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Integrating accessibility analysis in ecosystem service and disservice mapping

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ACADEMIC DISSERTATION

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Abstract

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Keywords: ecosystem service, ecosystem disservice, mapping, Geographic Information System, spatial accessibility, spatial flow, supply, demand, service providing area, service benefiting area, service connecting area

Ecosystems support human existence and well-being through supply of services such as food, materials and energy flows, and by opportunities for cultural experiences. These are called ecosystem services (ES). There is a growing body of literature that recognizes also ecosystem functions which do not provide benefits to humans. These ecosystem drawbacks, namely ecosystem disservices (EDS), cause negative effects on human well-being. In both cases, most ES and EDS exist only if there is transfer of goods and (dis)services to people. However, there is often a spatial discrepancy between places where ES or EDS are produced and the location where people use or are exposed to them, which is a major challenge in the assessment and mapping of ES and EDS. Therefore, spatially explicit information on the geographical connections between the ES or EDS supply and demand areas is essential, and sustainable utilization possibilities of services are flawed without this knowledge.

In this thesis, the transfer of services or disservices from ecosystems to people across an area was addressed using the concept of spatial accessibility, which determines how easily a location can be reached from another location or the potential for reaching geographically distributed opportunities. The main aim was to investigate the applicability of the Geographic Information System-based accessibility approach in ES and EDS mapping. This thesis consists of three separate studies, of which each one tested the approach using different sets of ES and EDS indicators at different spatial scales. **The first study** assessed the availability and access of cultural ES in Finland, **the second** the balance between food ES supply and demand across Europe and **the third** the suitability of the accessibility methods for measuring the negative effects of disease vectors on Finnish people. The goals of these studies were to increase the understanding of people’s ability to utilize different ES and estimate the negative impacts EDS can cause for people as well as respond to the need to develop a practical tool and easy-to-read maps for both ES and EDS research.

The results showed that the accessibility approach has great potential as a practical tool for illustrating the utilization possibilities of ES. Accessibility analysis can be used to assess the potential use of cultural ES as well as the balance between ES supply and demand. In general, the method effectively showed the areas where people have limited possibilities to use cultural services or where the risk of overuse of ES is increased. At the European level, the method showed its strength particularly in densely populated areas where spatial mismatch between supply and demand was assessed more appropriately compared to the analysis where supply and demand was estimated using overlay of map layers. By using the accessibility approach, it was also possible to demonstrate how transportation distances and nation borders may affect the balance between ES supply and demand. The results showed that spatial accessibility also has potential in EDS mapping. The method not only provided a new way to evaluate the amount of EDS potential encounters and the number of exposed people, but also the activity level of people in high-risk EDS areas. Overall, the approach has potential for enabling efficient biodiversity policies and management when it is important to understand both exposure potential to harmful aspects of ecosystems as well as their benefits in order to increase human well-being.

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List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:

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II Ala-Hulkko, T., O. Kotavaara, J. Alahuhta and J. Hjort (2019). Mapping supply and demand of a provisioning ecosystem service across Europe. *Ecological Indicators* 103: 520–529. https://doi.org/10.1016/j.ecolind.2019.04.049 [2]

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Author's contributions

I TAH was responsible for the study idea. TAH, OK, JH and JA contributed to the study design. TAH processed the data and did the analysis with OK. TAH led the writing with contributions from OK. JH, OK, JA and PH commented on and edited the text.

II TAH developed the original idea with OK. TAH, OK, JH and JA contributed to the study design. TAH and OK processed the data. OK did the accessibility analyses with contribution from TAH. TAH was responsible for the preparation of the manuscript, while OK, JH and JA commented on and contributed to the text.

III The original study idea came from TAH. TAH, OK, JH and JA contributed to the study design. OK, MK and TAH processed the data and executed the analysis. TAH was responsible for the writing. OK, JH, JA and MK commented on the text.

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Glossary

The glossary consists of the key concepts and their brief definitions used in this thesis. Definitions in this Glossary are quoted from different sources (as indicated).

Accessibility: Determines how easily a location can be reached from another location (Rodrigue *et al.*, 2017) or the potential for reaching geographically distributed opportunities (Páez *et al.* 2012).

Enhanced two-step floating catchment area (E2SFCA): An accessibility method which consist of two steps that 1) determine what population falls within the catchment of each service provider and 2) allocate available services to populations by determining what services fall within the catchment of each population (Luo & Qi 2009).

Beneficiary: A person or group whose well-being is changed in a positive way by an ecosystem service (Potschin *et al.* 2016; TEEB 2010).

Common International Classification of Ecosystem services (CICES): The classification is developed by the European Environment Agency to standardize the use of terminology of ecosystem services to improve comparability of environmental accounting and ecosystem assessments (Haines-Young & Potschin 2018).

Cultural ecosystem service (CES): All the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people. CES are primarily regarded as the physical settings, locations or situations that give rise to changes in the physical or mental states of people, and whose character are fundamentally dependent on living processes; they can involve individual species, habitats and whole ecosystems (Haines-Young & Potschin 2018)

Disservice exposure areas (DEA): Spatial unit where people are exposed to an ecosystem disservice (cp. SBA) (Defined by author).

Disservice providing areas (DPA): Spatial units that are sources of ecosystem disservices (cp. SPA) (Defined by author).

Ecosystem capacity: The ability of a given ecosystem (or ecosystem asset) to generate a specific (set of) ecosystem service(s) in a sustainable way (Potschin *et al.*, 2016). Often used as a synonym for ecosystem potential to produce services (Syrbe & Grunewald 2017).

Ecosystem disservices (EDS): Negative contributions of ecosystems to human well-being (Lyytimäki & Sipilä 2009). Health EDS (used in this thesis) include the direct consequences resulting from unwanted effects of biota on human health, including the outputs from their existence (Vaz *et al.* 2017).

EDS exposed people: A person or group whose well-being is changed in a negative way by an ecosystem disservice (opposite to beneficiaries).

Ecosystem services (ES): The contributions of ecosystems to benefits obtained in economic, social, cultural and other human activity (e.g. MA 2005; TEEB 2010; Burkhard & Maes 2017)

ES demand: The sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period (Burkhard *et al.* 2012).

ES flow: The amount of an ecosystem service that is actually mobilized in a specific area and time (Maes *et al.* 2018).

ES supply: The capacity of a particular area to provide ES within a given time (Burkhard *et al.* 2012).

ES mapping: The process of creating a cartographic representation of (quantified) ecosystem service indicators in geographic space and time (Burkhard & Maes 2017).

Generalized additive models (GAMs): A statistical non-linear regression method that fits non-parametric smoothers to the data without requiring the specification of any particular mathematical model to describe nonlinearity (Hastie & Tibshirani 1990).

Geographic Information System (GIS): A special-purpose system composed of hardware and software in which a common spatial coordinate system is the primary means of reference. GIS contains subsystems for data, storage, retrieval, and representation; data management, transformation, and analysis; and data reporting and products generation (Rodrigue 2017).

Goods: The objects from ecosystems that people value through experience, use or consumption, whether that value is expressed in economic, social or personal terms. Note that the use of this term here goes well beyond a narrow definition of goods simply as physical items bought and sold in markets, and includes objects that have no market price (e.g. outdoor recreation). The term is synonymous with benefit (UK National Ecosystem Assessment 2011).

Indicator: An indicator is a number or qualitative descriptor generated with a well-defined method which reflects a phenomenon of interest (the indicandum) (Maes *et al.* 2018).

Least-cost path / shortest path: The shortest distance or time between nodes along the road network (Chang 2019)

Maxent: The maximum-entropy approach for modeling species niches and distributions. The model expresses a probability distribution where each grid cell has a predicted suitability of conditions for the species (Phillips *et al.* 2006).

Provisioning ES: Those material and energetic outputs from ecosystems that contribute to human well-being (Haines-Young & Potschin 2018).

Service connecting areas (SCA): Area connecting providing and benefiting areas (see SPA and SBA). The properties of the connecting area influence the transfer of the benefits (Syrbe & Walz 2012).

Service benefiting areas (SBA): Spatial unit at which an ecosystem service flow is delivered to beneficiaries. SBA spatially delineate groups of people who knowingly or unknowingly benefit from the ecosystem service of interest (Syrbe & Walz 2012).

Service providing areas (SPA): Spatial units (or areas) that are the source of an ecosystem service (Syrbe & Walz 2012).

Spatial flow: The spatial (transportation) connection between provisioning and benefiting areas (modified from Bagstad *et al.* 2013)

1 Introduction

Humankind is strongly dependent on well-functioning ecosystems and natural capital that are the basis for a constant flow of ecosystem services (ES) from nature to society (MA 2005). There is a large variety of goods and benefits that humans freely gain from the natural environment (Costanza *et al.* 1997; MA 2005; Haines-Young & Potschin 2010). For example, products like food and materials, as well as recreation and disease control, can be included as ES. Recently, ecosystem functions which do not provide benefits to humans (Shapiro & Báldi 2014; Shackleton *et al.* 2016) have gained more attention. These ecosystem drawbacks causing unpleasant and harmful effects on human well-being are called ecosystem disservices (EDS) (e.g. Lyytimäki & Sipilä 2009; Vaz *et al.*, 2017). However, the rapid progress and complex nature of the ES and EDS topics have increased the need for practical applications of the concepts (Daily & Matson 2008; Carpenter *et al.* 2009; Daily *et al.* 2009; Burkhard *et al.* 2012; La Notte *et al.* 2017). Regarding that, ES maps constitute an essential tool to bring the complex spatial information of ES and EDS into practical application (Burkhard *et al.* 2012; Maes *et al.* 2018). There is a wide consensus that high-quality, robust and reliable ES maps are crucial when the aim is to provide accurate and comparable information for decision-making and environmental planning (José Martínez-Harms & Balvanera 2012).

The spatial patterns of ES and EDS are complex and poorly understood due to spatial mismatches between areas that provide services and areas where the benefits of services are realized (Fisher *et al.* 2009; Syrbe & Walz 2012; Syrbe & Grunewald 2017). ES and EDS are commonly produced and consumed (or encountered) in different geographical locations, which is a major challenge in the assessment and mapping of ES and EDS (UNEP-WCMC 2016; Syrbe & Grunewald 2017; Schirpke *et al.* 2019). In such cases, in order to benefit from ES, people need to move actively to an area where a certain ES is provided or to facilitate transfer from a supply area to the receiving area where ES goods are transported to beneficiaries. Therefore, a detailed understanding of the different types of movement is crucial to adequately manage ES and EDS (Fisher *et al.* 2009; Bastian *et al.* 2012; Crossman *et al.* 2013). In this thesis, the spatial relationship between ES providing and benefiting areas as well as EDS exposure areas are mapped with multiple ES and EDS datasets and cutting-edge Geographic Information System (GIS)-based accessibility analysis on national (Finland) and continental (Europe) scales.

1.1 The link between people and nature

The negative impacts of global change on ecosystem properties and biodiversity has raised concerns about ecosystems' ability to sustain human well-being (MA 2005; TEEB 2010; IPBES 2019). The ES concept was proposed to meet this challenge – to increase public attention and grow people's awareness of the ways in which humans and nature are connected (Fu *et al.* 2013). Over the past few decades, progress has been made in understanding the ES-generating mechanisms (e.g. Palmer *et al.* 2004; Kremen 2005; Lamb 2018; McGinlay *et al.* 2018; Tan *et al.* 2020), mapping its supply and demand (e.g. Syrbe & Walz 2012; Syrbe & Grunewald 2017; González-García *et al.* 2020) as well as evaluation of its value (e.g. Costanza *et al.* 1997, 2014; Daily 1997; TEEB 2010; Burkhard and Maes 2017; Tammi *et al.* 2017). However, at the same time, the concept has become multiform and harder to understand, and it has generated debates about definitions and classifications (Boyd & Banzhaf 2007; Costanza 2008; Wallace 2008; Fisher *et al.* 2009; Seppelt *et al.* 2011).

The link between people and nature is complex, which has inevitably resulted in different definitions and classifications of ES (Costanza 2008; Fisher *et al.* 2009; de Groot *et al.* 2010). The ES concept has roots in ecology and social sciences (Gómez-Baggethun *et al.* 2010). Scientists have discussed ecosystem services implicitly for decades, but not until in the early 2000s did The Millennium Ecosystem Assessment (MA 2005) popularize this concept for a wider audience by defining it to consider all the benefits that people obtain from nature. In addition, it categorized services as supporting, regulating, provisioning and cultural services. The overlaps and interdependence of these categories (Wallace 2007, 2008) have led to refinements. These refinements require the separation of the final ES that provide goods and values to humans from the intermediate ecological and environmental processes within ecosystems (Figure 1) (Boyd & Banzhaf 2007; Fisher & Turner 2008). Interactions among biotic and abiotic components of nature involving these ecological properties and conditions lead to stocks and flows that underpin the final ES that people use as goods. This flow from the ecological systems (ecological structures and processes) to the socio-economic systems (benefits and values of ES) is represented well in the "cascade framework", where the ES flows have been divided into five steps (Figure 1) (Haines-Young & Potschin 2010). The chain starts from the ecosystem properties and conditions that create the capacity of ecosystems to provide actual services and ends at the benefits that are taken from the pool of ecosystem service potentials (Fisher & Turner 2008; Haines-Young & Potschin 2010; Bastian *et al.* 2013). Values are determined for the benefits and can be both marketable and non-marketable (Costanza *et al.* 1997; Chan *et al.* 2012; de Groot *et al.* 2012). Changes (e.g. human actions) in any step of the cascade could cause changes to the rest of the chain (Haines-Young & Potschin 2010).

Whilst even the researchers agree with the general idea of ES where the concept creates a bridge between the natural world and human well-being, the multiplicity of the ES concept (Vihervaara *et al.* 2010; Lamarque *et al.* 2011; Spangenberg *et al.* 2014) has maintained the problem of incomparability between different studies (Saarikoski *et al.* 2015; Boerema *et al.* 2017). One attempt to partly overcome this problem is the Common International Classification of Ecosystem Services (CICES) that has been developed to provide a way of characterizing final services (Figure 1). The main objective is to help the wider ES community to define measures of ES and map them (Haines-Young

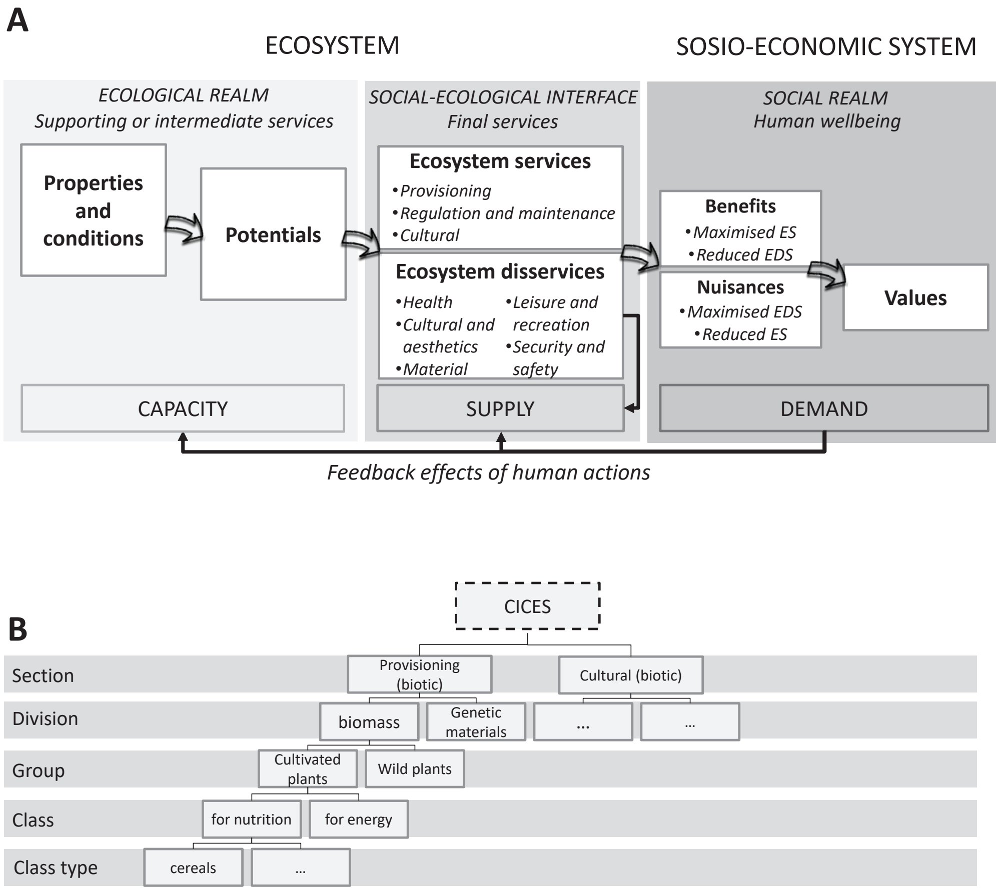


Figure 1. (A) The Cascade Model describes the flow from nature to people by dividing the ecosystem service flow into five steps. The Cascade Model is adapted from Fisher & Turner 2008; Haines-Young & Potschin 2010; Bastian *et al.* 2013; UK National Ecosystem Assessment 2011 and Mononen 2017 and original first two steps `biophysical structure or process' and `function´ have been replaced by the terms `properties and conditions´ and 'potentials' (see Bastian *et al.* 2013; Spangenberg *et al.* 2014) to harmonize these terms with the mapping aspects of ES (see chapter 1.2. Mapping ecosystem services). The concept of ecosystem disservice has been integrated as a part of the Cascade Model following Vaz *et al.* (2017). (B) An example of a hierarchical five-level structure of biotic provisioning ES based on the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018).

