, and Portugal, as well as Northern Europe and southwestern Germany. Conversely, wood ES demand decreased in many French regions within the studied period. The patterns of demand temporal trends in the period studied were highly intensifying but different from those of supply. An upward trend in wood ES demand was detected across regions of Estonia, Latvia, Poland, Romania, Bulgaria, Ireland, and Portugal, as well as Northern Europe and southwestern Germany. Conversely, wood ES demand decreased in many French regions within the studied period.

4.2 O2: Spatial patterns of European wood supply–demand mismatches

On average, when the spatial flow of the wood ES was not taken into consideration (overlay analysis), the overall continental supply surplus remained at 55.1% (in 1291 regions), while the unsatisfied demand was at 36.8% (in 1366 regions) during the period studied (Figure 9, Table 7). The pattern of oversupply was especially visible across rural, highly forested areas with better wood ES potential (e.g., Fennoscandia and Central Europe). Unsatisfied demand was apparent in larger population concentrations, such as major metropolitan areas and European capital cities.

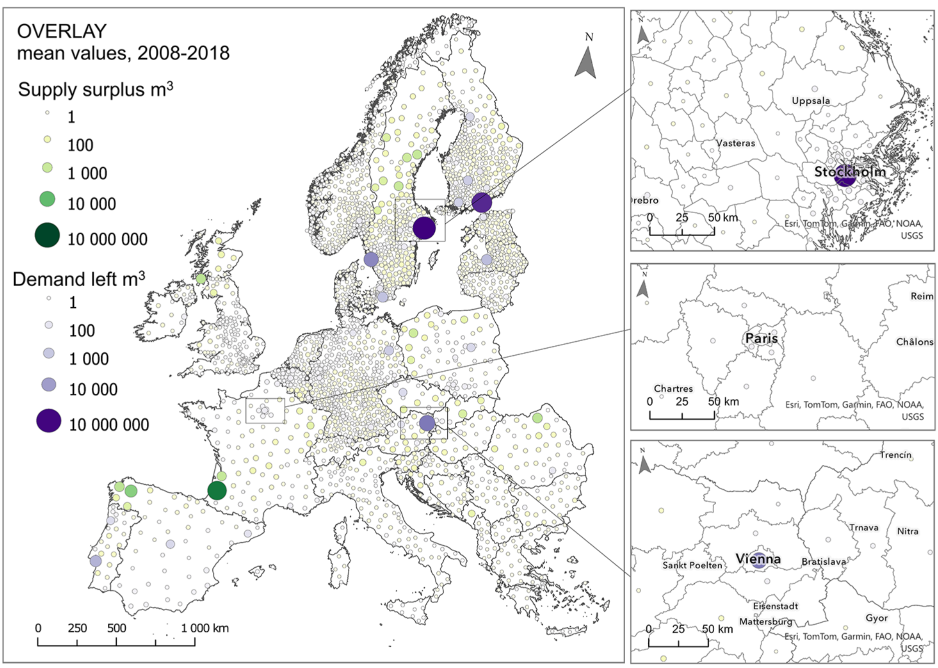

Figure 9. Overlay analysis for average annual wood ecosystem service supply and demand between 2008 and 2018 (m^3 per 10 years). Overlay map illustrates the balance between supply and demand within each region studied, without considering ecosystem service spatial flow (the service is not transported outside the region's borders). Three zoomed-in maps give a closer look at the balance evaluation around the cities of Stockholm, Paris, and Vienna. The figure is adapted from Article II. The overlay for a single year (2018) is available from the Supplementary Materials of Article II.

Table 7. Comparison between the overall continental wood ecosystem service supply surplus and the unsatisfied demand percentage for each transport distance (km), based on the average annual supply and demand values between 2008 and 2018. Detailed information regarding these values, as well as a comparison to the most recent year's values (2018), is available in Article II and its Supplementary Materials.

Transportation distance (km)	Average annual unsatisfied demand	Average annual supply surplus
0 (within the region, overlay)	36.8%	55.1%
150	23.4%	37.4%
300	11.5%	27.7%
600	2.2%	20.1%

Three predefined transport distances were tested (150, 300, and 600 km) to estimate how far the supplied wood ES needs to be transported, without the structures of logistics and industry, to meet the average demand of wood ES consumers across the studied European regions. The results of accessibility analysis within the 150 km distance from provisioning to benefiting areas indicated that much of the demand of the rural regions can be met within the local transportation distance of 150 km (Figure 10). In this transportation distance scenario, the supply surpluses were mostly observed across areas with high capacity for wood ES supply, like central Fennoscandia or Eastern Europe (Figure 10a). The unsatisfied demand remained in big population concentrations and areas that were less accessible by the transportation network and had low capacity to provide wood ES, such as Mediterranean islands or parts of Lapland (Figure 10b). The overall European supply surplus remained high but was lower compared to the results of the overlay analysis. Simultaneously, only about one-quarter of continental demand remained unmet within this transportation threshold (Table 7).

