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Published in:
Ecological Indicators

DOI:
10.1016/j.ecolind.2025.113116

Published: 01/01/2025

Document Version
Publisher's PDF, also known as Version of record

Ecological Indicators 170 (2025) 113116

Contents lists available at ScienceDirect

Ecological Indicators

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

A spatial accessibility framework for mapping the mismatch between wood supply and demand across Europe

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ARTICLE INFO

Keywords:
Spatial accessibility
Wood ecosystem service
Ecosystem service supply
Ecosystem service demand
Spatial flow

ABSTRACT

Wood is one of the most important provisioning ecosystem services (ES) of forest, crucial for maintaining the welfare and wellbeing of the population. This study maps the spatial mismatches between wood ES supply and demand across the European continent, using the concept of ES spatial flow. We first examine how balanced the relationship between wood ES supply and demand is within the region, using overlay analysis. We then test how the balance changes when applying the spatial flow of wood ES at different transport distances, using the spatial accessibility methodology. Our findings reveal that Europeans have good spatial accessibility to wood resources produced across the continent when considering spatial flows of services. Approximately 65% of demand can be met in Europe without considering spatial flows, due to the abundance of wood resources. However, interregional transport needs to be included in the analysis to fully meet European demand. This illustrates how provisioning ES spatial flow can be effectively incorporated in evaluation of ES mismatches. We suggest that spatial accessibility methods and the concept of ES spatial flow can be used to increase understanding of the balance between supply and demand, as well as issues related to the sustainable use of ES and ecosystems exploitation in the future.

1. Introduction

Forests high level of biodiversity makes them an important source of many ecosystem services (ES) (Gustafsson et al., 2012; Perera et al., 2018; Verkerk et al., 2019). Wood production is the most economically important ES provided by forests (FAO, 2010; Verkerk et al., 2015), often transported over long distances to meet the demand of local markets. As timber remains a valuable resource with growing global demand, policies are being implemented to combat deforestation and improve forest management (FAO, 2022).

In Europe, forest transition actions and policies led to an increase in forested areas across the continent (Kauppi et al., 2018). Forests and their management have been shifted during recent century and remain one of the continent's critical ecosystems (European Commission, 2021a). Markets of wood-based resources are important for EU, as forest industries represent about 7% of EU manufacturing GDP (European Commission, 2023). However, the pressure for European forests in relation to exploitation of wood resources is growing and potentially threatens the provision of other forest ES and forest biodiversity (Pohjanmies et al., 2021; Pötzelsberger et al., 2021; Lerink et al., 2023). Mapping of wood ES supply, demand and their spatial mismatches at different spatial scales can provide valuable information, first regarding the sustainable use of this important service, and second for understanding the need for forests as a limited resource to meet demand in different regions.

Mapping provision and consumption imbalance in the ES framework can be deepened by consideration of spatial aspects of service provision, beneficiaries, as well as service flow from production to consumption areas (Syrbe & Walz, 2012; Syrbe and Grunewald, 2017). Assessing ES begins with defining areas of service provision and estimating the needs for service consumption (Syrbe & Walz, 2012). Service provisioning areas (SPAs) are spatial representation of service supply, whilst service benefiting areas (SBAs) illustrate the spaces that demand a consumption of the service (Syrbe and Walz, 2012). If the SPA and SBA do not overlap, the service needs to be transferred through the service connecting area (SCA; Syrbe and Walz, 2012). This is particularly the case for many provisioning ES, such as wood. The SCA is a theoretical representation of the spatial flow of services (e.g. through transport) which helps to better

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https://doi.org/10.1016/j.ecolind.2025.113116
Received 11 September 2024; Received in revised form 13 January 2025; Accepted 14 January 2025
Available online 17 January 2025

understand the possibility of using such services in benefiting areas that are geographically distant from the providing areas (Syrbe & Walz, 2012; Ala-Hulkko et al., 2016, 2019).

In this study, we use the term ES spatial flow to illustrate the transport of ES through the service connecting area, distinguishing spatial flow from ES flow, which commonly refers to service provision (Villamagna et al., 2014; Bagstad et al., 2014). The concept of ES spatial flow allows us to identify regional spatial imbalances between supply and demand of wood ES. Through considering the spatial flow, it is possible to identify the impact of different frictions, such as transport time or distance, on the supply–demand balance when applying different spatial flow limitation values (e.g., time, distances). We use the concepts of spatial accessibility as a representative of the spatial flow (Ala-Hulkko et al., 2019).