& Potschin 2018). Categorizing and describing are the basis for measuring, valuing or mapping ES (Boerema *et al.* 2017). CICES is hierarchical in structure, splitting the major sections (provisioning, regulating and maintenance and cultural services) into divisions, groups and classes. This hierarchical structure can address the issue of scale, as more aggregated categories (divisions and groups) can be used for reporting at broader spatial scales. At the local level, these categories might be represented by the specific classes

(Haines-Young & Potschin 2018). CICES is available online (www.cices.eu) and is constantly being updated. A consistent ES typology development via these practices facilitates comparative studies and enables repeatable quantification and valuation of ES (Feld *et al.* 2009; Saarikoski *et al.* 2015)

1.1.1 Nature as a nuisance

Alongside the benefits that people received from the nature, ecosystems also produce attributes that are perceived as unwanted, unpleasant or economically harmful, namely EDS (Lyytimäki & Sipilä 2009; Escobedo *et al.* 2011; Lyytimäki 2014; Shackleton *et al.* 2016). Together with ES, EDS are co-produced by ecological and human factors within social-economic systems (Blanco *et al.* 2019). EDS can be revealed through direct negative impacts on human well-being (e.g. via animals which pose danger to people by spreading diseases), or through a negative impact on an ES supply (e.g. pests reducing crop production) (Dunn 2010; Wielgoss *et al.* 2014). In addition, ecosystem functions can generate EDS, for example, through volatile organic compounds emitted by forests, or by the response of an ecosystem to human practices (Blanco *et al.* 2019).

The idea that ecosystems have negative impacts on human health is not a new one, and studies on this issue are conducted across several scientific disciplines. However, framing the negative ecological effects as part of ES seems to be rarely discussed (Von Döhren & Haase 2015; Shackleton *et al.* 2016; Blanco *et al.* 2019). For example, Shackleton *et al.* (2016) and Dunn (2010) have pointed out the fact that harm caused to human well-being by some ecosystems is seriously overlooked in ES studies. However, the use of the EDS concept has been since growing in the scientific literature (Daily 1997; Lyytimäki & Sipilä 2009; Dunn 2010; Escobedo *et al.* 2011; Shackleton *et al.* 2016; Potgieter *et al.* 2017; Blanco *et al.* 2019; Ceaușu *et al.* 2019). Though, incorporating the concept of EDS into ES research has faced criticism (Blanco *et al.* 2019).

In the field of nature conservation, EDS were claimed to reinforce the tendency of people to pay too much attention to the negative effects of nature (Shapiro & Báldi 2014). This is supported by many studies that show that, under some circumstances, EDS may influence people's actions more than ES (see Blanco *et al.* 2019 and references therein). In addition, the criticism of EDS is based also on the concern that the concept compromises conservation efforts by emphasizing the harms of natural ecosystems, further supporting arguments for intensive management and utilization of natural resources (Shapiro & Báldi 2014; Villa *et al.* 2014). A previous study by Saunders and Luck (2016) established that, depending on the context, the EDS concept promotes a black-and-white approach where the possibility that every ecosystem may contribute both ES and EDS is ignored. The fact that the complex nature of ecosystems may produce both positive and negative impacts on human health at the same time has caused a lack of clarity on how to integrate conceptually both ES and EDS in human well-being studies (see Von Döhren & Haase 2015; Saunders & Luck 2016). To overcome this problem, taking the full range of both positive and negative ecosystem functions into account for solving controversies related to environmental management, particularly in planning, has been suggested (Lyytimäki 2015; Shackleton *et al.* 2016; Vaz *et al.* 2017; Blanco *et al.* 2019). Schaubroeck *et al.* (2017) have further highlighted the importance of including EDS into ES studies as they both are part of the continuum.

Shackleton *et al.* (2016) suggested that one reason for the neglect of EDS from the discourse and policy debates around ES is because there is no widely accepted definition and typology for EDS. Several studies have put forward their understanding of the term and presented the categorization for EDS, applying the pre-established classification of ES (Lyytimäki & Sipilä 2009; Escobedo *et al.* 2011; Lyytimäki 2014). For example, Escobedo *et al.* (2011) categorized EDS into financial costs, social nuisances and environmental pollution. Whereas, Lyytimäki and Sipilä (2009) classified EDS based on their origin (as ecological, social-ecological and social) and impacted societal actors (individuals, societies and humankind). So far, several studies have argued that most of the introduced categorizations are mainly based on empirical research and are useful only in specific cases, lacking provision of the means for distinguishing between occurrence of perceived EDS and the reduction of an ES (Shackleton *et al.* 2016; Vaz *et al.* 2017; Blanco *et al.* 2019). In response, Vaz *et al.* (2017) presented a classification that integrates EDS into a general ES framework by using the ES Cascade Model (Haines-Young & Potschin 2010) and CICES (Haines-Young & Potschin 2018) categories of ES as a background (Figure 1). As a result, the integrated ES and EDS framework includes three main components: *the ecological realm* that consists of ecosystem attributes and functions that create or generate both ES and EDS (Spangenberg *et al.* 2014); *the social realm* that relates elements of human values, preferences and principles, defining the demand of ES and exposure to EDS (Chan *et al.* 2012; Spangenberg *et al.* 2014); *the social-ecological interface* that depends on the attributes and functions generated in the ecological realm, while it contributes to benefits in the social realm (Vaz *et al.* 2017).

Although EDS have since been addressed in the scientific literature and the strengths of the concept to achieve more balanced policies and sustainability have been perceived, the discussion around the conceptual framework that incorporates both ES and EDS still continues. As the concept of disservices is not yet fully established, and EDS and ES are closely linked to each other (can be considered as an opposite side of the same coin), the reader should bear in mind that EDS are discussed in this dissertation through the framework of ES and the mapping procedures are introduced here mostly based on ES literature.

1.2 Mapping ecosystem services (ES)

ES and EDS have a spatial constituent, as ecosystems have a capacity to produce services or disservices at a certain location and the benefits or nuisances will be derived and consumed at the same or another location (UNEP-WCMC 2016). Map-based spatial analysis constitutes an important method to bring the complex information of the spatial distribution of ES and EDS into practical application and easy-to-read form (Burkhard *et al.* 2012; Maes *et al.* 2018). By mapping ES and EDS, it is possible to visualize data, identify spatial patterns, overlaps and gaps that are otherwise difficult to illustrate (Burkhard and Maes 2017). In addition to this, maps can be applied to describe trade-offs (e.g. Alahuhta *et al.* 2018) as well as congruence or mismatches between supply and demand of different ES (e.g. Syrbe & Walz 2012; Syrbe & Grunewald 2017; González-García *et al.* 2020). Measuring and monitoring of ES and EDS both biophysical units and spatially in the form of map presentations could provide useful information for decision-makers and institutions, for example, to uncover ecosystem health risks, unsustainable use of ecosystems or reduced spatial flow of ES (Burkhard and Maes 2017). Such information can indicate which areas should be maintained due to their high ES provision (Balvanera *et al.* 2001) or prioritize areas that will allow alignment of multiple conservation goals (Egoh *et al.* 2008; Naidoo *et al.* 2008; Nelson *et al.* 2009; Raudsepp-Hearne *et al.* 2010; José Martínez-Harms & Balvanera 2012).

As maps are useful communication tools which improve the understanding of locations where valuable ecosystem services are produced. Mapping ES have been identified as one of the key objectives of the several actions to protect, conserve and enhance natural capital. The European Union's (EU) Biodiversity Strategy to 2020, for example, involved EU member states mapping and assessing the state of ecosystems and their services in their national territory (European Commission 2011). This aim is implemented, for example, via projects of MAES (Mapping and Assessment of Ecosystems and their Services) (Maes *et al.* 2012, 2018), IPBES (The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) (IPBES 2019) and ESMERALDA (Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking) (Santos-Martin *et al.* 2018). One of the main objectives of these projects have been attempts to harmonize the use of ES classification and indicators, but also methods for mapping and assessing ES.

However, during the past decades the integration of methods and models to map and assess ES has been expanded. ES provision and utilization are complex phenomena, with multiple aspects (e.g. ES properties and conditions, potential, supply, flow and demand) that can be mapped, assessed and monitored (see Syrbe *et al.* 2017). These components are interrelated, but can be mapped separately using quantitative indicators or qualitative estimations. Several attempts to map different aspects of ES are presented in the literature (Egoh *et al.* 2012; Bagstad *et al.* 2014; Schulp *et al.* 2014; Baró *et al.* 2016; Burkhard and Maes 2017), and much of the approaches are still under development (Seppelt *et al.* 2011; José Martínez-Harms & Balvanera 2012; Crossman *et al.* 2013; Malinga *et al.* 2015). For example, methods for mapping and assessing the ES flow from the ecological systems to the socio-economic systems are prerequisite for producing comprehensive information of the human dependence on functioning nature in practice (UNEP-WCMC 2016; Schirpke *et al.* 2019).

1.2.1 Measuring ecosystem services

Measuring ES is a key question when assessing and mapping ecosystem services (see Brown *et al.* 2014). As human-environmental systems have very high complexity of elements, connections and cause-effect relations (Müller & Burkhard 2012), finding an accurate way to measure them is not a simple task. Despite including multiple perspectives to quantify and define ES (see chapter 1.1), there is not yet a generally accepted approach to measure and assess the wide range of ecosystem services provided by an area (Feld *et al.* 2009; Brown *et al.* 2014). This has led to the use of different indicators to measure or indicate a single ecosystem service (Feld *et al.* 2009; Müller & Burkhard 2012; Saarikoski *et al.* 2015; Mononen *et al.* 2016). Although the ES indicators and measures have proliferated in response to several regional and national-level activities during the past years (Brown *et al.* 2014; Maes *et al.* 2016; Mononen *et al.* 2016), the choice of specific indicators is still quite often strongly dependent on the characteristics of the investigated ecosystems and on the decision context for which they are being applied (Boyd & Banzhaf 2007; Fisher *et al.* 2009; Reyers *et al.* 2010; Müller & Burkhard 2012). Therefore, quantifying and valuing ES are highly case-specific (Kandziora *et al.* 2013).

The main aim of using indicators is to simplify and quantify information, making it easier to understand for policy and decision-making but also for scientific purposes (Layke 2009a; Kandziora *et al.* 2013). Indicators could provide a logical link between ecological processes and human well-being by offering a useful and simple basis to measure the complex nature of ES provision (Boyd & Banzhaf 2007; Wallace 2007; Tallis *et al.* 2008; Fisher *et al.* 2009; de Groot *et al.* 2010; Potschin & Haines-Young 2011; Mace *et al.* 2012; Brown *et al.* 2014). As there are many different ES and measurable components of human well-being, indicators can also cover different stages of the ES cascade model. They can either measure the biophysical or the socio-economic (see MA 2005; Boyd & Banzhaf 2007; TEEB 2010; Lorilla *et al.* 2019) perspective of ES. Biophysical quantification focuses, in particular, on the measurements of ecosystem properties, conditions and potentials, i.e. the capacity of an ecosystem to supply services (Figure 1), while the socio-economical side identifies the aspects of the demand for them (e.g. the social or the economical units). Most of the studies have concentrated on the supply side of the cascade model, although the assessment and management of ES requires understanding about both supply and demand (e.g. Burkhard *et al.* 2012; Syrbe & Walz 2012; Bagstad *et al.* 2013; Crossman *et al.* 2013; Goldenberg *et al.* 2017; González-García *et al.* 2020). Measuring the balance between them is at the heart of the contemporary sustainability debate and is a key approach when assessing the way people and nature are linked.

1.2.1.1 Spatial and temporal scales in ES mapping

A good ES indicator contains information on whether they assess a capacity, supply or demand (UNEP-WCMC 2016). In addition to this, indicators need to consider the relevant spatial and temporal scale which is mostly dependent on the subject and purpose of the ES study (Andersson *et al.* 2015; Malinga *et al.* 2015; Raudsepp-Hearne & Peterson 2016). According to Reid *et al.* (2006), spatial scale has been defined "as the physical dimension of a phenomenon or process in space or time, expressed in spatial units". This unit might have either a local, regional, national, continental or global extent. Moreover, spatial scale can be addressed through a spatial resolution of maps. Generally, the higher the resolution, the more detailed statements can be derived from maps (Goodchild 2011). Increasing the extent and resolution, however, makes ES mapping usually more challenging, since less quantitative data and poorer knowledge of ecological processes are available at broader scales. Quite often, the most limiting factor affecting a map's scale is the spatial resolution of available data (Feld *et al.* 2009; Egoh *et al.* 2012; José Martínez-Harms & Balvanera 2012; Malinga *et al.* 2015). In addition, indicators are quite often defined at municipal, regional and national levels, as these scales are better situated to inform land use policy development (Malinga *et al.* 2015).

The issue of scale is a complex question in ES assessment mostly because human activity, ecosystem structures, processes, functions and services act on different scales (Grêt-Regamey *et al.* 2014; Malinga *et al.* 2015; Raudsepp-Hearne & Peterson 2016; González-García *et al.* 2020). Ecosystems' capacity to supply services may change over time, as most ES depend on specific ecological processes or/and cycles that take place over a range of temporal and spatial scales. Also, ES demand is usually dynamic, correlating, for example, with the environmental cycles (e.g. crop production), specific consumer demands (e.g. increase of certain food products during holidays) or recreation cycles (e.g. increase of leisure trips during summer). Interactions of spatial and temporal scales make mapping even more complex (Scholes *et al.* 2013; Malinga *et al.* 2015; Hein *et al.* 2016; González-García *et al.* 2020).

Thus far, studies have assessed ES at many different spatial scales; mostly at regional or national scales (José Martínez-Harms & Balvanera 2012; Burkhard *et al.* 2013; Malinga *et al.* 2015). However, how scale matters in ES assessment is still not clear enough (Scholes *et al.*, 2013; Raudsepp-Hearne & Peterson 2016). It has been recommended that development of scale-independent indicators that can be freely downscaled and upscaled from one scale to another could be useful in ES mapping (Feld *et al.* 2009; Dick *et al.* 2014). Nevertheless, the lack of such indicators could be problematic and even if such measures are available, the use of scalable indicators could introduce uncertainties when global data is downscaled or local data upscaled (e.g. Scholes *et al.* 2013; Dick *et al.* 2014). The challenges of statistical biasing effect, known as the Modifiable Area Unit Problem (MAUP), is closely related to the foregoing problem. MAUP emerges when high-resolution raster data or point-based data is aggregated to arbitrary and modifiable spatial units (e.g. districts) (Jelinski & Wu 1996). Changing the extent or resolution of the data or the criteria to divide the study area into units can greatly impact spatial analysis results (see Salmivaara *et al.* 2015). Therefore, and for these reasons, identifying the appropriate spatial and temporal scale (e.g. extent and the spatial resolution of maps and relevant temporal amplitude that allows the capture of the full extent of ecosystem service supply) is the core of a meaningful selection of indicators and precise mapping of ES (Grêt-Regamey *et al.* 2014; Raudsepp-Hearne & Peterson 2016).

1.2.1.2 Indirect measures and modeling

After all, perhaps the greatest obstacle in measuring ES is the lack of appropriate data. Many ES are challenging or even impossible to measure (Fisher *et al.* 2009; Eigenbrod *et al.* 2010; Schulp *et al.* 2014). For example, it is less straightforward to quantify people's aesthetic experiences than the amount of crop production in certain area. Most accurate way to measure ES is the use of primary data, so-called direct measurements of ES (Layke 2009b; Egoh *et al.* 2012; Kandziora *et al.* 2013; Boerema *et al.* 2017). Those measures quantify the actual state, quantity or a process of ES and are based on observations, monitoring, surveys or questionnaires (Vihervaara *et al.* 2019). However, the biggest limiting factor for using such indicators is that they become impractical and expensive especially at broader scales or they are simply not available for all ES. Some ES, such as regulating and cultural services, could be difficult to measure and need to be relied through proxy indicators (e.g. through remote sensing and Earth observation derivatives such as land cover) (Layke 2009a; Layke *et al.* 2012; Vihervaara *et al.* 2019). These limitations have often led to use of indirect measurements of ES, which are often easier to quantify and valuate. Evidently, this is one of the reasons why proxy-based maps are more commonly used than maps based on primary data (Chan *et al.* 2006; Troy & Wilson 2006; Egoh *et al.* 2008; Eigenbrod *et al.* 2010; José Martínez-Harms & Balvanera 2012; Zhao & Sander 2018).

Overall, if direct measures are not available, different modeling approaches have considerable potential to evaluate the ES themselves or underlying environmental aspects from which ES are derived (Schröter *et al.* 2015; UNEP-WCMC 2016; Dunford *et al.* 2017). There is a wide range of different modeling approaches available and several existing models that can be used for ES assessment (Burkhard *et al.* 2009; Villa *et al.* 2009; Kareiva *et al.* 2011; Sherrouse *et al.* 2011; Vihervaara *et al.* 2019). Generally, the basic idea of modeling is to simulate ES trends (e.g. supply, flow and demand) across space and time by using diverse types of input variables, usually environmental variables (e.g. species counts, tree cover, river flows) but also survey responses (e.g. interviews) or the outputs from other models (e.g. climate model) (Burkhard *et al.* 2012, 2013; Dunford *et al.* 2017). However, modeling is not easy for all ES. For example, a large number of biophysical models with a long tradition in environmental science have been used for modeling provisioning and regulating services but usability of such methods for beneficiary-oriented ES is less deliberately obvious (Dunford *et al.* 2017). Modeling the benefiting side of the cascade framework requires measures of social and cultural meanings that are more difficult to link to environmental variables. Recently, the use of participatory and citizen science approaches has proven to be a promising tool for mapping cultural ES (Brown & Fagerholm 2015; Richards & Friess 2015 Oteros-Rozas *et al.* 2018; UNEP-WCMC 2016; Vihervaara *et al.* 2019).