When the transport distance increased to 300 km, the balance between the supply and demand of wood ES was already noticeable in some regions, for example, Central Europe (Figure 10c & d). Nevertheless, regions with unmet demand remained, especially in big cities such as London and Stockholm, as well as in southern Finland and southern Spain. The level of overall unsatisfied demand decreased to approximately 11%, while the supply surplus fell to around 28% (Table 7). Increasing the transportation distance to 600 km resulted in nearly full satisfaction of continental demand, with a substantial supply surplus remaining across Europe (Figure 10e & f, Table 7). This indicates that the needs of the European population for wood ES were almost fully satisfied within a reasonable transportation distance during the period studied.

Even though the variation in the data was low, there may be differences in demand satisfaction in individual years of the studied period. To exemplify this variation, a comparative accessibility analysis for the year 2018 was performed. The results of this analysis showed that, in 2018, both the supply surplus and the level of demand satisfaction were slightly higher than for the average supply and demand values (see the Supplementary Materials of Article II for details).

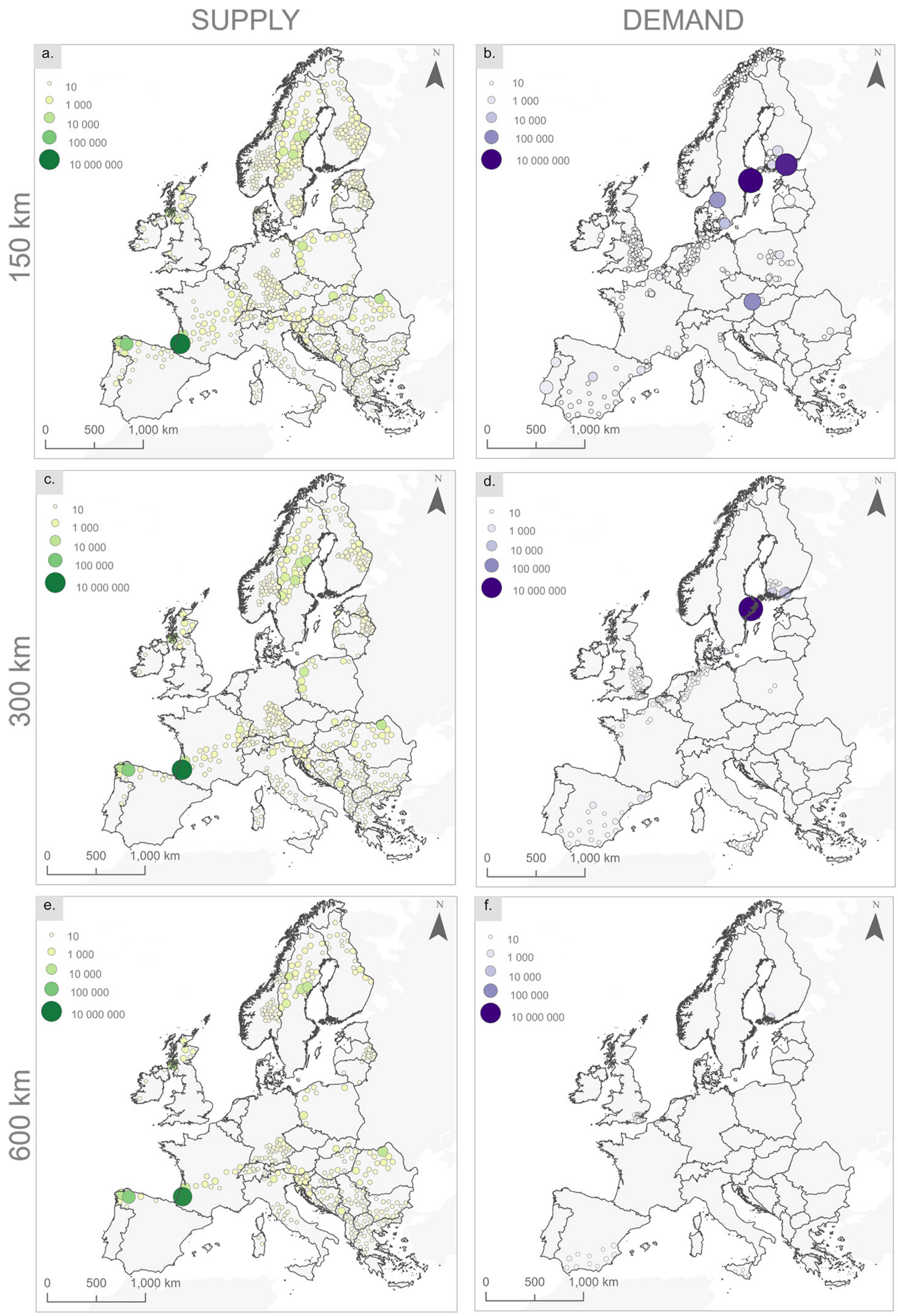

Figure 10. Results of accessibility analysis of average annual wood ecosystem service supply and demand (2008–2018; m^3 per 10 years) in considered distances: (a) supply surplus within 150 km, (b) unmet demand within 150 km, (c) supply surplus within 300 km, (d) unmet demand within 300 km, (e) supply surplus within 600 km, (f) unmet demand within 600 km. The results of comparative single-year analysis for the most recent year from the data (2018) are available in the Supplementary Materials of Article II.