Spatial accessibility consists of components of availability and proximity (McGrail & Humphreys, 2009). This concept is often applied to explore the density and equality of opportunities to reach a service through the transport network and can be studied in different scales and measures like time or distance (Páez et al. 2012). For example, spatial accessibility based floating catchment methods have been widely used in mapping the access to health care by population (Luo & Wang, 2003; Luo & Qi 2009; Langford et al. 2016). These sorts of analysis are commonly performed in local scales, like cities (e.g., Chen et al. 2024), but also across regions (Huotari et al. 2017). Spatial accessibility is also studied from the perspective of equal or unequal opportunities in reaching places with services. For instance, Rosik et al. (2020) analyzed the regional dispersion of potential accessibility quotients across European NUTS 3 regions and individual countries, focusing on co-periphery patterns and discontinuity belts. Weiss et al. (2018) on the other hand, used spatial accessibility framework to map travel time to cities globally, aiming to measure the impact of socioeconomic inequalities. Moreover, spatial accessibility has also proven to be a practical indicator in mapping spatial mismatches between supply and demand of provisioning ES (e.g. Ala-Hulkko et al., 2019).

The transport networks provide a basis for estimating spatial accessibility. In the case of provisioning ES, when SPAs are often not overlapping with SBAs, service beneficiaries are dependent on the transport systems, to meet their service consumption needs. Therefore, it is important to estimate the spatial flow of ES in ES mapping, as many services, such as wood, are consumed far from production areas (Bagstad et al., 2014). So far, the mapping of ES has mainly focused on the supply characteristics, as it is easier to find appropriate data for this than for the demand side (Wolff et al., 2015; Tao et al., 2018). In addition, mapping ES demand is more complex because its definition varies depending on the category of the service (regulating, provisioning, or cultural ES; Tao et al., 2018). However, mapping the balance between supply and demand can be possible only when and if the demand site of a service is already understood and mapped. The popularity of research on mapping supply–demand mismatches and evaluating the spatial flow of ES has recently increased. The most common examples of studies considering the spatial flow of ES are studies on regulating (e.g., Esse et al., 2019; Wu et al., 2023) and provisioning ES (e.g., Ala-Hulkko et al., 2019; Xu et al., 2022; Liu et al., 2022). Nevertheless, more studies regarding various types of ES, where the ES spatial flow is considered are needed to further develop the understanding of its importance and application in policy making.

This study refers to wood resources as mapped and analyzed provisioning ES. Our objective is to answer questions concerning the spatial balance of wood ES supply and demand in general across Europe. Wood ES supply is estimated using ten-year averaged regional wood production statistics across the forest area, while the demand is based on surveys and represents the average annual regional wood consumption estimate per capita across the studied regions. The spatial flow that takes place in the SCA, is examined through a developed spatial accessibility-based supply–demand balance analysis utilizing Geographical Information System (GIS) network analyses (see Páez et al., 2012). The network is crucial for mapping spatial flows at various distances, which is essential for estimating the balance between regional service provision and consumption patterns across Europe. To further underline the strengths of including ES spatial flow through accessibility analysis, separate overlay analysis is also carried out. The results of these two methods are then compared. The specific research questions of this article are:

1) How much regional wood ES supply can meet demand if the interregional spatial flow of services is not considered?
2) Considering spatial accessibility and spatial flow, what are the transport distances required to satisfy the general demand for wood ES in different parts of Europe?

It is important to understand that accessibility to different ES plays a major part in maintaining humans' wellbeing and welfare in general (Sangha et al., 2022) and mapping of wood ES is a crucial part of the larger entity. The suggested framework and conducted analysis in mapping spatial ES mismatches across Europe can not only be useful for testing the methodology for spatial flow mapping but is also an opportunity for a better understanding of the balance between wood ES provision and consumption patterns across the continent.

2. Materials and methods

2.1. Study area

Europe was selected as the study area for this research due to the availability of data to map the supply, demand, and spatial flow of wood ES, but also because wood plays a crucial role for sustaining the welfare of the European population.