Despite numerous useful modeling techniques for ES assessment, this thesis will focus on statistical models, more precisely on species distribution models, to refer to the potential of ecosystems to provide certain ES or EDS. Species distribution models are often used to predict the distributions of plants and animals across space and time but also species responses to changing environmental conditions using, for example, climate and land use scenarios (Guisan & Zimmermann 2000; Guisan & Thuiller 2005; Elith & Leathwick 2009; Franklin 2010). These models can provide information about the underlying environmental systems and processes for ES assessment. In many cases, these models are useful as existing data (e.g. from monitoring networks) can be used to predict the distribution of species across scales (e.g. Elith & Leathwick 2009). There is a wide range of species distribution modeling approaches, such as regression-based techniques (e.g. generalized additive models, GAM (Hastie & Tibshirani 1990) and techniques that use machine learning (e.g. maximum entropy models, Maxent (Phillips *et al.* 2006). In general, the output of species distribution models provides the probability map of species occurrences that can be used to assess ES provisions related to these species. For example, maps of wild game or harmful species (such as ticks) distributions can be used as a proxy-indicator for the potential of an environment to produce such services or disservices.

1.2.2 Spatial characteristics of ES

The ES and EDS frameworks are anthropocentric concepts, as the ecosystems' properties and processes become a service or disservice only when they are consumed or encountered by humans (Fisher *et al.* 2009; Goldenberg *et al.* 2017). This definition requires human demand or presence and creates a flow of services from ecosystems to socio-economic systems across an area (UNEP-WCMC 2016; Syrbe & Grunewald 2017). Because there is often a spatial discrepancy between places where ES are produced and the location where people use or are exposed to them, spatially explicit units of supply and demand are needed to quantify ecosystems' benefits or nuisances to humans (Fisher *et al.* 2009; Bastian *et al.* 2012; Crossman *et al.* 2013). The spatial characteristics of ES were first introduced by Costanza (2008), who classified ES into five categories: `global non-proximal´, `local proximal´, `directional flow related´, `in-situ´ and `user movement related´. This opened the discussion for more structure-dependent indicators presented by Fisher (2009) and a few years later modified by Syrbe and Walz (2012). They defined terms that could be used to describe the spatial relationship between the place of service production and the area where the benefits are realized.

In the concept of Fisher (2009) and Syrbe and Walz (2012), the spatial units that are the source of the ES are called service providing areas (SPA). In the case of EDS, the concept of a disservice providing areas (DPA) can be used to separate it from the SPA. The SPA/DPA include entire ecosystems, their properties and conditions, that are required to deliver certain ES (or EDS) (Syrbe & Walz 2012; Burkhard *et al.*, 2014). The ES supply is commensurate with SPA (Crossman *et al.* 2013), whilst service benefiting areas (SBA) are a complement to the SPA and refer to areas where the beneficiaries receive the ES (Syrbe & Walz 2012). ES demand comes from people who want to benefit from services and it can be designated at benefiting areas (Crossman *et al.* 2013). Because in the case of EDS, for example people being exposed to nuisances instead of benefits, these areas could be referred to as disservice exposure areas. For a clearer understanding, the spatial characteristics of EDS are explained in the following section through the concept of ES.

The SPA and SBA area may be identical or overlap when the supply and demand of ES are in the same area (Figure 2A). However, quite often the ES are used at different locations and scales from where they are produced. If a benefiting area is located at a far distant from the relevant SPA, ES are delivered from provisioning to benefiting areas either passively through biophysical processes (e.g. water flow) or through human-induced processes (e.g. transport) (Villamagna *et al.* 2013; Serna-Chavez *et al.* 2014; Wolff *et al.* 2015). For example, fresh air, that is generated by open space in the surroundings may flow from the SPA to the central demand area through air flow, or vice versa, the SBA may surround a SPA (e.g. pollination or carbon sequestration) (Figure 2B-C).

Many provisioning ES, such as food, freshwater, timber or energy resources, are transported actively from the provisioning site either through the road network or other human-managed flows (e.g. artificial watercourses and pipelines) (Figure 2D). This means that providing and benefiting areas are connected to each other via a service connecting area (SCA) (see Syrbe & Walz 2012). The properties of this connecting space may influence the transfer of the service. This highlights the importance of a spatial connection (e.g. ES flow) (Syrbe & Walz 2012; Bagstad *et al.* 2013; Serna-Chavez *et al.* 2014; Wolff *et al.* 2015; Schirpke *et al.* 2019) between ES production areas and the corresponding benefit areas (beneficiaries). Regrettably, even the term `ES flow´ is ambiguous, referring either to general service provision or to the path of delivery from the providing to the benefiting areas (Bagstad *et al.* 2013; Villamagna *et al.* 2013; Schröter *et al.* 2014). In this thesis, the term *spatial flow* is used to separate it from ES flow to determine the spatial (transportation) connection between provisioning and benefiting areas (Bagstad *et al.* 2013).

In the above example, ES are transported actively to the consumption site of ES. However, the delivery of some types of ES are strictly dependent on the presence of people in the area where services are produced. Costanza (2008) has defined those services as `user movement related services´, which commonly require traveling between the areas where beneficiaries are located to the SPA. For example, to benefit from the cultural ES, such as recreation, people need to be able to reach those areas (Paracchini *et al.* 2014; Schirpke *et al.* 2019). In that case, SBA are identical or overlap the SPA because people must be in the SPA in order to benefit from the ES (Figure 2E).

Understanding how ES production is connected with beneficiaries is recognized as an important issue in the framework of ES that needs further attention. Reliable evaluation of ES requires assessment of the actual needs of human societies in relation to the service supply that is available, as well as an assessment on how people are able to reach the main demand areas through spatial flows. The pathways and processes of service flows from areas of potential supply to those of potential demand

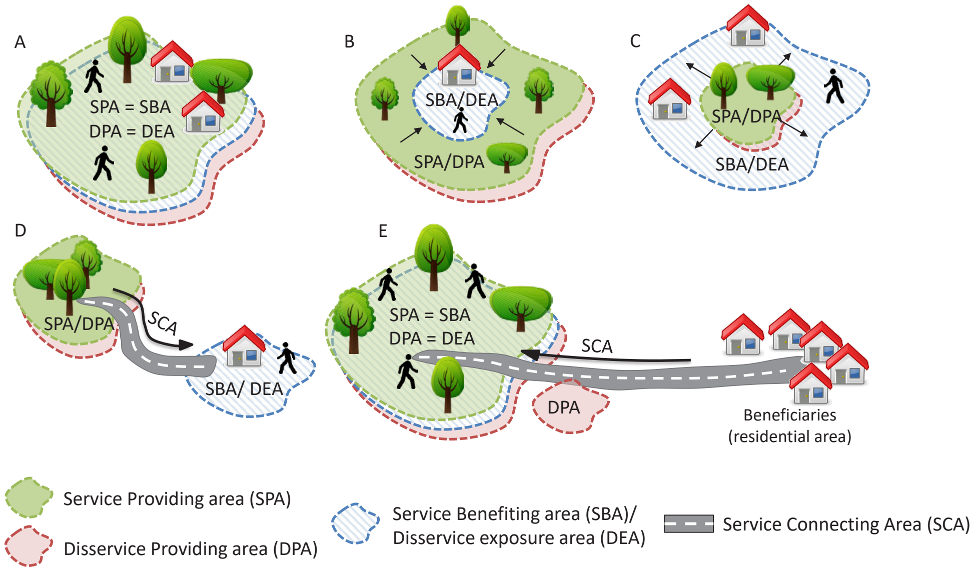


Figure 2. (A-E) The types of spatial relationship between service providing area (SPA), service benefiting area (SBA) and service connecting area (SCA) (according to Fisher *et al.* 2009 and Syrbe & Walz 2012) and concomitantly disservice providing area (DPA) and disservice exposure area (DEA) (for more details, see the text). (Images: Pixabay, CC0 license)

are essential for determining the supply-demand relationship (Crossman *et al.* 2013; Serna-Chavez *et al.* 2014; Goldenberg *et al.* 2017). Hence, maps have a high potential to respond to this requirement by illustrating and quantifying the spatial connections between ES delivery and demand (Crossman *et al.* 2013). Nevertheless, studies typically depict ES as site-bound on static maps and more attention should be paid to the tools that measure and map the transmission of services from provision to benefit areas (Bagstad *et al.* 2013).

1.2.3 Accessibility analysis for ES mapping

Spatial accessibility is a well-developed concept and serves as a common research framework within the field of transport and health geography (e.g. Gulliford & Myfanwy 2003; Luo & Wang 2003; Rodrigue *et al.* 2017), where the concept has been applied in describing, explaining, and predicting flows of people, goods, and information across space (Black 2003; Giuliano *et al.* 2015). The word `accessibility´ is derived from the words `access´ and `ability´, meaning the ability to access (El-Geneidy & Levinson 2006). Having access to ES requires that there is an adequate supply of ES available to people. According to this aspect, access to ES (or EDS) is concerned with the opportunity to obtain services (see Gulliford *et al.* 2003) and the availability of services can be determined as the potential of ecosystems to provide ES or EDS.

In the literature, many definitions of accessibility have been used depending on the goal of the study (see Geurs & Ritsema van Eck 2001 and references therein). In general, accessibility determines how easily a location can be reached from another location (Rodrigue *et al.* 2017) or the potential for reaching geographically distributed opportunities (Páez *et al.* 2012). More precisely, spatial accessibility measures the extent to which a land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) particular transport mode(s) (Geurs & Ritsema van Eck 2001). Typically, accessibility measures contain two basic components; the physical distance or cost of travel as well as quality/quantity of opportunities (Páez *et al.* 2012). In the ES context, the quality and quantity of opportunities might be translated into quality of SPA (e.g. health of ecosystems) and quantity of potential ES in the SPA (e.g. crop yield). These qualities and quantities can be deployed in a number of different ways depending on the degree of available network data, different modes of transportation, inherent differences of mobility of people (Páez *et al.* 2012) as well as available SPA and SBA data.

Measuring accessibility could be useful when ES are produced and consumed in different geographical locations. Accessibility can be measured from the perspective of the location of beneficiaries (e.g. people's opportunity to reach ES) or the potential to transport ES goods from the areas where ES are produced (supply) to areas where these ES are consumed (demand) (Figure 3). Furthermore, as the movement of people is a fundamental part of societies and people have the potential to be exposed to EDS when they move across different environments, the accessibility approach can also be used in the framework of EDS. Overall, accessibility can provide a promising tool to recognize the spatial flow between ES providing and benefiting areas as ES or EDS exist only if there is some kind of transfer of services to a beneficiary. If people are unable to access the SPA, there is no actual use of services (Science for Environment Policy 2015). Furthermore, people's ability to reach or utilize ES is a key aspect, for example, when evaluating the sustainable use of natural resources.

As said, human welfare is indisputably dependent on the availability of ES. In order for people to be able to utilize different ES, more attention has to be paid both to the spatial distribution of ecosystems which provide services and accessibility properties, such as infrastructure (de Groot *et al.* 2010; Crossman *et al.* 2013; Paracchini *et al.* 2014; Martínez Pastur *et al.* 2016), but also on the spatial structure of a population and its ability to utilize such services. A study by Paracchini *et al.* (2014) suggested that accessibility through roads and related traveling time is one of the approaches to study the accessibility of ES. Additionally, Syrbe and Walz (2012) have proposed that network analyses of roads give insight into the accessibility of SPA and have several utilizations for evaluating SBA. Improvements in GIS (Geographic Information System) capacity for data management, and the availability of a range of spatial datasets, has opened up new opportunities for modeling accessibility (Brabyn & Sutton 2013), increasing the applicability of GIS models also in ES and EDS mapping (see Heino *et al.* 2017). Despite the fact that accessibility

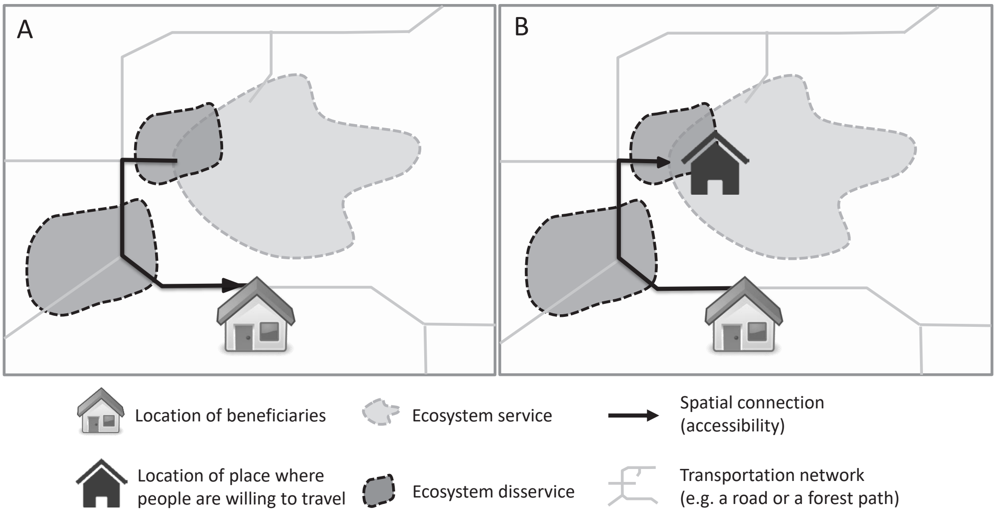


Figure 3. A schematic presentation of the spatial relationships between areas that produce ecosystem services (ES) or disservices (EDS) and where beneficiaries are located. (A) Describes a situation in which the transportation network connects providing and benefiting areas and delivers goods and services from ES-providing areas to benefiting areas (the arrows illustrate the direction of the movement of, e.g. food products). In this case, ES-providing and benefiting areas may be distant from each other. This simplified figure does not illustrate the multiple nodes and paths which several marketable ES, such as food products, are transported through before reaching the final consumer. (B) Describes the 'user movement related ecosystem services' such as recreation, where people must travel to the area providing ES in order to benefit from the ES. Accessibility describes the beneficiaries' possibility to utilize ES via a road network. In addition, subfigures A and B illustrate a potential EDS which people might be exposed to when traveling between different locations. (Images: Pixabay, CC0 license)

has been an important explanatory factor in a multitude of geographic phenomena for decades (Kwan 1998), it is still rarely used in the spatial assessment of ES and EDS. So far, only relatively few studies have been paid attention to the role of the accessibility between SPA and SBA (see the recent studies e.g. of Schirpke *et al.* 2018; Fu *et al.* 2020), hindering the possibility to indicate how well people can actually benefit from ES. It is evident that poor spatial accessibility reduces the use of ES.

There is a wide range of methodologies that can be used to measure the accessibility of transport systems (Kwan 1998; Páez *et al.* 2012). For example, least-cost path (also called shortest path) analysis has a direct relevance for understanding accessibility of `user movement related ES´. It measures the shortest distance or time between population location and ES opportunities along the road network (Brabyn & Sutton 2013; Chang 2019). The analysis provides easily understandable assessment of the relationship where people live and ES opportunities are available for them, also giving information about the spatial link between ES providing and benefiting areas. However, the nearest service is not necessarily the one that is actually used and the attractiveness of sites could affect people's willingness to reach services.

The gravity model is a highly practical formulation determining spatial interaction. It assumes that the attraction of a site is comparable to size (or some other attribute) and again decreases with increase in distance, travel time, or cost in a gravitational way (Haynes 2003; Rodrigue *et al.* 2017). In the ES framework, this could be understood in a way that some SPA may attract or serve more individuals than another SPA with the same distance, time or cost. On the other hand, increasing distance, cost or travel time could make each destination progressively less attractive. This means that some locations are more accessible than others as there are differences, for example, between cost of travel and attractiveness between locations (Rodrigue *et al.* 2017).

The two-step floating catchment area method (2SFCA), first proposed by Radke and Mu (2000) and later modified by Luo and Wang (2003), is a special case of a gravity model. The method takes into consideration not only the volume of ES provided relative to the size of demand but the proximity of the provided ES relative to the location of the demand. In other words, a large supply located spatially near to demand does not automatically equate to satisfied demand. Correspondingly, close proximity may not ensure good accessibility due to competing demand for an available ES (McGrail & Humphreys 2009). This kind of GIS-based spatial accessibility analysis can provide a promising approach to evaluate the spatial flow between provisioning and benefiting areas. Dunford *et al.* (2017) have highlighted that there is a need to develop models that account for service-specific flows, instead of just identifying in situ supply-demand mismatches. Thus, accessibility approaches have potential to receive more exact and useful information on the balance or mismatch of ES delivery (i.e. production capacity) and demand compared with more simple approaches, such as overlay analysis which can lead to over-simplification, inaccuracies and misunderstandings in ES mapping (Bagstad *et al.* 2013).

2 Aims of this thesis

The central focus of this thesis was to introduce the accessibility analysis in ES and EDS mapping using three different sets of ecosystem service and disservice indicators across national and continental scales (papers I–III). With the help of these datasets the aim of the thesis was to explore people's ability to utilize different ES and estimate the negative impacts EDS can cause to people. By relating and testing the potential of the GIS-based accessibility method to map the spatial flow between ES, ESD and people, the purpose of this thesis was to develop a new and efficient way to assess the potential use of ES and exposure risk to EDS. The main objective was to investigate *how well spatial accessibility analysis is suited for ecosystem service and disservice mapping* in three separate studies addressing the following general research questions, which are elaborated below:

Q1 Could the GIS-based accessibility approach offer a robust and informative way to measure the potential usability of `user movement related ES´? (Paper I)

Q2 How can the transport network-based accessibility method be applied to assess the spatial flow between supply and demand at a continental scale? (Paper II)

Q3 Can we use the GIS-based accessibility approach in evaluating the exposure risk to ecosystem disservice at the national scale as well? (Paper III)

The main target of Paper I was to study how well people can reach areas that produce different cultural ES in Finland (Figure 4). Cultural heritage and outdoor recreation were selected to represent the cultural ES that people need actively to reach in order to benefit from them. GIS-based least-cost path accessibility analysis was used to measure the spatial flow between residential areas and the nearest SPA along a road network to indicate people's ability to utilize studied ES opportunities. With the help of the accessibility approach, it was possible to evaluate where people have limited possibilities to reach ES within a reasonable travel time. In addition, accessibility analysis gives an overview of the spatial distribution of cultural ES and number of potential users of these services indicating the human pressure of each service.