4.3 O3: Characteristics supporting frequent human–nature interactions in green spaces

I explored the correlation between the studied explanatory variables (sociodemographic, cultural ES consumption, perceived accessibility, and environmental and infrastructure groups of variables) and the number of visits before analyzing their roles in the frequency of visits to urban and peri-urban green spaces in the studied cities. There were no major correlations (r_s) between the studied variables, with most not exceeding 0.3. The highest statistically significant correlation ($r_s = -0.5$, $p < 0.001$) was observed between the number of visits to marked locations and the perceived distance from home reported by PPGIS survey respondents. All four panel models showed improvements over the null model (Table 8), as suggested by likelihood ratio tests (Model 1 $\Delta LL = +20.5$, Model 2 $\Delta LL = +30.3$, Model 3 $\Delta LL = +50.5$, Model 4 $\Delta LL = +40.8$). Pseudo-R^2 values were rather low; however, in the case of the panel model, they do not suggest a bad fit but rather reflect the improvements in deviance.

The results of four panel models (Figure 10) showed the role of each group of studied characteristics in the frequency of visits to spaces marked in green in the PPGIS survey. According to Model 1 (Figure 11a), which included the respondents' sociodemographic characteristics, the visit frequency was highly dependent on the survey mode (invitation answers: IRR = 0.73, $\beta = -0.32$, $p < 0.001$), the respondents' education level (higher education: IRR = 0.86, $\beta = -0.15$, $p < 0.05$), and their city of residence (IRR = 0.83, $\beta = -0.18$ for Kuopio and $\beta = -0.19$ for Jyväskylä, $p < 0.05$).

Model 2 (Figure 11b), which considered the role of cultural ES for the number of visits, suggested a statistically significant negative association between peacefulness (IRR = 0.9, $\beta = -0.10$, $p < 0.05$), cultural heritage (IRR = 0.85, $\beta = -0.16$, $p < 0.05$), and the number of visits to marked locations. Moreover, a nearly significant negative association ($p < 0.1$) was observed between the visits and beautiful scenery of marked locations (IRR = 0.92, $\beta = -0.09$). Even though some other cultural ES suggested decreases or increases in visit frequency, their roles were not statistically significant. No major differences were found between the impact of sociodemographic variables in Model 2 compared to Model 1.

Table 8. Panel model fit statistics, performed for all models included in the analysis in Article III (LogLik = Log Likelihood; AIC = Akaike information criterion; Δ*Df* = Delta Degrees of Freedom; Δ*LL* = Delta Log Likelihood; LRT= Likelihood Ratio Test; Pseudo R^2 = McFadden's Pseudo R-squared).

Model	**LogLik** non-panel GLM	**LogLik**	**AIC** non-panel GLM	**AIC**	**Δ*Df***	**Δ*LL***	**LRT *p*-value**	**Pseudo-*R*²**
null model	—	–4836.7	—	9675.427	—	—	—	0.000
Model 1	–15610.43	–4823.0	15628.0	9661.957	+7	+27.5	0.00027 ***	0.0028
Model 2	–15560.72	–4812.4	15597.0	9658.706	+9	+21.3	0.0116 *	0.005
Model 3	–15413.52	–4756.1	15440.0	9536.227	–5	+112.5	<2e-16 ***	0.015
Model 4	–15361.56	–4782.5	15392.0	9592.978	+2	+52.8	3.5e-12 ***	0.011

*Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$*

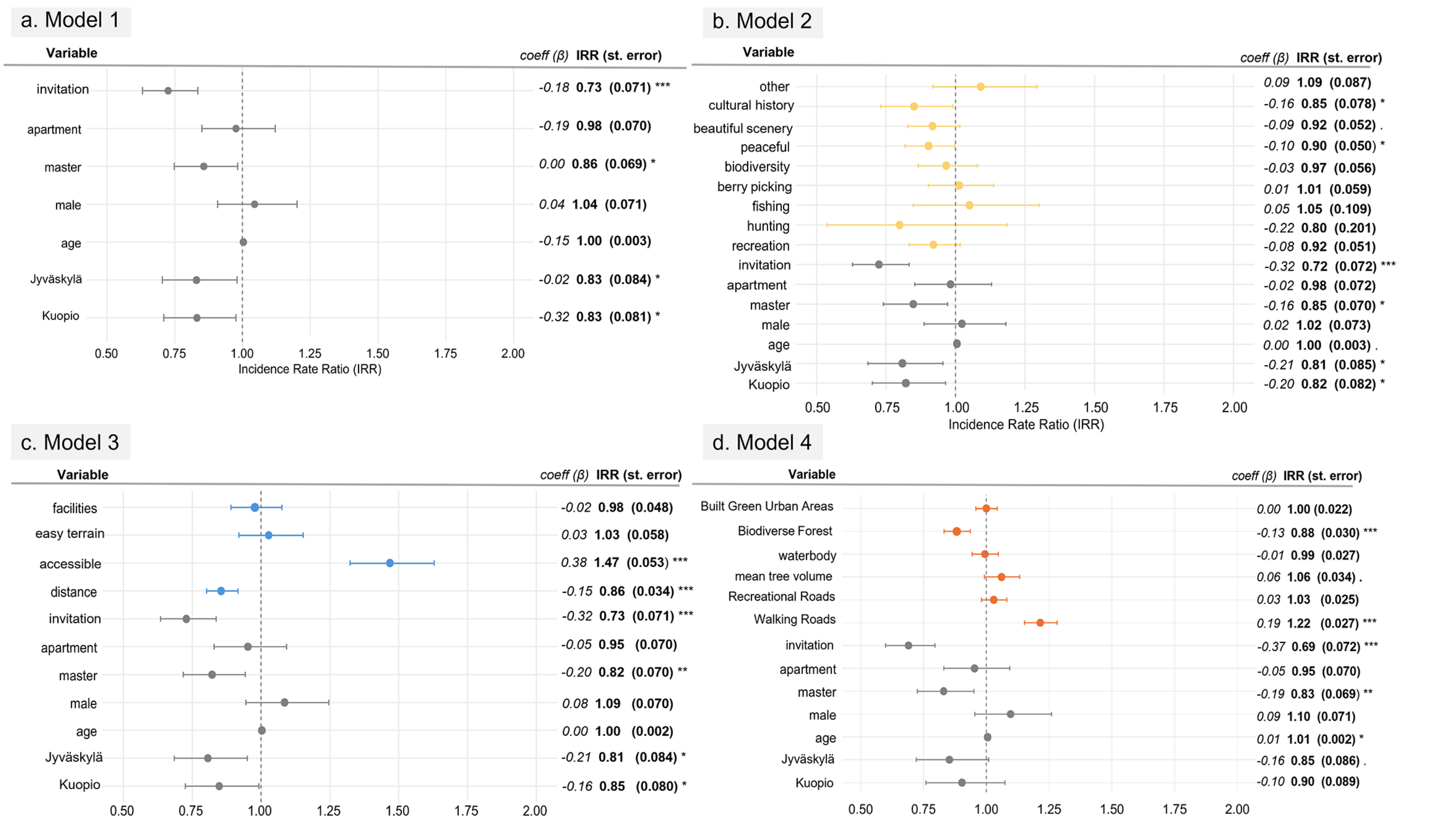

Figure 11. Visualization of the incidence rate ratios (IRRs) for each model included in Article III, along with the standard error values (in parentheses) and the statistical significance codes (*p*-value significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, . $p < 0.1$). The detailed results of the model calculations are available in Article III.

Model 3 (Figure 11c) explored the roles of perceived accessibility and infrastructure characteristics in the frequency of human–nature interactions in marked locations. The model revealed a highly statistically significant positive role of perceived accessibility in the number of visits (IRR = 1.47, $\beta = 0.38$, $p < 0.001$), followed by the negative statistically significant role of perceived distance (IRR = 0.86, $\beta = -0.15$, $p < 0.001$). As in Model 2, the impact of sociodemographic variables remained the same.

Finally, Model 4 (Figure 11d) considered the role of objectively measured environmental and infrastructure characteristics of the visited locations. The results indicate a link between high visit frequency and the presence of walking roads in the area surrounding the marked locations (IRR = 1.22, $\beta = 0.19$, $p < 0.001$). Additionally, a nearly significant positive association of bigger tree volume coverage close to marked locations was observed (IRR = 1.06, $\beta = -0.06$, $p < 0.1$). On the other hand, the presence of biodiverse forests (IRR = 0.88, $\beta = -0.13$, $p < 0.001$) was negatively associated with high visit frequency. The role of sociodemographic variables remained similar to all other models, with age appearing as a statistically significant variable ($p < 0.05$) for a higher number of visits; however, the IRR values remained low (increasing from 1 to 1.01).

5 Discussion

Through the results of this thesis, I exemplified the mapping of ES components, incorporated ES spatial flows into the analysis of ES supply–demand spatial mismatches, and highlighted the importance of human needs and perceptions of nature as vital parts of the ES framework. In this section, I first reflect on the main findings, strengths, and limitations of each article. Then I discuss the potential future research directions of ES assessments and opportunities for its practical application in policy- and decision-making.