In Paper II, the spatial scale was extended to Europe, where the spatial flow from the areas which produce ES to areas where beneficiaries are located were analyzed. Food ES, more precisely crops, were used as an example of ES where transportation is required to satisfy demand. This paper utilizes GIS-based spatial network accessibility analysis (enhanced two-step floating catchment area) to determine the potential to transport crop products from the ES providing areas to areas where these ES are consumed along a road network. The aim of this paper was to estimate hypothetically how well supply is able to satisfy the demand of crop products nationally and continentally. In this study, 250, 500 and 1000 km distance thresholds were used in the analysis to explore how far crop products need to be transported to balance demand.

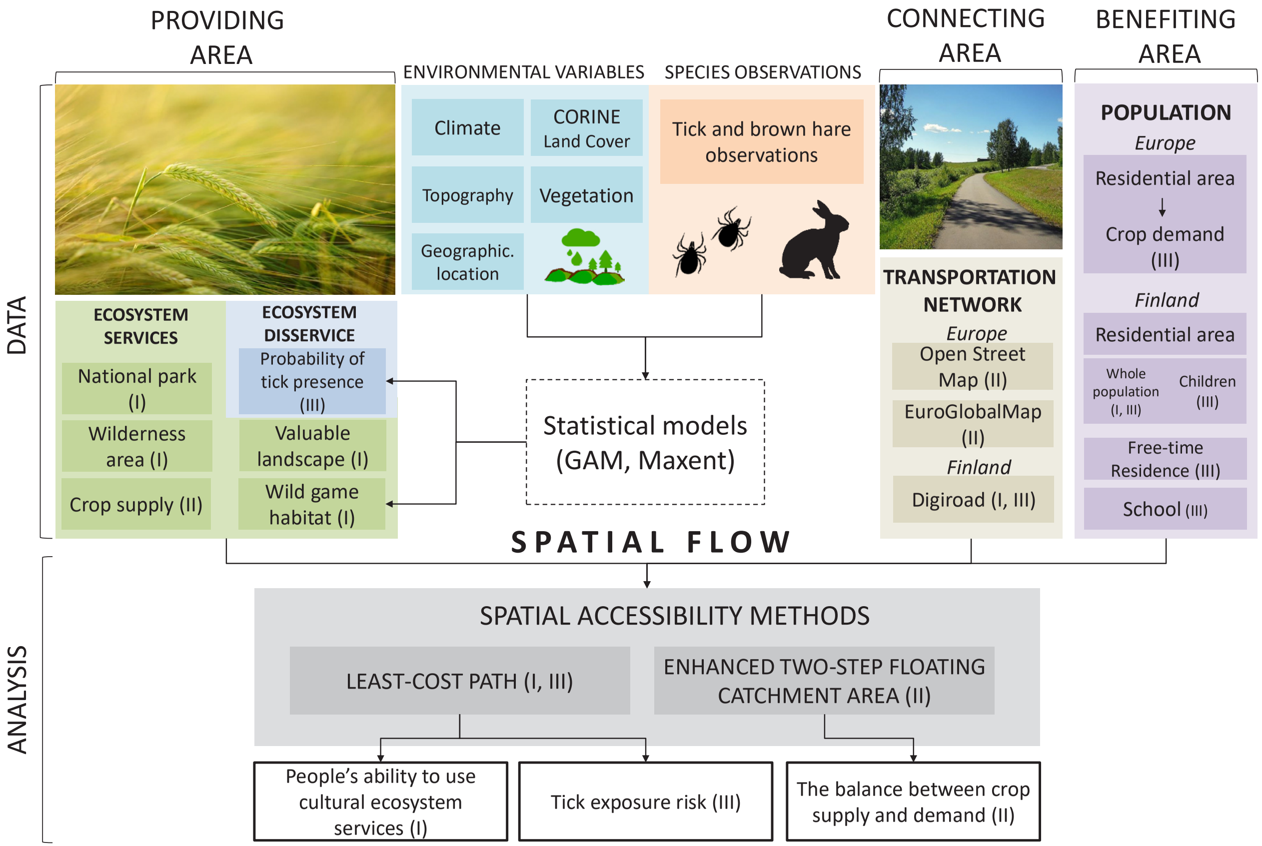


Figure 4. A schematic summary of the study design including the used datasets of ecosystem services and disservice, transportation networks and population. Statistical models (generalized additive models, GAM and maximum entropy models, Maxent) were used to predict the potential distribution of ticks and brown hare (wild game habitats) in Finland. The Geographic Information System-based least-cost path and enhanced two-step floating catchment area analyses were used to measure the spatial accessibility (spatial flow through service connecting area) between service (or disservice) providing areas and benefiting (or exposure) areas. Roman numerals refer to the study papers. (Images: Pixabay, CC0 license)

In Paper III, the accessibility method was applied from the opposite perspective. In papers I and II, the method was tested from the beneficial point of view, but in Paper III the method was tested in assessing the negative impacts of ecosystems on human health. In this paper, the central focus was to evaluate what kind of potential threat EDS, namely ticks (genus *Ixodes*), pose to people in Finland. This was conducted by modeling the probability of tick presence in Finland based on tick observations and environmental variables and relating the probability map of tick presence to the residential areas and free-time residences. Then the applicability of spatial accessibility analysis was tested by calculating if the movement of people (here school children) in the everyday environment increased tick exposure risk.

3 Study areas

Three different study areas were used in this thesis (Figure 5). Papers I and III test accessibility of ES and EDS at the national level. Both national studies were situated in Finland, which is a country located in northern Europe bordering Sweden, Norway, Russia and the Baltic Sea (19°–31°E, 60°–70°N). Paper II tests the accessibility approach at a continental level, covering altogether 31 European countries (Figure 5).

3.1 Finland

Studies I and III were located in Finland (Figure 5). Paper I covered the whole country. In Paper III, the study area ranged from the southern parts of the country to the northernmost

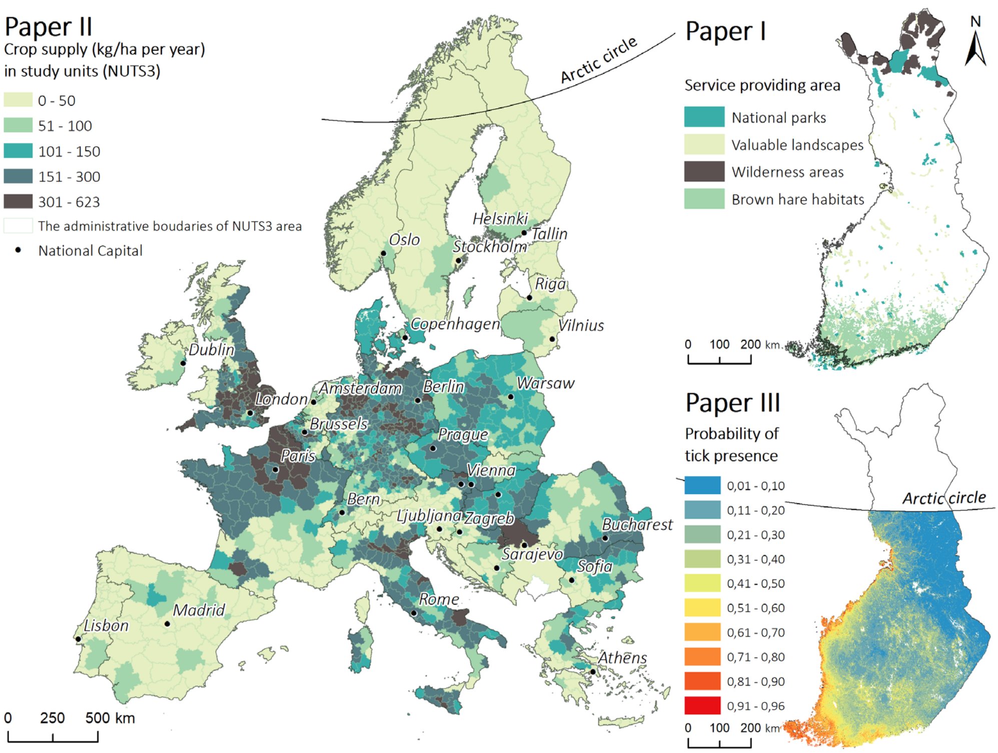


Figure. 5. Potential of ecosystems to provide different ecosystem services and disservice in thesis study areas. Paper I: Location of the studied cultural ecosystem service providing areas in Finland. Paper II: Graduated colors indicated how much crop ecosystem services (kg/ha per year) are provided in each study unit (NUTS 3 areas). Paper III: indicates the probability value (ranging between 0 and 1) of tick presence at 1-km^2 resolution in the study area. The northern part of the country was excluded based on the northernmost tick observations. (Data: Finnish Environment Institute, Natural Resources Institute Finland, European Environment Agency, FAOSTATS, ArcGIS 2014)

tick observation. Finland belongs to the boreal vegetation zone characterized by landscapes dominated by coniferous forests. A majority of Finland has an elevation of less than 200 m, with the highest peaks found in the far north. The annual average temperature ranges from –2 °C in the northern parts of the country to +6 °C in southern parts (Pirinen *et al.* 2012). Finland is relatively sparsely populated and a significant proportion of its 5.5 million inhabitants live in urban settlements in southern parts of the country around major cities and river networks (Official Statistics of Finland 2019a).

Finland has an extensive road network with a total length of nearly 450,000 km (Finnish Transport Agency 2019), which enables good possibilities for passenger mobility throughout the country. Finnish daily traffic consists primarily of private cars, but walking and cycling are also popular. Finns made approximately two trips per day (41 km in total), of which at least one is related to leisure. About 30% of trips are made on foot or by bicycle (Finnish Transport Agency 2010-2011). Concomitantly, Finland is an exceptional country where children typically walk or bicycle to school when the distance between home and school is less than five kilometers.

Nearly all Finns enthusiastically recreate in outdoor environments near their home or free-time residence and most of these trips are made by foot. People have identified especially water and forest areas as attractive environments (Sievänen & Neuvonen 2011). Finns have a good opportunity to enjoy these environments, as `the country of thousands of lakes´ and forest covering three fourths of the land area (Natural Resources Institute Finland, 2019; Official Statistics of Finland, 2019b) provides people a relatively high level of recreation potential fairly homogenously throughout the country, even in the densely populated areas. Thus, nearly 90% of recreational use of nearby nature is directed to forested environments (Sievänen & Neuvonen 2011). However, forest and water environments are identified as significant areas for tick encounters (Cayol *et al.* 2018; Sormunen 2018). This increases the risk of encountering infectious ticks in the everyday environment, especially if people are walking from one place to another across different environments. Moreover, the use of free-time residences takes place especially during spring and summertime (Sievänen & Neuvonen 2011) when ticks have their seasonal activity peaks (Laaksonen *et al.* 2017; Sormunen *et al.* 2020), increasing the possibility of tick contacts in those areas in Finland.

Ticks are the primary vectors of several dangerous diseases (e.g. Lyme borreliosis, LB or tick-borne encephalitis, TBE), which pose danger to people. In Finland, the abundance of two important tick species (*Ixodes ricinus and I. persulcatus*) have increased and their geographical distribution has expanded significantly during the past few decades (Feuth 2017; Laaksonen *et al.* 2017). Tick densities and tick-born pathogen prevalence is reported to increase especially in coastal areas in south-western Finland, but also within and around urban and suburban areas such as urban city parks, yards and vegetation-flanked walkways (Sormunen 2018). Laaksonen *et al.* (2017) found that 16.9% of *I. ricinus* and *I. persulcatus* ticks were positive for *B. burgdorferi* s.l., and 1.6% were positive for TBE. People can come into contact with infected ticks even in urban environments not populated with suitable tick host animals like deer or moose (Junttila *et al.* 1999). However, a recent study by Klemola *et al.* (2019) reported that a relatively high abundance of ticks in the urban environment indicates a dense presence of tick hosts like avian hosts in the city. Hence, urban ticks may potentially form a larger threat to human welfare in Finland than previously thought (Cayol *et al.* 2018; Lohr *et al.* 2015; Sormunen 2018).

3.2 Europe

The study area consists all European Union (EU) countries for which the availability of food statistics was relatively good (Figure 5). Only Malta, Cyprus and overseas territories were excluded from the study. To supplement the study area, non-EU countries Switzerland, Norway, Bosnia and Herzegovina, Montenegro and Serbia were also included. The analytical resolution of Paper II was the administrative boundaries of the NUTS3 area (Nomenclature of Territorial Units for Statistics, n=1379) (Eurostat 2016a). These boundaries were selected for the analysis because they correspond well to counties, being an appropriate discrete unit of data for continental-scale analysis. Moreover, the NUTS3 administrative boundaries corresponds well with the accuracy at which beneficiaries receive the service (Raudsepp-Hearne *et al.* 2010; Walz *et al.* 2017).

4 Materials and methods

4.1 Ecosystem service and disservice indicators

The term `indicator´ is used in this thesis in a broad sense to mean quantitative proxies for ES and EDS. In this dissertation, outdoor recreation and cultural heritage were selected to represent the cultural ES (I), crops to represent the provisioning ES (II) and tick distribution to represent the health-related EDS (III). The selected indicators describe either the ecosystem's potential to provide services and disservices or the supply of ES (Figure 6). The classifications of the studied ES and EDS are based on CICES (Haines-Young & Potschin 2018) and Vaz *et al.* (2017) (see Chapters 1.1 and 1.1.1 and Figure 1).

In Paper I, areas which have a clear potential recreation status or natural state were used to represent outdoor recreation sites. Recreation areas (national parks, wilderness areas and wild game habitats) and cultural heritage (nationally valuable landscapes) represent the SPA which was defined as spatial units that have recreational or cultural heritage potential for people. The experience of ES provided by these SPA clearly depends on the flow of people and accessibility is an important component for assessing such ES (Costanza 2008; De Groot *et al.* 2010; Crossman *et al.* 2013; Paracchini *et al.* 2014). Hence, the transportation network represents the service connecting area (SCA) between the SPA and SBA. In the case of cultural services, the providing and benefiting areas are overlapping and the connecting area enables people to move from the area where beneficiaries are located to the area where service is provided. In some cases, the SPA, SBA and the residential area can be situated at the same location.

In Paper II, crops were selected as an example of provisioning ES as the availability of food statistics was relatively good from the whole study area. The arable land areas from Corine Land Cover (European Environment Agency 2000, 2006) describe potential to provide an ES and represent SPA in this thesis. Harvested crop yield (crop production) defines the supply of provisioning ES in SPA. SBA are delineated in areas where beneficiaries are located and the food consumption has been selected to describe the demand in these sites. Burkhard *et al.* (2012) have defined supply as "a capacity of a particular area to provide ES within a given time" (where the 'capacity' refers to an actually used set of natural services) and demand as "the sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period." The ES are benefitted from in residential areas and ES are transported from the SPA to the SBA through a transportation network (SCA).

Respectively, in Paper III, the spatial distribution of ticks (*Ixodes ricinus* and *I. persulcatus*) were used as an example of EDS as it have possibility to cause negative impacts on human health. The tick distribution map represents the potential of ecosystems to provide disservices. The exposure risk to ticks includes the dynamic role of humans and for this reason it is categorized as EDS (see Figure 1). The DPA is situated in the environment that produce EDS (Figure 6). The nature of EDS is slightly different

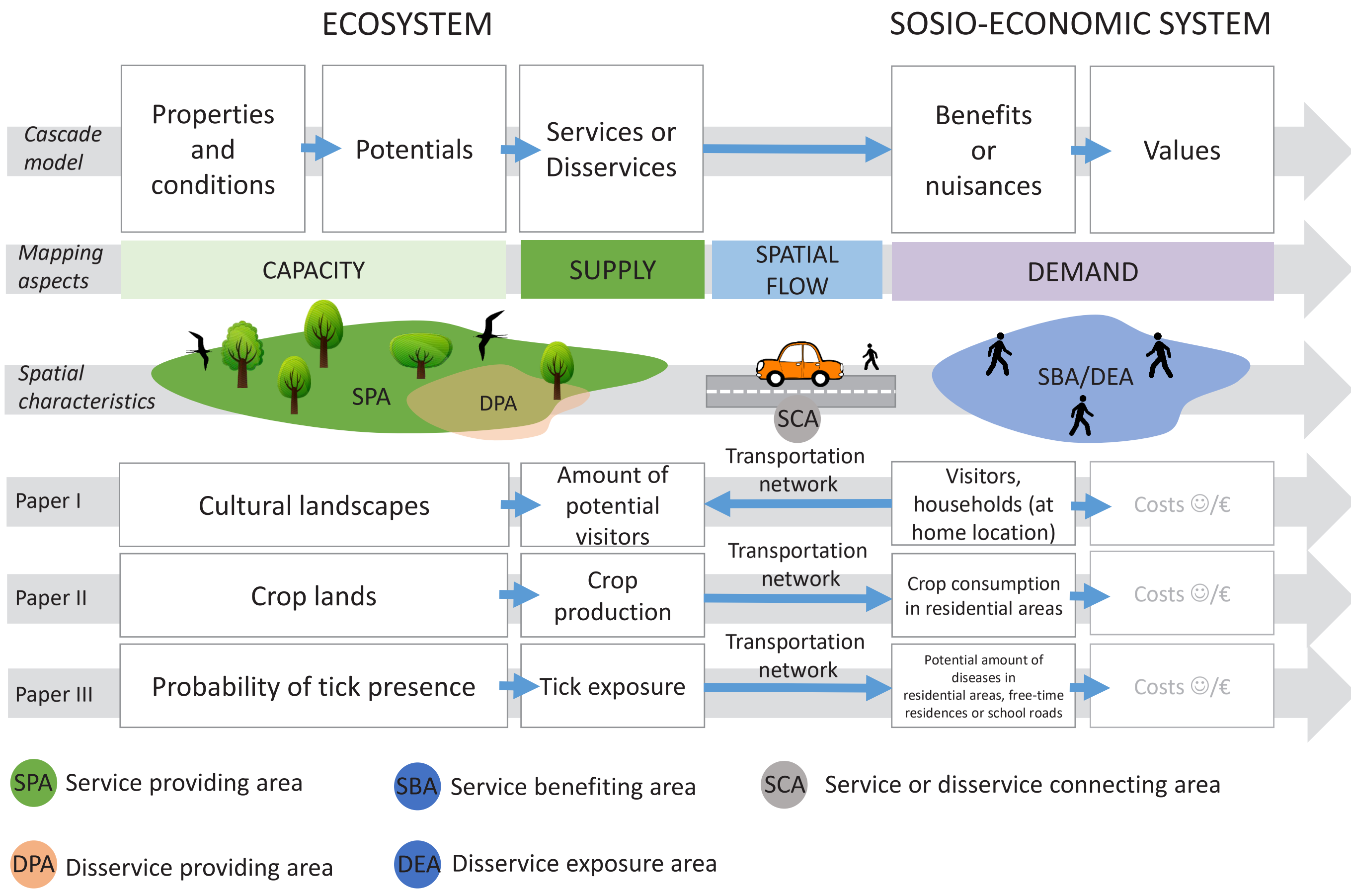


Figure 6. A schematic presentation of the used ES and EDS indicators' (Papers I–III) relationship to the Cascade Model, mapping aspects and spatial characteristics of ES and EDS. Light grey boxes have not been measured in this thesis. (Images: Pixabay, CC0 license)

as exposures to nuisances are distinguished in residential areas, around free-time residences or within the way from home to school along a road network (SCA). Hence, the disservice exposure areas are located either in the providing area, connecting area or in the residential area.