5.1 Spatiotemporal trends of wood ecosystem service across Europe (Article I)

In Article I, I examined patterns in wood ES potential, supply, and demand across three spatial scales over a decade (2008–2018). The results support the hypothesis that spatial scale influences this ES assessment, as analyzing the regional distribution and trends of wood ES provides more detailed insights compared to national and continental scales. Based on the findings, all the assessed indicators of wood ES, including potential, supply, and demand, showed an upward trend between 2008 and 2018. The increase in wood ES potential was steady, which aligns with previous studies where similar ES potential indicators were explored (Blattert et al. 2023; Eurostat & Cook 2021). The growth of wood ES potential across Europe can be explained, for instance, by the adoption of forest transition actions, which integrate social, economic, political, and cultural efforts toward the restoration of European forests (FAO & UNEP 2020; Maes et al. 2020; Palmero-Iniesta et al. 2021). The data indicated an increase in forest area during the period studied, but they do not allow for conclusions regarding changes in forest ecological quality over the studied timeframe.

The patterns of the upward trend in wood ES supply and demand differ from those of ES potential. The supply and demand of provisioning ES are often impacted by changes in societal needs for services and economic shift-related events, such as crises, wars, and pandemics (Brack 2018; Bull 2018; Maes et al. 2020). For example, the demand for wood ES dropped in 2009, possibly as a result of the global economic crisis, which may also have impacted supply. Additionally, supply and demand are influenced by a range of other factors, such as wood harvest restrictions, policy, and area-specific legal limitations, or bioeconomy-related drivers, like the more common use of wood-based energy globally (Bull 2018; Jonsson et al. 2013).

During the period studied, supply reached its highest levels in Northern and Central Europe, while demand was concentrated in the most populated areas, such as metropolises and capital cities. Supply grew more steadily than demand, and the annual variation in demand levels was greater than that of supply. However, the supply levels at both the beginning and the end of the studied period were significantly higher than the demand levels. This can be explained by the fact that only the demands of European populations were taken into account in the data collection, without considering international trade needs for European wood ES supply.

When looking at the regional distribution and trends of wood ES supply and demand, it is noticeable that both supply and demand increased in most of the studied administrative areas. Although our results, along with evidence from other studies (e.g., Blattert et al. 2013), show that wood ES potential is also increasing, societal demands place significant pressure on European forests. In the long term, these intensifying pressures of supply and demand can affect potential and possibly endanger the positive outcomes of the forest transition (Palmero-Iniesta et al. 2021). Consequently, this trend can affect sustainable forest management goals and conservation efforts.

The discussion regarding the benefits and disadvantages of exploiting wood ES contains many contradictions. For example, growing bioeconomy pressures related to the increased use of wood-based energy may be one reason why wood ES potential, supply, and demand levels have been rising during the period studied (Bull 2018; Daigneault & Favero 2021; Jonsson 2013). According to Favero et al. (2020), the increasing efforts by developed countries to treat forest biomass as a renewable and carbon-neutral energy source have significant implications for forest management related to, for example, climate mitigation strategies and exploitation of wood ES. However, the sustainability of wood-based bioenergy and its ecological impacts remain debated and warrant further investigation from multiple perspectives (Favero et al. 2020). The faster forest growth indeed supports bioeconomy; however, it may negatively affect other ES provided by forests. As suggested by previous research (e.g., Bull 2018; Dasgupta 2021; Jenkins & Schaap 2018; Mitchell et al. 2014; Pohjanmies et al. 2018), intensifying wood ES exploitation impacts the quality and connectivity of forest habitats, the provision of non-wood ES, forests' biodiversity, and their attractiveness, for example, in terms of cultural ES consumption.

Article I presents a general overview regarding growing trends of wood ES potential, supply, and demand across Europe; however, it's important to acknowledge the study's limitations when engaging in a deeper discussion of the results. I considered all tree species in the analysis, without taking into account information such as species diversity or monoculture dominance, the duration of tree growth, or country- or region-specific forest management approaches, which can impact the dynamics of wood ES potential, supply, and demand (Palmero-Iniesta et al. 2021). In addition, the supply and demand data, which I used as proxies for mapping, have some limitations. Wood ES supply data were collected and compiled based on country-specific statistical information. There might be errors, as the methods of collecting data across Europe vary and include only officially reported harvests. The wood ES demand data, on the other hand, are based on the final consumption statistics and do not consider the complex stages of wood industry chains or the economic affordability of the resource. Moreover, one of the major limitations of Article I is that the sustainability levels of wood ES exploitation, related to, for example, the intensification of forest management practices, were not captured or analyzed. Upward trends were detected, which suggests intensification of the resource's use and may indicate disturbances in aiming for more sustainable management of wood; however, more specific analyses were beyond the scope of the study.

Despite its limitations, Article I exemplifies a consistent assessment of ES potential, supply, and demand within the ES cascade, focusing on the specific case of the provisioning service of wood and directly addressing the need for comparable mapping of these ES components. Through this article, I provide an overview of the allocation of ES elements and their annual changes over a decade. The findings show that incorporating annual data into the analysis allows for the detection of more precise trends compared to six-year intervals (as in Maes et al. 2020) or single-year assessments. I also offer a distinctive perspective on how the analysis of different spatial extents can influence the outcomes of ES assessments, and how ES pattern trends may vary depending on the chosen spatial resolution.

My findings demonstrate that more detailed data at finer regional scales can shed brighter light on patterns of ES exploitation. The easy-to-read maps of wood ES potential, supply, and demand represent a concrete output of the study, which can potentially be used to communicate the state of wood ES across Europe. The maps and overall findings of Article I support resource use monitoring and offer valuable input for forest management strategies and development plans, such as the EU's Biodiversity Strategy (2020) or new initiatives regarding the developments in monitoring European forests (European Commission 2023). Overall, the study highlights the need for spatial and temporal evaluation of ES, which should be conducted also for other services than wood, provided by forest. A comparative assessment of the potential, supply, and demand of ES can shed light on trade-offs between forest ES across spatial and temporal scales. This concerns not only provisioning services, but also other types of ES, including cultural and regulating ones.

5.2 Incorporating spatial flow in mapping wood ES supply and demand mismatches (Article II)

In Article II, I applied a spatial accessibility analysis to explore spatial mismatches between the supply and demand of the provisioning service of wood, the distribution and trends of which I mapped in Article I. This analysis served as a tool for exploring the spatial flow of wood ES from SPA (wood-provisioning regions) to SBA (wood-demanding regions) through the SCA, represented in this study by the road and ferry transportation network. The study evaluated the mismatches between supply and demand of wood ES, testing three transportation distances to reveal local, regional, and interregional mismatch patterns.

The results of the accessibility analysis were compared with the overlay analysis, which does not account for the spatial flow of the services but is commonly used for mapping ES mismatches (e.g., Burkhard et al. 2012; Martínez-López et al. 2019). Transportation distances are an important factor to consider when examining the spatial relationship between the SPA and SBA. Also, the quality of the SCA and the transport mode matter. The distances tested in the analysis of the supply–demand balance are based on the actual estimated distances of wood across local, regional, and inter-regional scales on the European continent (Eurostat 2023; Strandström 2022).

While the results of the overlay analysis indicated much higher levels of unsatisfied demand across Europe, the results of the accessibility analysis within a 150 km cost distance showed that the delivery of wood ES already within this short transportation threshold can satisfy about three-quarters of the average European demand for this service. Satisfaction grew to around 90% within a 300 km distance and fulfilled almost all the average demand of Europeans within a 600 km distance. These findings revealed that the spatial accessibility of wood ES across Europe is good, as the service can reach all the places where it's demanded within this transport distance.

Even though the findings revealed good spatial accessibility of wood ES across Europe, I did not take into account economic factors that influence how people actually use wood ES. These include, for example, economic competition and the affordability of the resource for the population, which depends on changes in the wood market and is not static over time (Nepal et al. 2021). Moreover, I did not consider the economic costs of transporting wood ES from provisioning to benefiting sites, even though this can affect the actual availability and affordability of the service for end users (Mensah et al. 2025; Orazio et al. 2017). Additionally, it was out of the scope of the study to consider the global wood trade, which pressures European wood production. Even though substantial wood ES surpluses were identified, they were most likely directed to the global wood market. As predicted by FAO (2022), global demand for wood is expected to rise by approximately 37% over the next 25 years. This growing demand may lead to further exploitation of European wood ES and, consequently, increased pressure on European forest ecosystems (Lerink et al. 2023; Pohjanmies et al. 2021; Pötzelberger et al. 2021). Additionally, the economic prioritization of wood over other forest services may further disrupt their overall quality and availability (Pohjanmies et al. 2021; Verkerk et al. 2015).

Nevertheless, as hypothesized, through the results of Article II, I showed how incorporating ES spatial flow enables more effective and accurate examination of ES supply and demand spatial mismatches than a simple, in situ overlay of supply and demand within a studied region or area. In the context of wood ES, not incorporating spatial flows in mismatch assessments would have resulted in supply being disconnected from demand centers. This is particularly relevant given that consumption tends to be concentrated in areas with high population density. Based on the results of Article II, I can conclude that spatial accessibility should be applied in the evaluation of supply and demand balances for wood ES, as well as other ES that depend on movement to benefit from the service, across scales and in distinctive transportation scenarios. This approach has an additional value for spatial assessment of the ES tradeoffs. It can also be used beyond the research field of ES, to map the supply and demand balance of other services than ES, such as health care or transportation services. The maps of wood ES supply and demand mismatches can be used alongside the results of Article I to further support the forest monitoring strategies targeted by various European initiatives (e.g., European Commission 2023).