4.1.1 Cultural ES

National parks and wilderness areas. For recreation purposes, natural ecosystems have an important role as places where people can go to refresh themselves (De Groot *et al.* 2002). National parks and wilderness areas were used to demonstrate the applicability of accessibility analysis in ES research. The used GIS data (managed by the Finnish Environment Institute) contains 35 national parks and 30 wilderness areas. The size of national parks varies between 6.7 to 2859 km^2 and wilderness areas between 0.0005 to 2956 km^2.

Nationally valuable landscapes can represent cultural heritage as being a landscape with high historical or cultural value deemed worthy of maintenance (de Groot *et al.* 2010; Hernández-Morcillo *et al.* 2013). These valuable landscapes were officially inventoried in Finland in 1995 based on their regional variations in natural and cultural characteristics. The used GIS data on nationally valuable cultural environments (managed by the Finnish Environment Institute) consists of data layers on traditional architecture, culturally valuable natural diversity and cultivated agricultural landscape polygons (n = 156 in total, the size of the areas varies between 0.005 and 4 km^2).

Wild game habitats could nowadays provide recreational activities or cultural traditions for hunters (de Groot *et al.* 2002; MA 2005). In Finland, approximately 300,000 persons obtain a permit to hunt annually. This amount is high in relation to overall population size, compared to other parts of Europe. Most hunters hunted at least once during the hunting season and nearly all of them hunted small game. The most important small game mammals are mountain hares (*Lepus timidus*), raccoon dogs (*Nyctereutes procyonoides*) and brown hares (*Lepus europaeus*) (Official Statistics of Finland 2013; The Finnish Wildlife Agency 2014). In this thesis, the brown hare was used as an indicator for wild game. Due to a lack of data on leased hunting areas, the potential hunting areas for brown hare were modeled on a national scale by using game triangle (n=1132) information (Lindén *et al.* 1996) and different environmental variables (climate, topography, geographical location and land cover, see Table 1). The modeling was carried out by using generalized additive models (GAM) (Hastie & Tibshirani 1990). The modeling was performed in R with the mgcv package (R Development Core Team 2011). On the basis of the predicted brown hare distribution, probability values ≥ 0.5 were selected to represent an abundant occurrence of wild game in Finland. Based on these predicted distributions, national parks and settlements were removed to better describe those areas in which hunting is possible.

Table 1. List of environmental variables used in modeling the distribution of brown hares (Paper I) and ticks (Paper III) in Finland. The variables used in each paper are marked with an X in the table. The bold underlined X represents the variables selected in the final models.

Environmental variables	Unit	Original resolution	Time	Source	Model resolution	Paper I	Paper III
Topography							
Elevation (std, mean)	m	25 m	-	DEM	1-km^2	X	X
Topographical wetness index (mean)	-	25 m	-	DEM	1-km^2		**X**
Radiation (mean)	kj/cm^2/a	25 m	-	DEM	1-km^2		X
Slope angle (std)	%	25 m	-	DEM	1-km^2	X	
Climate							
Growing degree days (>5°C)	GDD	1 km	1980-2010	FMI	1-km^2	**X**	X
Mean temperature	°C	1 km	1980-2010	FMI	1-km^2		**X**
Annual precipitation	mm/a	1 km	1980-2010	FMI	1-km^2		X
Water balance	mm year -1	1 km	1980-2010	FMI	1-km^2	X	
Geographical location							
X-coordinate	-	-	-	-	1-km^2	X	X
Y-coordinate	-	-	-	-	1-km^2		**X**
Vegetation							
EVI, Enhanced vegetation index (mean)	-	250 m	2010-2015	NASA (TERRA/ MODIS)	1-km^2		X
Land cover							
Built-up area	m^2	25 m	2006	CORINE	1-km^2	X	
Coniferous forest	m^2; %/km^2	25 m; 20 m	2006; 2012	CORINE	1-km^2	X	X
Deciduous forest	m^2; %/km^2	25 m; 20 m	2006; 2012	CORINE	1-km^2	X	**X**
Mixed forest	m^2; %/km^2	25 m; 20 m	2006; 2012	CORINE	1-km^2	X	X
Cultivated field	m^2; %/km^2	25 m; 20 m	2006; 2012	CORINE	1-km^2	**X**	X
Shoreline	m/km^2	20 m	2012	CORINE	1-km^2		**X**
Wetland	m^2; %/km^2	25 m; 20 m	2006; 2012	CORINE	1-km^2	X	X
Water	m^2	25 m; 20 m	2006	CORINE	1-km^2	X	

Abbreviations: FMI, Finnish Meteorological Institute; DEM, Digital Elevation Model; NASA, TERRA/ MODIS satellite image; CORINE, CORINE land cover classification. *Year 2006 land cover information was used in Paper I and a year 2012 data in Paper III. The unit of 2006 data was m^2 and resolution of original data was 25 m. The unit of year 2012 was % / km^2 and resolution 20 m. All environmental variables were aggregated at a resolution of 1 km^2 for brown hare and tick distribution modeling.

4.1.2 Provisioning ES

Crop supply was mapped according to the capacity of cultivated fields to provide a food service (see Schröter *et al.* 2014). The location of arable land areas across Europe was obtained from the Corine Land Cover (CLC) 2000 and 2006 seamless vector data (European Environment Agency 2000, 2006) in which the information about the crop yield (kg per country per year) based on FAOSTAT's Food Balance Sheets was combined. All cereals except rice were included in the annual crop yield. In addition, only crop yield for human consumption was included in the analysis, as the majority of the crop yield is used as animal feed and by industry in general. In the calculations, food waste (lost during the food supply chain) was taken into consideration. The total loss of cereals considering all food supply chain stages is approximately 30% in Europe (FAO 2011). Finally, all ES providing areas, SPA (supply location), were re-set to the centroid of the largest cultivated area (based on the information on Corine Land Cover) within each NUTS3 area. The mapping and assessment of the budget of ES undersupply, neutral balance or oversupply are made in the same units of measure (kg per NUTS3 area in a year) as recommended by Burkhard *et al.* (2012), Kroll *et al.* (2012), Syrbe & Walz (2012) and Baró *et al.* (2015).

4.1.3 Ecosystem disservice (EDS)

Tick distribution was modeled in this thesis using Maxent (maximum entropy model), which was developed for species distribution modeling based on presence-only data (Phillips *et al.* 2006). Maxent models were built using 777 individual tick observations and ecologically relevant environmental variables (Jaenson *et al.* 2009; Gilbert 2010; Del Fabbro *et al.* 2015; Feuth 2017), which consisted of CORINE land cover data (year 2012 at 20-m resolution), climate characteristics (mean for 1980–2010 at 1-km^2 resolution), topographic factors (25-m resolution), and productivity variables (250-m resolution) (Table 1). The tick observations were obtained from crowdsourcing-based, nation-wide tick collection for 2014 carried out by the University of Turku (ArcGIS 2014; Laaksonen *et al.* 2017). For modeling purposes, observations were converted to grid cells of 1-km^2 to correspond to the resolution of environmental variables. Modeling of tick distribution was carried out with the Maxent 3.3.3k version. As an output, Maxent gives tick probability values on a continuous scale ranging between 0 and 1, where 1 indicates a high probability of species presence.

4.2 Transport network data

The GIS data of the transportation network (SCA) in Paper I and III was obtained from the Digiroad, which is the most comprehensive road dataset in Finland (Finnish Transport Agency 2019). The Digiroad database includes information on the geometry of the transport network and traffic-related attribute data, such as road types and speed limits (Finnish Transport Agency 2014, 2016). The speed limit information is available inclusively for primary and secondary roads as well as for streets. In Paper I, a travel time from home to the nearest SPA by private car was estimated using Digiroad for the year 2012 (Finnish Transport Agency 2014). The information about speed limit estimates was added for local low-class road segments which have no speed limit information available. An approximate speed of 30 km/h was used in developed environments and 50 km/h for roads outside of built-up areas. In addition, the effect of turning on travel times was estimated by applying time penalties of 24 seconds for left turns and 12 seconds for right turns (Spurr 2005). A few connections in the road network rely on scheduled ferry connections. To include areas connected by ferry links in the analysis, the travel speed of road ferry links was estimated at 20 km/h, except in the case of a few cable ferries for which the speed estimate was 10 km/h, and a time penalty of 15 minutes was included in the cost of ferry travel in order to take the waiting time into account (Kotavaara *et al.* 2012, 2017).

In Paper III, the shortest route from home to school was estimated by using Digiroad for the year 2016 (Finnish Transport Agency 2016). The data was modified according to the same principles as in Paper I for sections of the road network missing information on speed limits. In addition, to direct the analysis to calculate the shortest route along walking and cycling tracks, 25% of the travel cost estimate for regional roads and local main streets was added. As children typically walk or bicycle to school in Finland, calculations were made more realistic by removing road types such as motorways, carriageways, slip roads and ferries from the analysis. Only routes less than five kilometers were considered in analysis.

In Paper II, the transport accessibility components of a spatial flow of ES from SPA to SBA was quantified using open-source and publicly available road and ferry network data in standard GIS-based formats. The majority of the road and ferry network data was derived from EuroGlobalMap (EGM) (2016), which is a topographic dataset of 1:1 million scale containing information on roads and railways, ferry lines and airports. It covers 45 countries and territories across the European region. Despite its extensive coverage, EGM data did not cover the entire study area. In the case of Bosnia-Herzegovina and Montenegro, the network data of Open Street Map (OSM) (OSM 2016) was used to supplement the EGM. The topology errors of OSM were corrected manually. To explore how barriers such as state borders potentially affect food ES delivery, both a single free trade area and an area where food delivery is restricted to nation borders were considered in the study. The national boundaries of NUTS3 data (Eurostat 2016a) were used to produce national road networks for the analysis where borders are considered. The effects of national borders as a creator of barriers to the free flow of goods were detected in the study by Chen (2004). Also, Salas-Olmedo *et al.* (2016) have recommended considering the growing role of borders in international trade in accessibility studies.

4.3 The population data

The information about the location of ES beneficiaries and people potentially exposed to EDS was obtained from Statistics Finland's population grid cell database for the year 2011 (Official Statistics of Finland 2011) in Paper I and for 2015 in Paper III (Official Statistics of Finland 2015a). These databases are raster layers of 250 × 250 m resolution representing the number of inhabitants per grid cell. The population data is based on a national register that contains basic information about inhabitants in Finland and is free of estimation-related uncertainties, giving an opportunity to observe phenomena in different areas independently of administrative boundaries. Because a large number of original grid cells (approximately 325,000 in Paper I) constituted a computational challenge for route solving when using desktop GIS, the data was aggregated at a resolution of 2 × 2 km to prepare population data applicable for accessibility analysis (42,629 populated grid cells in total). Populated grid cells, relying on unscheduled coastal and inland maritime water transports, were omitted from the analysis as well as the settlements which are located more than 5 km from the closest point along the road network.

The population data in Paper III was aggregated at a resolution of 1-km^2 to correspond to the resolution of the modeled tick distribution. Tick exposure risk was calculated separately for the entire population, and grid cells including information only on children between 7 and 14 years of age, by comparing these areas with the tick probability map. In addition to residential areas, the nature of the tick threat to people around free-time residences was also investigated by a resolution of 1-km^2 using the above-mentioned method. The locations of free-time residences across Finland were obtained from Statistics Finland (Official Statistics of Finland 2015b) and also aggregated to the resolution of 1-km^2. For the accessibility analysis, the residential pattern of the children between 7 and 14 years of age was selected to represent the points of origin for travel to school. The resolution of residential locations of children was 250 x 250 m. The centroids of each grid cell were used as the spatial reference of origins during accessibility analysis. The locations of the schools (destinations) have been obtained from Official Statistics of Finland (2015c).

In Paper II, the population data of Europe was used to indicate the amount of crop demand together with the European Food Safety Authority's (EFSA) survey of food consumption (EFSA 2011). In most of the research area, the population data is based on a grid cell database at the resolution of 1x1 km for the year 2011 (Eurostat 2016b). The population information for Serbia and Bosnia and Herzegovina was compiled from the ArcGIS ESRI (2016) database. The population grid databases are used to indicate the population centroids of each NUTS3 area. The most densely populated grid from each NUTS3 area was selected to represent a location of demand (destinations) in the accessibility analysis. Information about the total population of a NUTS3 area was then aggregated to the population centroids. The Comprehensive Food Consumption Database (EFSA 2011) is a survey data of 16 countries in the EU between 1997 and 2008. The survey statistics on food consumption are based on 20 main food categories of which grain and grain-based products were selected to represent food consumption in this thesis. Consumption rate is reported in grams per day for different age classes (infants, toddlers, other children and adolescents, adults, elderly and very elderly). Only the food consumption of the adult population was available for all 16 countries surveyed. For this reason, the demand was measured in this thesis by calculating the average consumption per adult (18–64 years of age). Average values from the data of the 16 surveyed countries was used to indicate food consumption for the 15 European countries that had no consumption information available. To measure supply and demand with similar and comparable units, the consumption was calculated as amount of food consumed (kg per year) per each NUTS3 area.

4.4 Geographic Information System-based accessibility methods

The accessibility calculations in Paper I and III are based on the network analysis which determines the closest facility between origin and destination (Figure 7). The network analysis requires vector-based and topologically valid network data (Chang 2019). In this thesis, the Finnish digital road network database (Digiroad), EuroGlobalMap and Open Street Map were used as they include accurate road geometry and attribute data such as link impedance, nodes, turns and restrictions. A link (also called edges or arcs) refers to a road segment between two end points and link impedance determines the cost of traversing a link (physical length or travel time). A node (also called a vertex or junction) refers to intersections between road segments and turn impedance, the time of transition from one road segment to another. Restrictions refers to routing requirements (e.g. one-way or closed roads) on a network (Chang 2019) (Figure 7).

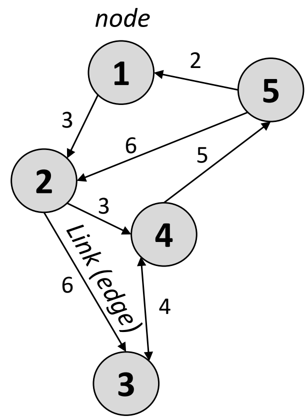
Together with origin (e.g. population data) and travel destination data (e.g. SPA and school locations), the road network can be analytically considered as either a graph or a weighted graph (a graph that has one or more real numbers associated with each edge) when some attributes are added to the vertices connecting nodes (see Miller & Shaw 2001) (Figure 7). A graph represents the structure of the network and reveals its connectivity (Rodrigue *et al.* 2017). The shortest or fastest road (least-cost) between the origin and destination can be calculated in a GIS, when the spatial data of travel speed and time, or other relevant travel cost estimates, for the graph model of a road network are available. In this thesis, the least-cost path is based on a non-planar graph, since there is a possibility of links (edges) `passing over´ others (Miller & Shaw 2001; Rodrigue *et al.* 2017). The least-cost path was calculated using the closest facility ArcGIS Network Analyst extension in ArcGIS desktop 10.2 and 10.6. The extension uses a multiple-origin and multiple-destination algorithm based on Dijkstra’s (1959) algorithm and its heuristic applications (ESRI 2010). In practice, the analysis finds the closest facility among candidate facilities to any location on a network. At first, the analysis computes the shortest paths from the select location to all candidate facilities, and then chooses the closest facility among the

A

i \ j	1	2	3	4	5
1	-	3	-	-	-
2	-	-	6	3	-
3	-	-	-	4	-
4	-	-	4	-	5
5	2	6	-	-	-

B

From-node	To-node	Shortest path	Minimun cumulative impedance
1	2	1⇨2	3
1	3	1⇨2⇨3	9
1	4	1⇨2⇨4	6
1	5	1⇨2⇨4⇨5	11



GRAPH REPRESENTATION

Figure 7. Basic graph representation of a transport network where nodes and links represent the structure of a network. The direction of the movement between nodes is represented as an arrow. (A) The impedance matrix among five nodes, where i refers to an origin, j destination, and − means no direct connection. (B) The summary of shortest path from node 1 to all other nodes.

candidates. In Paper I and III, the centroids of the population grid cells were used as a spatial reference of origins for the grid cells during accessibility analysis. In Paper I, the intersection points of the road network and SPA represent the destinations. In those cases where SPA cannot be reached directly by car (e.g. if the road network does not intersect SPA), a road network less than 500 m from the SPA is considered to be reachable in practice. In Paper III the location of comprehensive schools represents the destinations.

In Paper II, the potential to transport crop products from the areas where they are produced (supply) to areas where these ES are consumed (demand) was calculated based on the enhanced two-step floating catchment area (E2SFCA) method (Figure 8) with the ESRI ArcGIS Desktop 10.6 and USWFCA (Enhanced Two-Step Floating Catchment Area Accessibility Add-In tool) (Langford *et al.* 2014). The two-step floating catchment area (2SFCA) techniques are mostly applied in the field of health geography and it was firstly developed to analyze the accessibility to primary health care (Radke & Mu 2000; Luo & Wang 2003). The method is a special case of a gravity model and is easy to use, interpret and understand as it measures accessibility in two steps by considering both supply and demand. Its importance lies in the improvement where it combines supply, demand and transport network information into a single spatial index that allows comparisons to be made across different locations (Luo & Wang 2003). The 2SFCA technique was enhanced

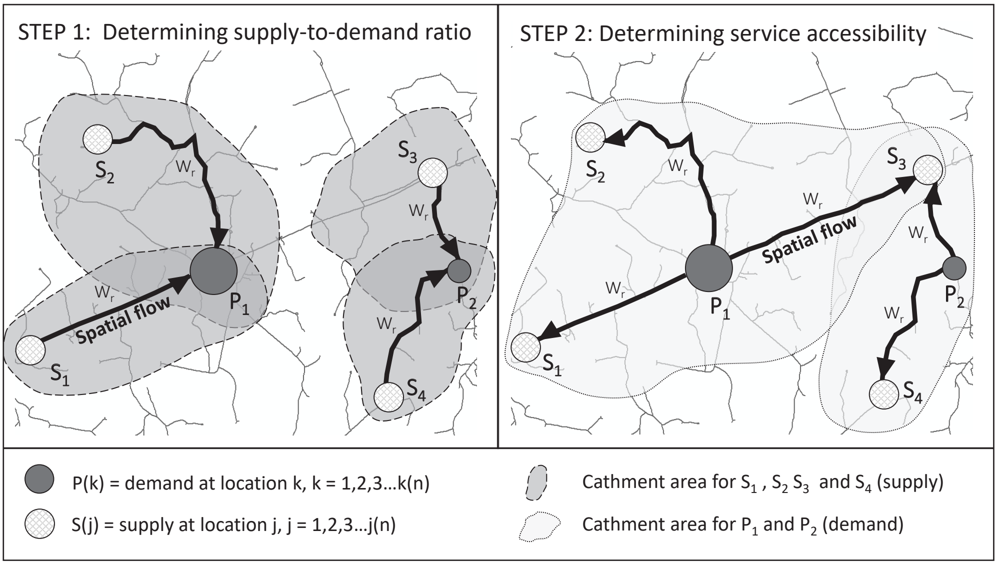


Figure 8. A simplified schematic figure of the principle of enhanced two-step floating catchment area (E2SFA) accessibility calculations. Dark grey dots represent demand and light grey dots represent supply. The size of dots indicates the volume of supply and demand. The first step of the analysis is illustrated on the left figure and abbreviations correspond to the formula of E2SFCA. The different shapes of catchment areas are the result of the actual street network and are based on the distance threshold around each supply point (S_j). In step two (right figure), the catchment areas are generated with the same threshold as in step 1, but in this case, demand points (P_k) are the points of origin. As each supply point has an assigned value (fraction from step 1), all values within the catchment area of a demand point can be summed. As more supply points fall inside the catchment area, the higher will be the final score for this demand point. The enhanced model has also distance impedance (W_r) which leads to weighted 2SFCA values depending on the travel distance between supply and demand. The final value is an indicator of accessibility.

further to include a distance decay parameter within catchments (Luo & Qi 2009). The used enhanced method is better explained in the following steps:

Step 1: A demand was derived for supply nodes within the catchment area as production-to-consumption shares R_j in location j:

$$R_j = \frac{S_j}{\sum P_k W_r} \mid k \in \{d_{kj} \in D_r\} \quad [1]$$

Where S_j is the amount of food production at location j, P_k is the demand at location k whose centroid falls within catchment j ($d_{kj} \in D_r$), and d_{kj} is the travel time between k and j. In other words, this first step counts what demand centroids (population) fall within the catchment (determined with the used threshold travel distance zone) of each supply centroid (ES provider). W_r is the distance weight function with linear form for the rth catchment zone. Calculations are weighted 1.0 at zero distance from the supply or demand point and this weighting decays linearly to reach 0.0 at the set threshold distance. This means that people become less inclined to utilize a service as their distance to it increases. In this thesis, three different transportation distance thresholds (250, 500 and 1000 km) were used to demonstrate how far crop products are transported through the road network.

Step 2: Production-to-consumption shares (R_j), are derived for population nodes and summarized to accessibility to production ratios A_i^F in a location j:

$$A_i^F = \sum R_j W_r \mid j \in \{d_{ij} \in D_r\} \qquad [2]$$

Where R_j is the production-to-consumption share at location *j* within the catchment at population location *i* (i.e., $d_{ij} \in D_r$), and d_{ij} the travel time between *i* and *j*. The second step allocates available crop production to population, by deriving the share of the production that falls within the catchment of each population. As a result, the analysis assigns accessibility scores determined by the supply to demand ratio. In the case of Paper II, the values less than one indicate less supply than demand, a value of one indicates a balance between supply and demand, while values greater than one represents more supply than demand within the studied threshold distance.

As the E2SFCA method generates an origin-destination matrix of the network travel costs between the selected service supply and demand points subject to a threshold distance, the NUTS3 was selected for a reference scale to keep the origin-destination matrix at a reasonable size in computations. Because the analysis uses point-type nodes to connect the origin and destination, the supply and demand centroids of each of the NUTS3 areas were applied as reference points (see details on how the centroid is calculated from the data description). To test the effect of barriers (such as state borders) on accessibility scores, the transportation of crop products was restricted to within nation-state borders in Paper II. In another case, the calculations were made without borders and Europe was considered as a single free trade area.

5 Results and discussion

One of the main motivations of the ES concept is to reflect the value of nature for sustaining human well-being and show the reasons for using ecosystems carefully. The concept is developed to analyze and describe not only the ecosystem properties and conditions but also their relevance to society (Nelson 2009; Syrbe & Grunewald 2017). All the same, people are rarely aware of the role of natural goods, processes and potential to sustain their welfare. Whereas, from a socio-economic point of view, the majority of services exist only if there is demand from a beneficiary. This duality raises the need to distinguish at least the supply and demand side of service provision but also aspects of ecosystem potential and flows (Villamagna *et al.* 2013; Burkhard *et al.* 2014). Syrbe and Grunewald (2017) emphasized that for assessing and mapping the fair use of ES and for protecting the ecosystems' goods against overuse and impairment, it is necessary to pay attention to the spatial connections, especially the access for people to the benefits of nature. Besides these above-mentioned spatial relations, they suggested that also the transfer of goods and benefits should be included in the consideration.

The central objective of this thesis was to meet these mapping suggestions by testing the applicability of spatial accessibility analysis to assess the availability and access to ES, the balance between ES supply and demand, but also the suitability of the used methods for measuring the negative effects that nature can cause for people. These aspects are addressed here through three separate studies (papers I, II and II) where the accessibility was tested by using different sets of ES and EDS indicators. The following chapters give an overview of the key findings, discussion and themes for future research based on this thesis (in the order of the study questions).

5.1 Potential usability of user movement related ES (Q1)

In some cases, the usability of ES depends on the presence of people in a SPA. This applies to most cultural ES since people drive, walk or are transported to areas which provide these services. The most frequently assessed cultural ES are aesthetics of scenery or the possibility of recreation (Maes *et al.* 2012), of which the latter was selected to represent 'user movement related services' in this thesis. In addition to this, also cultural heritage was investigated in the study.

The utilization of these cultural ES depends in the first instance on the opportunity to access recreation sites but also people's travel habits. In general, the usability of cultural ES could be measured from two accessibility perspectives: normative and positive (Páez *et al.* 2012). Normative accessibility measures how far people should to travel or how far it is reasonable to travel, whereas positive accessibility measures how far people actually travel. That said, normative accessibility reflects an expectation of the people's behavior and it is uniform across individuals. However, if behavioral content is included in accessibility measures (see Páez *et al.* 2012), for example, by reflecting actual daily and seasonal travel times described on travel surveys (as did in this thesis), it can be used as a proxy of how far people are willing to travel.

In this thesis, people's travel habits were estimated based on a Finnish Transport Agency survey (2010-2011). According to this survey, people made approximately two trips per day, of which at least one was related to leisure in Finland. The average duration of each trip was approximately 21 minutes, meaning that on average people are accessing services on a daily basis within this travel time. The results showed that only 18% of the population can access national parks based on average daily travel time by private car (Figure 9A). Whilst access to nationally valuable landscapes was easy for a large share (80%) of the population and more than 65% of people could reach wild game (brown hare) habitats in 21 minutes (Figure 9B-C). If people are spending more time to reach destinations, the accessibility of cultural ES will obviously increase. For example, Finns made approximately eight nature trips per year, of which two are directed toward national parks (Sievänen & Neuvonen 2011). In that case, the travel time can reach up to eight hours, which means that almost all Finns have an opportunity to reach the nearest national park. Also, wild game habitats are easily accessible for the whole population, at least during the hunting season when people travel to hunting sites (Paper I).

Enjoyment of nature has been shown to follow the seasons (Martín-López *et al.* 2009). According to Sievänen and Neuvonen (2011), Finns take most of their nature trips between May and September, indicating that people are able to spend more time to reach the recreational ES during the summer. This observation is consistent with the study by the Finnish Transport Agency (2010-2011), which reported that people make the longest trips in July. During that month, each trip lasts on average 27 minutes, whereas in December the average travel time per trip decreased 10 min. This means that all studied cultural services were more accessible during the summer. For example, nine out of ten can easily reach nationally valuable landscapes in July given the average travel time during this typical summer holiday month, whereas in December the number drops more than 10%. In addition to this, it should be remembered that the supply of some ES may be seasonally restricted. For example, wild game habitats, such as those providing large brown hare populations, are permitted to be used only during the hunting season.

Although the travel habits of people vary seasonally or even on a daily basis, the proximity to residential areas has been detected to be a crucial factor generally affecting the recreational use of SPA (Schipperijn *et al.* 2010; Paracchini *et al.* 2014). Assuming that all people in Paper I have similar desires in terms of outdoor recreational opportunities, the availability of recreational sites close to people's homes and population density are important aspects when evaluating the expected number of people who are able to use each SPA. In Finland, the road network does not remarkably restrict the accessibility of studied cultural ES. Therefore, the number of potential visitors to the SPA depends mainly on its location. As Finland has its highest population density in the southern part of the country, areas which provide services in the south will more likely benefit more people than in the north

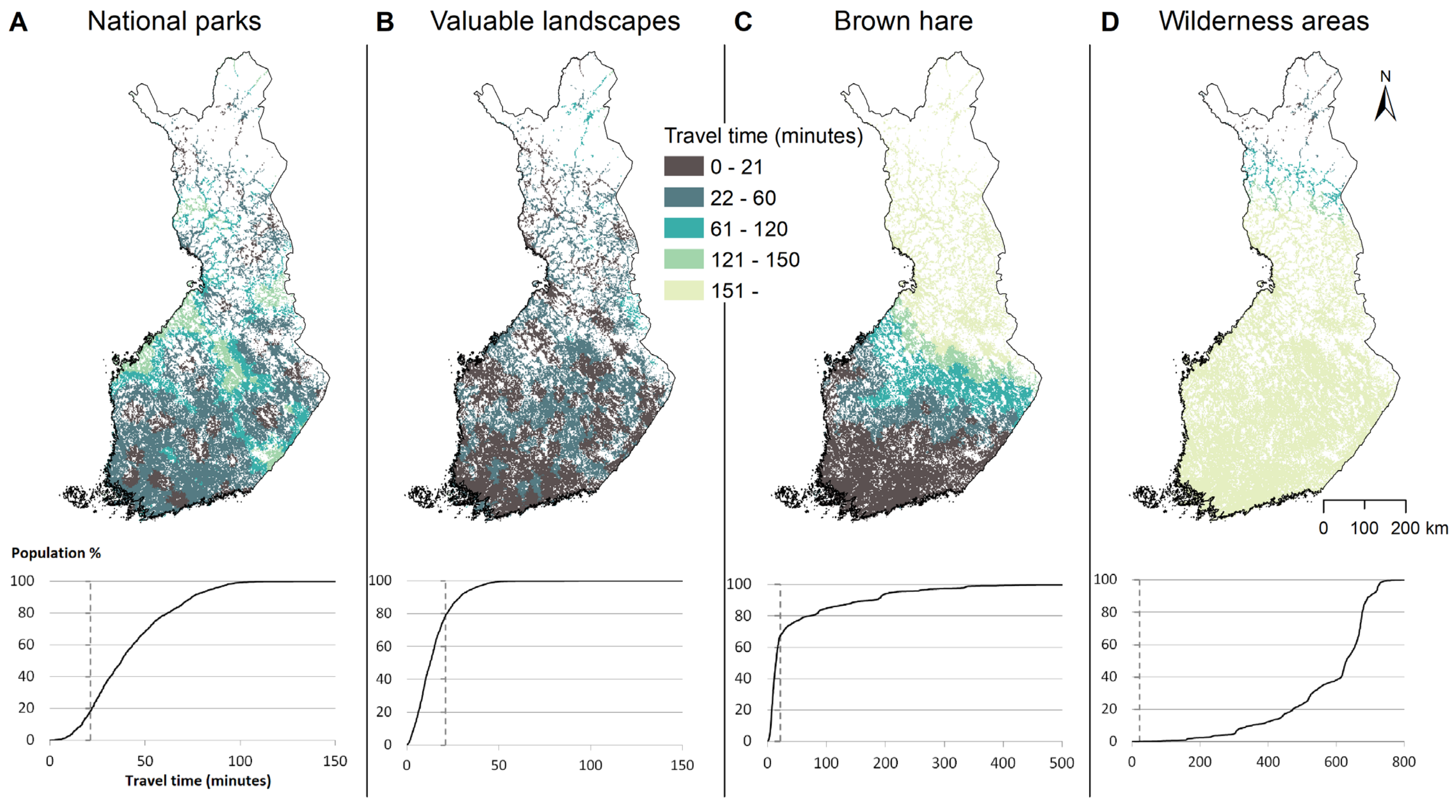


Figure 9. Potential accessibility of studied cultural ecosystem services A: national parks, B: nationally valuable landscapes, C: wild game habitats (brown hare) and D: wilderness areas. Maps represent travel time from each populated grid cell (resolution 2 x 2 km) to the nearest service providing area (SPA). Graphs below the maps describe the cumulative percentage of population (y-axes) in relation to travel time to the nearest SPA (x-axes). The vertical dashed lines in the x-axis represent an approximate daily travel time (21 min) used for one trip based on the survey of the Finnish Transport Agency (2010-2011). (Data: Finnish Environment Institute, Official Statistics of Finland, Finnish Transport Agency, Natural Resources Institute Finland)

with the same travel time. Wilderness areas are a good example of this (Figure 9D). These areas are extensive but are situated only in the northern part of the Finland, meaning that only less than 1% of the population have an opportunity to reach these natural sites within a 21-minute drive. For instance, wild game habitats, which are limited to the southern part of the country, are relatively well reached for most people because of the close proximity of the population to SPA.

Overall, the study shows that travel times to the closest studied SPA were higher in sparsely populated areas than in densely populated areas. In general, it seems that Finland is able to offer its residents convenient access to the analyzed SPA except for wilderness areas. Regarding ES accessibility, it is good that the density of SPA is higher closer to urban than to peripheral areas, as it increases people's opportunities to utilize SPA (see Páez *et al.*, 2012). People more likely use services when they are located close to people's homes (Schipperijn *et al.* 2010). Also Martínez Pastur *et al.* (2016) highlighted that good accessibility is a crucial factor that affects the utilization of cultural ES. However, the flip side of good accessibility is that SPA close to developed areas may be subject to deterioration if large amounts of people actually utilize these ES (e.g. Turner *et al.* 2014). The accessibility analysis demonstrated that SPA in the Helsinki metropolitan area, for example, may potentially receive more people than the SPA located in the sparsely populated areas, increasing the risk of ES overuse (see Paper I, Figure 8). Growing human pressure, such as overuse or congestion in SPA near urban areas, may have impacts on biodiversity, which in turn can directly or indirectly affect the provision of ES (e.g. Mace *et al.* 2012; Maes *et al.* 2012; Science for Environment Policy 2015).

This thesis shows that the accessibility analysis could provide easy-to-read quantifications and maps of ES which can improve guidelines for land-use management and policy actions. The findings can be effectively applied when identifying areas where conservation of ES must be improved or where it is meaningful to restore ES or invest in new ES sites (e.g. in the case of potential overuse of ES). In addition, the results can be used to indicate the residential areas where ES are not available within reasonable travel time or where the SPA is potentially underused. On this basis, it seems that the used accessibility approach is well-suited to measure the user movement related ES that require a direct interaction with people. Moreover, travel time serves as a highly applicable indicator in evaluating access to SPA between regions, or more specifically in geographical space. In general, the accessibility analysis is ready to be applied in various types of areas and at different scales (from a local up to global scale) corresponding to the need to analyze the spatial patterns of the cultural ES at wider scales (see Martínez Pastur *et al.* 2016). The only requirements are that a network analysis tool and accurate GIS-data, at least for residential locations, SPA and transport network are available.