5.3 The role of cultural ecosystem services for shaping human–nature interactions (Article III)

In Article III, I examined the roles of four groups of subjective (sociodemographic background, cultural ES consumption, perceived accessibility) and objective environment and infrastructure characteristics in shaping human–nature interactions in urban and peri-urban green spaces. Among these, perception characteristics, particularly those linked to the perceived accessibility of the visited locations, emerged as the strongest drivers of more frequent nature interactions. Although consumption of cultural ES was often reported in PPGIS survey responses across the studied cities, their role in frequent visits to green spaces was not found to be statistically significantly positive in the models. Despite the availability of high-quality cultural ES, such as scenic landscapes and biodiverse green spaces, people tended to prioritize how accessible a space felt when deciding which areas to visit. Additionally, proximity to users' homes and the presence of walking paths further support the importance of accessibility perceptions. While this study focused on perceived accessibility and self-estimated distance from home, the results align with the principle of distance decay, which states that the likelihood of visiting a place decrease as the distance to it increases (Philips et al. 2023).

Cultural ES consumption variables of peacefulness and cultural heritage were found to have statistically significant negative associations with the number of visits to a given marked location. Similar patterns were observed for objective features of these locations, such as biodiverse forests. However, these findings do not necessarily imply that cultural ES were not valued by the respondents of the PPGIS survey. Rather, they suggest that perceived spatial and accessibility characteristics were prioritized, and the consumption of cultural ES might occur at greater distances, making such visits less frequent, though still appreciated by the human beneficiaries.

High-quality ES are typically found in areas with denser vegetation, lower noise levels, and greater distance from major urban settlements (Fleming & Schwartz 2023). Consequently, these might be less visited because the cost (in this case, the perception of distance of access) is higher. Lower visitation rates in high-quality ecosystems can be beneficial from a conservation perspective, as higher visitation rates can lead to intensified disturbances (Littlewood et al. 2020; Tolvanen & Kangas 2016). However, frequently used spaces that are closer to home but have lower conservation value may not fully meet the needs of urban populations or adequately support their well-being. It is also possible that respondents prioritized accessibility in their answers, even if other factors were also noticeable in the marked location but were overshadowed by negative experiences. For instance, some high-quality urban green areas (e.g., protected sites, older urban forests) may not be perceived as such due to factors like small size, urban noise, or other disturbances (Simkin et al. 2021).

Due to an inability to locate the homes of PPGIS survey respondents, I could not assess or compare spatial accessibility with the studied variables of spatial perception. Integrating spatial accessibility into the assessment would be beneficial, as recent evidence suggests that when evaluating the accessibility of green spaces in urban areas, multiple perspectives on accessibility should be considered simultaneously (Battison & Schifanella 2024). Additionally, transportation systems and the ways users of green spaces travel to locations where they interact with nature were not included in the data collection. However, to fully understand the importance of accessibility factors, transportation systems and spatial accessibility should be considered (Terefe & Hou 2024). Moreover, the PPGIS data I used did not include information about seasonal variations in behavior or the intensity of human–nature interactions. Incorporating a temporal dimension would provide more diverse information about green space exploitation patterns (Rau et al. 2020; Renard et al. 2015). User satisfaction was also not considered in the data. Finally, due to the small sample size, I was unable to detect city-specific nature interaction patterns. However, the sample was sufficient for a general analysis of all the cities studied.

Despite these limitations, in Article III, I emphasized the importance of subjective, user-specific characteristics and the objective features of environments where human–nature interactions occur and where ES are consumed. The study's results reveal a connection between objective and subjective characteristics of green spaces, supporting the hypothesis that these factors jointly influence the frequency of human–nature interactions in urban and peri-urban areas in studied Finnish cities. With the use of panel models, I accounted for unobservable variation among respondents and factors influencing their decision to visit a place. The findings of Article III confirmed previous studies that accounted for the importance of accessibility and recreational infrastructure for enhancing human–nature interactions in green spaces (Hegetschweiler et al. 2017; Li et al. 2025). They underscore the need to preserve accessible, high-quality green spaces in urban areas and highlight the importance of user perceptions in urban and peri-urban green spaces. In practice, these results and PPGIS data used in Article III can be included as proof in developing more accessible green spaces for the populations of the cities of Kuopio, Espoo, and Jyväskylä and beyond. Finally, the paper offers an additional perspective on the importance of the concept of accessibility, not only spatial but also perceived, complementing the approach taken in Article II. It underscores that cultural ES should be evaluated by taking into account the less objectively measurable components of the cascade model.

5.4 Future directions of ecosystem service assessment approaches

Overall, my research exemplified how to select and interpret indicators for assessing ES potential, supply, and demand, and how to analyze them across various scales. This expands the potential application of these indicators in decision-making processes. My thesis demonstrated and clarified the application of concepts related to ES potential, supply, and demand, and advanced methodological approaches by integrating spatial flow into ES assessments. It also emphasized the value of spatiotemporal mapping of ES potential supply and demand. Additionally, it highlighted the importance of subjective factors related to the perception of space and environment for shaping more frequent nature interaction, and consequently ES demand, particularly in urban settings.