However, to gain a more comprehensive picture, a few suggestions need to be considered in future investigations. This thesis shows that private cars are needed in order to guarantee the flow of the people to the studied SPA. In reality, travel times are greatly influenced by which means of transport are used during the trip (Finnish Tranport Agency 2010-2011).

Also, the volume of the traffic and the condition of the road network affect the travel time. Due to the traffic congestion, the availability of ES for people, especially for those living in the cities, may vary during the day. Moreover, the available means of transport, or the lack thereof, could even constrain the final decision about the use of a SPA. In Finland, more than 80% of trips between 20 and 150 km and even 90% of nature trips are made by a private car (Finnish Tranport Agency 2010-2011; Sievänen & Neuvonen 2011), which is why significant attention was not paid to other forms of travel in Paper I.

This thesis focused on the accessibility of the closest SPA, but especially in the case of outdoor recreation people are usually seeking a variety of opportunities to engage in a range of activities (Brabyn & Sutton 2013). In further studies, more focus on assessing recreation opportunities also to the second closest site and the third closest site is therefore suggested (Brabyn & Sutton 2013). Another critical aspect that needs to be considered is that accessibility usually differs from one person to another and travel and destination choices where people actually go, are driven by various individual factors, such as information on inhabitants (e.g. age), personal preferences, available time, funds or even the weather. These accessibility components would be good to examine in future studies, if appropriate data is available.

Correspondingly, estimating the capacity of SPA to provide recreation ES can be used to assess the attractiveness of the SPA, which can then be used to evaluate people's preferences to reach ES. However, especially cultural ES have been criticized for being challenging to quantify and map, as they represent non-material benefits that people obtain from ecosystems (MA 2005; Daniel *et al.* 2012). In addition, people's perceptions can differ significantly not only from one person to another, but also between areas and cultures, making the assessment of a SPA's capacity to provide ES even more complicated (e.g. Hernández-Morcillo *et al.* 2013). Therefore, the capacity and demand for ES are quite often measured indirectly by utilizing, for example, expert knowledge-based matrix approaches (Burkhard *et al.* 2009), participatory mapping methods and contents of social media (Brown & Fagerholm 2015; Richards & Friess 2015; Oteros-Rozas *et al.* 2018; Toivonen *et al.* 2019), mobile phone data (Raun *et al.* 2016), or as in this thesis, by using normative accessibility measures, despite the potential biases induced by proxies (Eigenbrod *et al.* 2010).

In Paper I, cultural SPA (national parks, wilderness areas and nationally valuable landscapes) were selected on the basis of being clearly pre-defined to have a potential recreation or natural state status for people by decision of the Finnish Ministry of the Environment. Hence, the study only measures the presence of a potential service and did not consider the quality of SPA or its capacity to provide services. Therefore, integrating qualitative methods, such as surveys and social science approaches could be useful in supplementing or identifying starting points for the quantitative measurements. Combining both quantitative and qualitative methods could provide a more accurate picture of the quality of the people's experience in SPA and the places where ES are actually utilized (Busch *et al.* 2012). However, Seppelt *et al.* (2011) reminded that using more than one type of method to quantify and map certain ES might cause uncertainty that needs to be taken into consideration when designing ecosystem assessments.

5.2 Accessibility analysis in assessing spatial flow between supply and demand (Q2)

Understanding the link between supply and demand of ES is one of the key issues in the field of ES (Burkhard *et al.* 2014; Goldenberg *et al.* 2017; Syrbe & Grunewald 2017). Many provisioning ES such as food, fiber or timber are usually produced and consumed in areas geographically distant from each other (Fisher *et al.* 2009; Crossman *et al.* 2013; Serna-Chavez *et al.* 2014). The supply of these services may be linked to human beneficiaries through a spatial flow that occurs in the landscape between an area of ES provision and an area of ES demand. Properties of the connecting space where the pathways of spatial flows occur have an influence on the delivery and utilization possibilities of ES. Therefore, spatial flow is one of the key characters when assessing service transfer between service source and benefit at different spatial scales (Syrbe & Walz 2012; Bagstad *et al.* 2013; Serna-Chavez *et al.* 2014; Wolff *et al.* 2015). In this thesis, spatial accessibility analysis was used to model `carriers´ (see Bagstad 2013), which deliver food ES via the road network to beneficiaries in Europe. The approach has clear potential to provide information on spatial characteristics of supply and demand availability, proximity and trade barriers in Europe (Paper II).

Studies typically depict ES as site-bound static maps and explain the complex flow dynamics using simple overlay approaches (e.g. Bagstad *et al.* 2013). This thesis shows that overlay of two maps can lead to over-simplification, inaccuracies and misunderstanding when mapping the balance between ES supply and demand. The results of Paper II show that spatial mismatch between supply and demand would not have been identified appropriately using the overlay approach, especially in large demand centroids located in cities, such as London, Paris and Berlin. These areas have focal peaks in demand in relation to surrounding crop production which gives the impression of a strong imbalance between production and consumption. Although the overlay maps clearly show the areas where crop cultivation is concentrated (France, parts of Germany, Poland, Hungary, Romania and the British Isles) and the areas of high demand, the outcome does not take the spatial flow of ES into consideration.

Analyzing the spatial flow of services between provisioning and benefiting areas through accessibility analysis can receive more exact and useful information on the balance or mismatch of food delivery (i.e. production capacity) and demand. The differences between overlay and accessibility methods are particularly apparent around the large population densities, where demand has been better taken into account using accessibility analysis. The more the transport distance threshold increases in the accessibility analysis, the more the results of these two approaches differ statistically (Paper II). For example, if Europe is considered to be a single free trade area and food is delivered locally (within 250 km of supply), clear differences between oversupply and undersupply areas are distinguished across Europe and the results are more consistent with outcomes obtained from the overlay analysis (Figure 10 A). Whilst increasing travel distance from 250 km to 500 km and 1000 km, it can be detected that food products could be delivered to beneficiaries more evenly across Europe. Delivering the food via road networks, the proportion of people living in the shortage area falls from 60% (the result of overlay analysis) to 36% (the result of accessibility analysis at 1000 km travel distance without nation-state borders). This demographic inspection of the results supports the strengths of the accessibility method, especially in densely populated areas. For example, the area of high demand from the Netherlands to Italy clearly benefits from cross-border delivery of food products at longer distances.

However, restricting spatial flow of ES to borders of nation states could significantly impact the balance between supply and demand. Paper II shows that national overproduction of crop products is concentrated especially in France, the Baltic States, Hungary, Romania, Serbia and Bulgaria. Respectively, the Iberian Peninsula, mountainous areas in central and northern Europe, densely populated areas in the

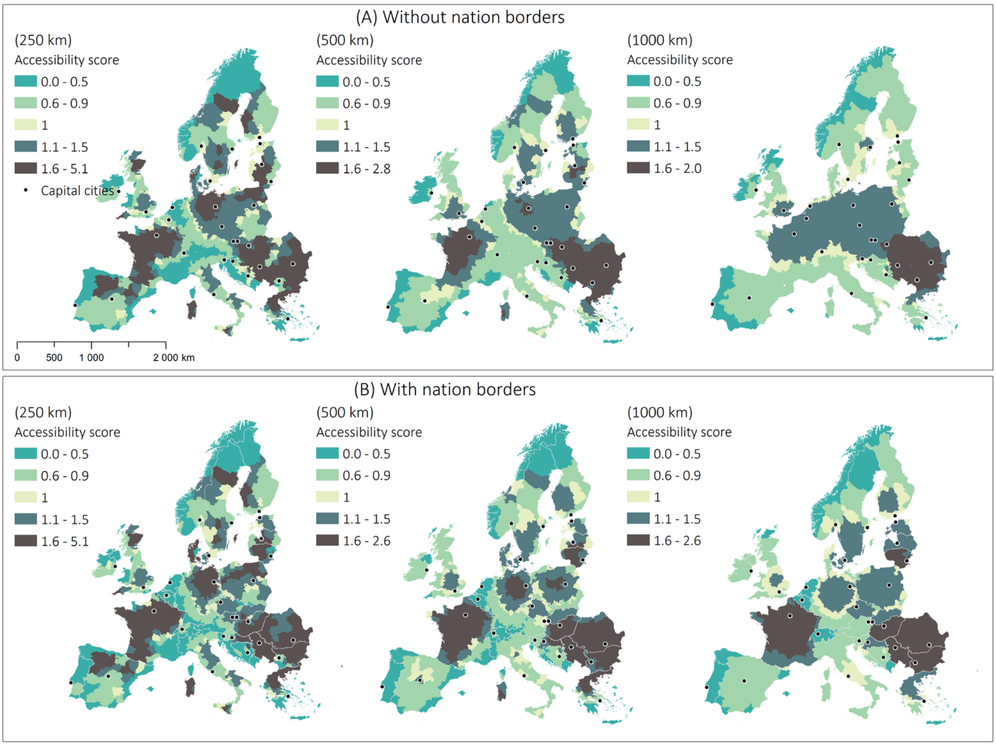


Figure 10. Supply-demand balance of crops when Europe is considered to be a single free trade area (A) and when impact of nation-based trade barriers is taken into consideration in accessibility analysis (B). In both analyses (A and B), different transportation distance thresholds (250, 500 and 1000 km) were used. The analysis gives accessibility scores determined by the supply to demand ratio. Values less than one indicate less supply than demand within the given threshold distance. Value one indicates a balance between supply and demand, while values greater than one represents higher supply than demand. (Data: Eurostat, EFSA, European Environment Agency, FAOSTAT)

middle of Europe and several coastal areas are suffering undersupply at all studied threshold distances (Figure 10B). It is somewhat surprising that almost the same proportion of the population is located in the areas of undersupply and oversupply across Europe (regardless of whether Europe is examined from the perspective of individual states or by Europe as a single region). However, at the country level, the benefits of cross-border delivery of food are significant. For example, in Belgium, Slovenia, Switzerland, Luxembourg and the Netherlands demand exceeds ecosystem capacity to provide crops at the national level. However, if crops are delivered across nationwide borders, the food balance turns from undersupply to oversupply in the above-mentioned countries. Hence, nearly all countries, but especially undersupply areas, clearly benefit from balancing the supply or demand via international trade, even at relatively close distances.

In this thesis, the effect of nation-state borders on spatial flow of ES was tested hypothetically, and the importance of free flow of ES across borders in Europe was confirmed. The importance of state borders as a creator of barriers to free flow of goods is highlighted also in the study of Chen (2004). Their study shows that, for example, European Union (EU) countries, which are expected to be highly integrated and should display small border effects, trades more with itself than with countries outside the EU. Also, several other studies confirm that national borders are still acting as a trade barrier within the EU region (e.g. Nitsch 2000). The effect of borders is detected to be greatest especially in small countries (Anderson & van Wincoop 2001; Chen 2004). Also, Salas-Olmedo *et al.* (2016) have emphasized the growing role of borders in international trade and underlined that accessibility studies should consider borders, which still are barriers that represent abrupt changes in international trade flows even within nearly borderless areas, like the EU. They further suggested that, in addition to the spatial impedance (which is examined in this thesis) also political, cultural or linguistic barriers between countries should be included in accessibility models.

The accessibility method gives a good overview of the supply-demand relationship, but it can be used also to identify areas where additional investments in the transportation network or management of crop production are needed to the meet demand. In contrast, accessibility analysis can also be used to identify areas where the investment of local-scale food production could reduce the need for transportation. For example, favoring efficiently grown local food has potential to decrease greenhouse gas emissions and food loss, but also supporting food security and energy efficiency (Mbow *et al.* 2019; Kinnunen *et al.* 2020). By optimizing the delivery of food ES from the areas of overproduction to the areas of high demand, may decrease transportation costs but also reduce the amount of greenhouse gas emissions emitted from the transportation. Optimizing the utilization opportunities of ES (both user movement related and transportable ES) is important because there is a growing need for the reduction of emissions of greenhouse gases from all human-made sources, including the transportation sector, to mitigate future climate impacts (Greene *et al.* 2011; IPCC 2014).

The accessibility analysis can provide a powerful tool to quantify the current state and use of food ES giving insights to evaluate the sustainability of service provision. The results of this thesis indicate that demand exceeds ecosystems' capacity to provide food ES within 1000 km travel distance in many areas in Europe, even when the transportation was not restricted to the borders. The use of ES is not sustainable when demand cannot be met by current capacity or when meeting demand declines the future provision of the same or other ES (Bommarco *et al.* 2013; Villamagna *et al.* 2013). Syrbe & Grunewald (2017) have emphasized that exceeding usage of naturally limited potential can harm ecosystems, causing less ES supply or quality of life due to environmental damage. The study by Villamagna *et al.* (2013) represented that in the case of imbalanced use of ES, society can usually choose to either enhance ecosystem capacity to produce ES, decrease demand or invest in transportation or in a technological substitute to balance the gap between production and consumption.

The accessibility analysis can also be used when assessing changes in future supply-demand balance. Identifying future risks or realizing how the balance between supply and demand can be maintained through reasonable cross-border delivery of food within Europe are important aspects when considering future food security questions. Future food security challenges are related to the predicted decline in crop production as a result of climate change, pollution, biotic invasions, loss of natural habitats and simplification of the agricultural landscape (e.g. Bommarco *et al.* 2013; Pirttioja *et al.* 2015), but also expected growth of demand. The consumption of food energy has increased over 100% in the past decades globally, and the same trend is expected to continue in the future (Vásquez *et al.* 2018). The balance between crop production and demand becomes even more important as the expansion of agricultural land is restricted (Ewert *et al.* 2005). For this reason, realizing the spatial flow of ES through the accessibility approach can provide a practical tool for decision-makers to assess the sustainability of ES use as well as to improve the development of ecosystem accounts with the aim to reach sustainable development goals for feeding people (Griggs *et al.* 2013; United Nations 2015).

However, despite the presented promising results and potential application opportunities of the accessibility approach in mapping the spatial flow of ES, the real world is complex and stochastic and assessing the spatial mismatch between ES supply and demand is not a simple task for many reasons. First of all, ES have complex flow dynamics that operate at different spatial and temporal scales (Andersson *et al.* 2015; Malinga *et al.* 2015; Raudsepp-Hearne & Peterson 2016). Services provided by ecosystems are heterogeneous in space and evolve through time (Fisher 2009). For example, crop supplies vary during the year and ecosystem potential to produce services is utilized normally 1–3 times per year when the yield is harvested (Burkhard 2012, 2014). Therefore, ecosystems provide food ES into market systems seasonally. Of course, in developed trade systems, warehousing and distribution of food products is not limited only to the harvesting seasons, but eating seasonal and locally produced food has been proposed to be one way to move towards sustainable consumption patterns (Macdiarmid 2019; Kinnunen *et al.* 2020). However, the problem is more that the current globalized trade markets allow people to consume more than SPA can provide in the same areas, which is directly linked to the global reduction of ES (Burkhard *et al.* 2012). The study by Kinnunen *et al.* (2020) showed that local crop production can satisfy demand for less than one-third of the global population with current production and consumption patterns. This means that large part of the globe would still depend on trade to feed themselves. Again, increasing unpredictability of future food markets as a result of rising incidence of climatic extremes may lead to crop failure, which again could increase food prices in the future (Iizumi *et al.* 2013).

As referenced above, many provisioning ES such as food have complex globalized market systems. Furthermore, the economic supports of production and long supply chains that services go through before reaching consumers makes the evaluation of supply-demand balance even more challenging. Instead of using crops as such, people benefit from final processed goods that are a result of the whole supply chain (Schröter *et al.* 2012; Burkhard *et al.* 2014). This remains a question of where to locate the demand and especially who should be considered to be a beneficiary as there is a large group of actors involved (Schröter *et al.* 2012; Burkhard *et al.* 2014; Syrbe & Grunewald 2017). Because, actors transport goods (e.g. crop products) from the SPA to the final consumers, the benefits are also shared between actors and consumers (incomes for the actors and final use by consumers) (Syrbe & Grunewald 2017). Since, actors not only transport ES but also modify, maintain or even damage ecosystems, the assessment of provisioning ES become increasingly complex (Lautenbach *et al.* 2011). Hence, tracking and defining the origins and transport paths of ES goods is problematic in today's globalized trade systems and complicate the assessment substantially. Especially, evaluating the demand side has been criticized to be manifold as it can include, for example, policies, population dynamics, economic factors, marketing, trends, cultural norms and governance (Burkhard *et al.* 2012). For this reason, Paper II followed Burkhard *et al.*'s (2014) suggestion to locate the demand at the site of the final beneficiary, the end-consumer. However, this will not remove the fact that the datasets which have been used in Paper II, could not define exactly where the goods and services originally come from and who benefits from them.

In addition to complex supply chains, there are two other characteristics which are typical to marketed ES, excludability and rivalness (Costanza 2008; Fisher 2009). The benefits are excludable if people can keep others from using goods. For example, food producers together with cultural and institutional mechanisms can affect the extent to which services are \`excluded´ from the consumers. Whilst rivalness means that if someone uses a certain good, there is less of it for others (e.g. buying a bread from the market reduces others option to buy it). These two characteristics together create inequalities to benefit marketed ES equally (Felipe-Lucia *et al.* 2015). In addition to this, also food waste, which is lost during the production, postharvest and processing stages, could decrease the final products going to human consumption (Parfitt *et al.* 2010). As a result, the original service is not fully available to the consumers and this is why the assessment of available ES relative to the needs of the population is challenging.

In terms of accessibility, the access to food resources varies across space as neither production nor population are homogeneously distributed. Measuring the potential accessibility indicates the probable entry of ES products, but does not ensure the automatic utilization of the available services (Luo & Wang 2003). After all, as there are no comprehensive measures of the demand including marketing, demographic changes or behavioral norms available, it is not possible to completely map the balance between supply and demand of food ES in Europe. However, Paper II illustrated well how different transportation distances and national borders affect the relationships of production and consumption of food ES, as suggested when studying the potential accessibility to markets (Salas-Olmedo *et al.* 2016). The results of Paper II also demonstrate how the balance between supply and demand in Europe can change if the international distribution of the food ES for one reason or another is prevented.