Future ES assessments should more often integrate the analysis of ES potential, supply, and demand across different spatial scales (Burkhard et al. 2012, 2014; Syrbe & Walz 2012) and for various types of ES. When possible, they should also incorporate the temporal dimension into the analysis. Capturing annual or seasonal ES dynamics anticipates evaluation of long-term mismatches between ES supply and demand and allows us to capture the complex patterns of ES potential, demand, and supply across not only space but also timeframes (Rau et al. 2020; Renard et al. 2015). It must be remembered that the scale of each ES assessment must be adjusted according to its objective and the type of service being assessed (Ala-Hulkko 2020; Burkhard et al. 2014; Martínez-Harms & Balvanera 2012; Raudsepp-Hearne & Peterson 2016). Additionally, a detailed assessment and analysis of ES supply and demand should be conducted simultaneously, integrating information about ES potential into the assessment. This is necessary for a more comparable assessment of service supply and demand patterns and distributions (Burkhard et al. 2014). More data measuring the supply and demand, as well as the potential, of ES must continue to be collected and compiled. The maps generated through the assessment should be disseminated to relevant audiences, as they provide a clear visual representation of ecosystem conditions and the services studied.

Methodologically, future work could deepen the integration of ES spatial flow into the analysis of supply and demand mismatches by, for example, using accessibility analysis or similar distance-based approaches. In addition, applying similar frameworks to other ES than wood, especially those dependent on movement or transportation, would provide a more holistic picture of ES trade-offs and synergies across landscapes (Ala-Hulkko et al. 2019). The incorporation of social and economic dynamics and events, such as the consideration of logistics chains or manufacturing processes, could be beneficial if suitable data are available. Furthermore, considering shocks (e.g., economic crises, sudden border closures due to trade conflicts or pandemics, the state of infrastructure, or inaccessibility reasons) in the analysis of ES supply–demand balance could be tested for many ES. This analysis could also be applied to other than provisioning types of services where a direct or indirect relationship exists between SPA and SBA or SDA. Additionally, different perspectives on exploring accessibility approaches (spatial and perceived accessibility of services) in ES research should be studied. Based on my findings, these methods offer promising tools for ES assessments that consider not only provisioning but also cultural services.

To improve societal awareness and understanding of the ES concept, it is important to continue using participatory approaches to engage local stakeholders and ES users in the evaluation of ES supply and demand, as well as other characteristics that affect the supply and demand patterns. Participatory mapping is a promising tool for influencing planning outcomes, and therefore, researchers who use PPGIS data should communicate their results to the decision-makers in the areas they study (Nurminen et al. 2024). This can enhance the development of green spaces with consideration of the subjective needs of urban residents. Through participatory approaches, the subjective value of services can be evaluated and used to further improve the assessment of ES tradeoffs for different types of services. Finally, future studies should consider not only the capacity of ecosystems to provide services and the economic need for these services, but also the subjective reasons for consuming them (De Vreese et al. 2016; Kabisch et al. 2015; Xia et al. 2025). This could be done by expanding the integration of socioeconomic data and exploring the long-term impacts of environmental change on ES provision and use.

6 Conclusions

In this thesis, I applied ES theoretical frameworks to a practical evaluation of the provisioning ES of wood provided by forest ecosystems and cultural ES provided by green spaces located in urban and peri-urban areas. My research results provide an integrated assessment of these ES across spatial and temporal dimensions.

The first objective of this thesis was to explore the distribution and temporal trends of wood ES potential, supply, and demand across Europe between 2008 and 2018 (Article I). Through this spatiotemporal assessment of wood ES, I improved our understanding of how their potential, supply, and demand changed over time. I also demonstrated the importance of spatial scale in mapping ES. This assessment promotes the use of spatiotemporal mapping in ES research, which remains underrepresented compared to spatial approaches.

The second objective addressed mapping spatial mismatches between the supply and demand of the provisioning ES of wood (Article II). I used the spatial accessibility methodology for this mismatch assessment, which improved the evaluation of the supply–demand balance by incorporating spatial flow into the analysis. This is particularly important for services that depend on movement or transportation from the areas where they are provided to the areas where they are used.

The third and final objective was to explore the role of cultural ES demand in the frequency of human–nature interactions in urban and peri-urban green spaces, while also considering other subjective and objective characteristics of these spaces (Article III). Through this assessment, I contributed to our understanding of how perceptions of space and the environment shape patterns of ecosystem use in urban and peri-urban green spaces. My results emphasized the importance of subjective characteristics and perceptions, particularly those related to the accessibility of green spaces, in evaluating the frequency of human–nature interactions and, consequently, cultural ES demand.

Overall, in this thesis, I demonstrated how to select and interpret indicators of ES potential, supply, and demand for various purposes. I integrated spatial flow into ES assessments using the spatial accessibility method, which can be used in future studies and has great potential for more precise evaluation of ES spatial mismatches. Additionally, I emphasized the importance of mapping the supply and demand of ES over time. Furthermore, I highlighted the importance of spatial perceptions and the accessibility of urban green spaces for more frequent interactions with nature that support human well-being.

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