5.3 Evaluating the exposure risk to EDS through accessibility analysis (Q3)

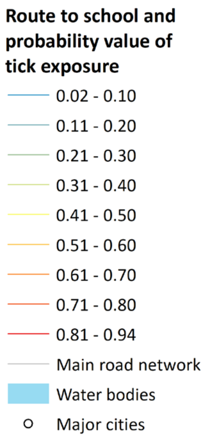
The movement of people, goods and services are intrinsic parts of a well-functioning society. The accessibility analysis can offer not only an approach to assess the usability of potentially available benefits that humans obtain from nature (papers I and II), but also a method to measure the negative effects arising from characteristics of ecosystems that are economically or socially harmful, or that endanger health or are even life-threatening (Dunn 2010). The issue of EDS has received attention in the last few years and recent studies have highly suggested integration of the negative side of ecosystems into ES studies to gain a more holistic understanding of the role of nature with regard to human well-being (Lyytimäki *et al.* 2008; Lyytimäki 2014; Shapiro & Báldi 2014; Villa *et al.* 2014; Von Döhren & Haase 2015; Shackleton *et al.* 2016; Schaubroeck 2017). However, EDS research has so far been dominated by qualitative approaches (Von Döhren & Haase 2015), and new studies are needed to strengthen the quantitative assessment (Campagne *et al.* 2018; Blanco *et al.* 2019). Von Döhren and Haase (2015) have highlighted that there is a growing need for spatially explicit information, for example, on the amount of people who are affected by EDS and ecosystems' probabilities to produce potential EDS.

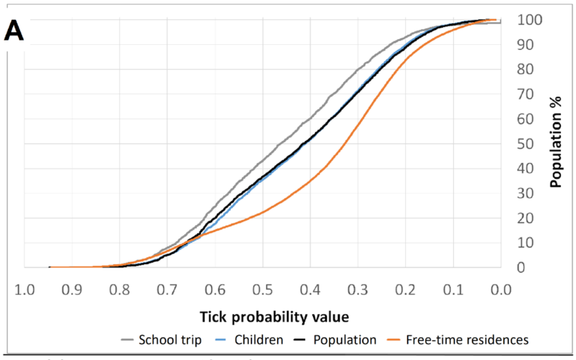
This thesis focused on ecosystems which are reservoirs for disease vectors, more precisely ticks, as a test case for developing a GIS-based EDS measures in a spatially explicit manner (Paper III). Ticks provide a good example of an EDS that has a direct negative impact on human well-being (e.g. Laaksonen *et al.* 2017; Sormunen 2018; Klemola *et al.* 2019). The number of tick-borne diseases has increased enormously in many European countries during the past decades and enhanced mobility of humans may promote new tick encounters in developed environments even more (Rizzoli *et al.* 2014; Sajanti *et al.* 2017; Klemola *et al.* 2019). Especially, densely populated urban and suburban areas have been identified as an important source of human pathogen exposure due to the high number of possible contacts between humans and ticks (Rizzoli *et al.* 2014). The increased prevalence of pathogens together with a large human population could pose considerable risk of tick-borne diseases even in maintained city parks, semi-natural forest patches and vegetation-flanked walkways (Sormunen 2018; Klemola *et al.* 2019). Therefore, Paper III tested whether people (here school children) have a higher potential to be in contact with environments suitable for ticks when they travel across different environments compared to probabilities of tick encounters only in the location of residential areas. This was done by modeling the probability of tick presence in Finland based on tick observations and environmental variables and then comparing the results of accessibility analysis to overlay analysis of residential areas, free-time residences and tick probability values.

Based on the predicted tick distributions (Maxent models, Figure 5), ticks have three clusters in Finland, where people have higher-than-average probability to encounter harm: on the coast of the Baltic Sea, between the cities of Tampere and Kouvola and around the City of Kuopio. This finding was consistent, for example, with the results of Laaksonen *et al.* (2017, 2018), who found the highest tick abundances along the coastline and shore areas in Finland's Lakeland region, but also in developed environments in southern Finland. Although the population settlements are manly concentrated in the southern part of the country where the tick density is highest, the overlay analysis indicates relatively low risk of tick encounters around residential areas and free-time residences. The results of Paper III show that only 20% of free-time residences and 35% of residential areas are located in the environments where the probability of being exposed to ticks is more than 0.5 (Figure 11A). There were no significant differences between the residential areas of the whole population and areas which contain information only on children. Assuming that people have a potential to be exposed to tick bite in environments where modeled probability of tick presence is more than 0.5, the risk of getting a LB from tick contacts in residential areas is 7.4% and around free-time residences 4.7% (Figure 11B). TBE risk is 0.7% and 0.4%, respectively.

When the movement of people was taken into consideration through a GIS-based accessibility analysis (as in Paper III) the probability of tick contacts increased. Paper III shows that 47% of children have at least a 0.5 probability of encountering ticks during a school trip and nearly 9% of them have a risk of getting LB. Especially, major cities in coastal area are located in high-risk areas and nearly all children have relatively high exposure risk to tick bite (> 0.5 probability) compared to inland cities (Figure 11C). For example, in the City of Oulu (population of 203,567 in year 2018 (Official Statistics of Finland 2019a)) the probability value of encountering ticks during a school trip could be in the worst case nearly 0.9, whilst in the City of Tampere (population of 235,239 in year 2018) the maximum probability values are less than 0.7 (Figure 11 C1 and C2). In in the Helsinki metropolitan area (population around 1,200,000 in year 2018) the probability values range between 0.41 and 0.84 being 0.6 on average (Figure 11 C3).

If a high number of people are using urban and suburban recreation areas and semi-natural forest patches, relatively low tick densities have been reported to be a relevant source of human pathogen exposure (Rizzoli *et al.* 2014; Sormunen 2018). Hence, the Paper III





B

Tick-born disease	Residential area population	Residential area children	Free-time residences	School trip
LB (%)	7.4	7.3	4.7	8.9
TBE (%)	0.7	0.7	0.4	0.8

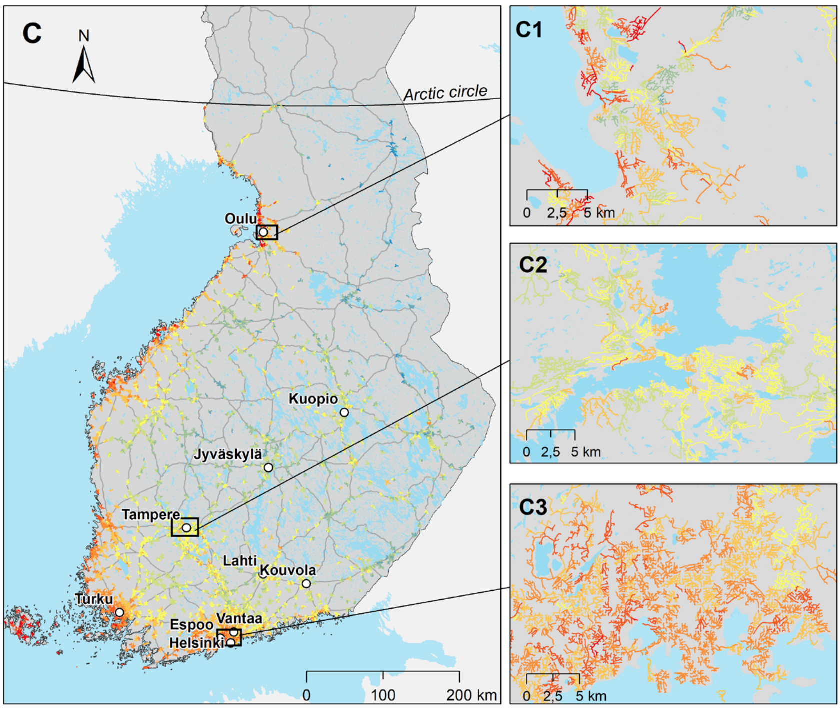


Figure 11. (A) Cumulative percentage of population (y-axes) in relation to probability of tick exposure (x-axes) in residential areas (population = whole population, children = only grid cells including information on children between 7 and 14 years of age), free-time residences and during a school trip. (B) Percentage values indicate the number of people whose residential area, location of free-time residence or a school trip exceeded the tick probability value of 0.5 and therefore have potential to get either Lyme borreliosis (LB) or tick-borne encephalitis (TBE). The pathogen prevalence of ticks was based on the results of Laaksonen *et al.* (2017). (C) Shortest routes from residential areas with children to comprehensive schools at the national and local level (in the City of Oulu (C1), Tampere (C2) and Helsinki metropolitan area (C3)). Route to school indicates the highest probability value (ranging between 0 and 1) for tick exposure during a school trip. (Data: Finnish Environment Institute, ArcGIS 2014, Official Statistics of Finland, Finnish Transport Agency)

assessed also the extent of tick exposure risk by calculating the total length of all school trips for high-risk areas. This information can be used when evaluating the activity level of people in high tick probability (>0.5) areas. Paper III shows that over 30% of children's school trips are located in areas where the probability of encountering ticks was more than 0.5. The greatest activity level was found along the coast of Baltic Sea, where the total length of all school trips can be more than 10,000-km in a single grid cell in urbanized areas (Paper III). Adding the information on how tick abundance and distribution are spatially connected with the movement of people, it is possible to get a good overview of the areas where the highest tick exposure is present due to high human pressure. This information can be used as a background for decision-makers, local and national health care professionals when pre-assessing public health strategies for minimizing tick-borne diseases. As long as we do not have preventive treatments against tick-borne diseases, apart from TBEV, a crucial way to minimize the negative effects of ticks is raising people's awareness of areas where tick inspections should be carefully conducted after outdoor movement, especially when ticks are at their highest activity peaks (Sormunen 2018; Klemola *et al.* 2019). Early diagnosis of LB also has economic benefits and would also reduce human suffering (Henningsson *et al.* 2010).

The results in Paper III showed that comparing residential areas, free-time residences and probability of tick presence alone, the risk of tick encounter appears to be lower than if people's movement in various environments has been taken into consideration. As people recreate in different outdoor environments during the day, it is central to evaluate the risk by using more explicit methods, such as accessibility analysis, instead of simple overlay analysis. However, there are a few things that should be considered when applying the results. First, tick exposure risk is usually seasonal. People have the highest risk of encounter ticks between mid-March to early November in northern Europe, when tick's activity peaks as they are seeking blood meal hosts (Sormunen 2018). Secondly, all ticks are not a source of pathogens as overall prevalence of *B. burgdorferi s.l.* has been detected to be 16.9% and TBE 1.6% in Finland (Laaksonen *et al.* 2017). At the same time, a recent study by Klemola *et al.* (2019) found even a 49% prevalence of *B. burgdorferi s.l.* in adult ticks in the City of Turku, a much higher percentage than recently reported in Finland. They also found that the pathogen prevalence is usually higher for adults than for nymphs, which is consistent with the study by Laaksonen *et al.* (2017). Interestingly, most of the crowdsource-based tick samples which were used to map ticks in Paper IIII were adults (Laaksonen *et al.* 2017). This means that the probability of tick presence has been modeled on the basis of more harmful life stages. Third, the results of Paper III provide only a rough estimate of actual tick contacts, as it is based on the assumption that humans have potential to be in contact with ticks while walking or bicycling. It is also important to bear in mind that predicted tick distribution models are based on the openly available data of tick observations and relevant environmental variables at a certain time. For future studies, more detailed data, for example on the tick host animals' distributions and tick's environmental requirements at different scales, are needed to develop more reliable models.

The accessibility approach has its prominence especially for EDS where human mobility plays a key role. This thesis focused on EDS which can cause human diseases via pathogen vectors, but also other EDS where exposure risk is easy to confirm can be assessed using accessibility analysis. For example, the potential effects of ecosystems that are reservoirs of allergens or dangerous or poisonous plants and animals can be linked with the movement of people. Similarly, nature-related fears and risks, such as fear of wild animals and natural darkness can be combined with the movement patterns of people (see Lyytimäki 2014; Von Döhren & Haase 2015; Vaz *et al.* 2017). Instead of being exposed to harm when people travel, it is also possible that an EDS itself can be transmitted through human processes accidentally or intentionally from one place to another. Good examples of this are invasive alien species that can cause health, security, safety or recreational EDS (Shackleton *et al.* 2016; Vaz *et al.* 2017) when they are transmitted into new geographical locations.

In EDS research, one of the main targets is to assess the harms that nature can cause for humans (Lyytimäki *et al.* 2008). Nevertheless, mapping health outcomes is difficult, as concepts or methods used to measure EDS are still poorly developed in the literature (Von Döhren & Haase 2015; Shackleton *et al.* 2016; Blanco *et al.* 2019). Meanwhile, the complex human-nature relationship makes the evaluation of net benefits even more complicated as the same ecosystem types can affect human health both positively and negatively, depending on individual and social perceptions, demographics and economic realities (e.g. Escobedo *et al.* 2011; Saunders & Luck 2016; Shackleton *et al.* 2016; Vaz *et al.* 2017). Perceptions of ES and EDS may vary even spatially and temporally (Chan *et al.* 2012; Shackleton *et al.* 2016; Vaz *et al.* 2017). For example, an aesthetically pleasing and comfortable landscape for someone can be a source of allergens for someone else.

In general, it is evident that ES provide people an attraction to reach areas that offer beneficial services. Although EDS are not typically considered an attraction, they can be located in the same area with ES. In addition to this, people have the potential to be exposed to negative influences of ecosystems on the way, especially if they walk, as in the case of school children in Paper III. Thus, people may encounter EDS when seeking benefits. EDS may, however, influence people's movements more than ES (Blanco *et al.* 2019). It has been noticed that if a certain ecosystem provides both ES and EDS, people's behavior is often driven by their awareness of EDS rather than their perceptions of ES (see Blanco *et al.* 2019 and references therein). This might lead to avoiding the areas that produce EDS, reducing the major benefits of ES. For example, in the northeast United States, Berry *et al.* (2018) observed that people have started to spend less time at outdoor recreation sites in order to avoid human-tick contacts. Because every ecosystem potentially delivers both ES or EDS depending on the context (Saunders & Luck 2016) and a wide variation of how EDS influence individuals (Blanco *et al.* 2019), we need further studies including both EDS and ES to deepen the understanding of what kind of potential harms, as well as benefits, ecosystems can produce for people (Lyytimäki *et al.* 2008; Schaubroeck 2017; Vaz *et al.* 2017). Accessibility analysis has the potential to be a novel approach to assess and map both the positive and negative impacts of ecosystems on human well-being.

6 Conclusions

In this thesis, the applicability of accessibility analysis for mapping spatial characteristics of ecosystem services and disservice was tested. By analyzing people's ability to utilize different ES and estimate the negative impacts that EDS may cause for humans with the GIS-based accessibility approach, this thesis has provided new perspectives to better understand the spatial flow between ES (or EDS) providing and benefiting areas. Furthermore, this thesis showed that the accessibility approach has a high potential to offer an efficient method to assess the transfer of ES and EDS through active transport of goods or traveling of people. This method also responded to the need to develop a practical tool for both ES and EDS research and decision-making. Based on the results, three main implications of this thesis can be summarized as follows:

1. **The spatial accessibility approach proved to be an effective tool for investigating the potential movement of people between residential areas and ES providing areas.** The results can be presented in easy-to-read maps, which help to indicate the areas where people have a limited possibility to reach services, but also where it is sensible to invest in the maintenance of ES if resources are potentially overused. Hence, accessibility measures presented in this thesis offer a good indicator which considers not only the location but also inequality conferred by distance. The method is ready to be applied across different scales and it provides a powerful tool especially when studying 'user movement related services' such as recreation.

2. **The results underline the applicability of accessibility methods when modeling the spatial characteristics of ES supply and demand.** The approach can efficiently indicate the areas of undersupply, neutral balance or oversupply receiving useful information on the balance between ES production capacity and consumption. The strengths of the analysis were particularly evident in densely populated areas where spatial mismatch between supply and demand was assessed more appropriately than using more simple approaches. This thesis also demonstrates that transportation distances and nation borders may affect the supply and demand balance significantly. The method was tested here using provisioning ES as an example, but it is suitable also for other types of ES where the spatial flow can be estimated. Instead of simply the road network, spatial flow can consist of various types of natural flows, where services are transferred, for example, via natural watercourses to beneficiaries. Spatial flow can also occur at landscape level, where the links between supply and demand areas can be estimated using a cost surface. Hence, the method has a high potential to deepen the understanding of ES transfer.

3. **The accessibility methodology can be used to produce information on areas where people have a higher probability of encountering EDS.** By using accessibility analysis, it was possible to evaluate the amount of potential EDS encounters and thus the number of exposed people, but also activity level of people in high-risk areas. Based on the results, it is recommended that people's movements are taken into consideration when evaluating exposure risk of EDS where human mobility plays a key role. Analysis of people's movement gives a more accurate picture of the overall EDS exposure risk compared to the analyses that evaluate only the overlay of EDS and population density.

Given that most spatial connections between SPA and SBA areas require human interaction, especially in order to enable the movement of people to benefit from certain ES or transport goods to consumers, the accessibility approach can provide a useful tool for decision-makers to influence ES transfer and consequently manage natural resources in a sustainable way. Concomitantly, the approach has the potential of enabling efficient biodiversity policies and management when it is important to understand both exposure potential to harmful aspects of ecosystems as well as their benefits in order to increase human well-being. Although promising results and applicability examples were presented in this thesis, more research is urgently needed to gain in-depth knowledge on wide-ranging and complex spatial relationships between areas of ES supply and demand. In future, research could focus more, for example, on the quality and attractiveness of SPA when studying 'user movement related' services. In case of supply and demand balance, concentrating on ES that are more regionally bound and not traded on globally could be more straightforward when realizing the transportation routes between production and consumption sites. In addition, more quantitative assessment of both ES and EDS are needed in order to obtain a more comprehensive picture of net benefits.

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