As a result of forest transition, European forest areas have been increasing during the past century (Kauppi et al., 2018; Palmero-Iniesta et al., 2021). Nevertheless, European forests and forest industry are facing many economical, technological, societal and environmental changes (Oberle et al., 2019, Wolfslehner et al., 2020). For instance, the demand for green consumption, construction or bio-refinery wood products is forecasted to grow, while traditional wood products are losing significance in the European market (Wolfslehner et al., 2020). Environmental challenges, such as more frequent endemic and pest diseases, growing occurrence of extreme weather events and other climate change related issues (e.g., droughts, wildfires, superstorms), growing importance of non-wood forest ES and general forest ES tradeoffs as well as the need for biodiversity and habitat protection will intensify in the nearest future (Forzieri et al., 2021; Himes et al., 2023). Forest strategies, including European Green Deal (European Commission, 2019), EU biodiversity strategy for 2030 (European Commission, 2021b) or New EU Forest Strategy for 2030 (European Commission, 2021a), address these challenges, aiming to ensure health and quality of EU's forests. Gathering more data for estimating and mapping production, consumption and the spatial flow of ES, including wood, can be useful for policy makers and solving these challenges related to sustainable forest ES consumption and implementation of mentioned strategies (Avtar et al., 2020; Nemec and Raudsepp-Hearne, 2013).

2.2. Mapping wood ES providing (SPA) and benefiting areas (SBA)

The wood ES supply and demand data used in this study is based on compiled wood production statistics and consumption estimates between 2008 and 2018. This data was previously used for mapping temporal trends of wood ES supply and demand across Europe (Poturalska et al., 2024a). The data structure details can be found from Fig. S1. A & B. Study area covers 25 European Union countries, United Kingdom, Switzerland, Norway, as well as Balkan states, including Albania, Croatia, Macedonia, Serbia, Montenegro and Bosnia and Herzegovina. The nomenclature of territorial unit for statistics (NUTS 3, n=

1326), local administrative units (LAU, n= 1313) and Bosnian regional division units (n= 18), are the basis for analytical resolution of this study (Fig. S2). These administrative regions represent the statistical units, for which the supply and demand data were gathered and calculated.

ES supply is defined as the amount of ES actually mobilized in specific time and space (Burkhard et al., 2012; Dworczyk & Burkhard, 2021) and spatially represents service provisioning area (SPA; Syrbe & Walz, 2012). The core of the supply data is based on compiled statistical information on average annual wood harvested (i.e. use of wood itself) in cubic meters (m^3) by administrative region (NUTS 3 and LAU) between 2008 and 2018 (Poturalska et al., 2024b; Eurostat, 2021; supplementary materials Fig. S1. A). In cases where only country level harvest statistics was available (see Fig. S1. A), supply in administrative regions was estimated by first, calculating the harvest per hectare, then multiplying it by the area of the forest available for wood supply in administrative regions. Forest cover available for wood supply was estimated using Corine Land Cover (CLC) data (EEA 2006; 2012; 2018). CLC 2006 was used as a proxy of forest cover in a year 2008, CLC 2012 in years 2009 to 2014 and CLC 2018 for the years 2015 to 2018. All forest classes were included in the data structure (coniferous, mixed and broad leaves). The protected areas (World Database on Protected Areas; IUCN & UNEP-WCMC, 2022) were excluded from the forest cover to get more realistic information on the potential areas capable of wood ES supply.

The end users' need for the ecosystem-based service is what we define as demand (Bastian et al., 2013; Burkhard et al., 2012; Potschin-Young et al., 2018), and spatially illustrates socio-economically focused service benefiting area (SBA; Syrbe & Walz, 2012). The demand is based on annual industrial roundwood estimated consumption data (per 1000 population) , for years between 2008 and 2018 (UNECE, 2022); supplementary materials Fig. S1. B). The data are based on Joint Forest Sector Questionnaire (JFSQ), which was initiated by the Food and Agriculture Organization of the United Nations (FAO), The International Tropical Timber Organization (ITTO), the United Nations Economic Commission for Europe (UNECE), and Eurostat to gather statistics on the global timber situation (Eurostat, 2023c). Eurostat is responsible for collecting the data from EU and EFTA countries, and UNECE collects the data from other European countries included in this study (FAO, 2001; Eurostat 2023c). JFSQ is based on timber-related national statistics, provided annually since 1997 (McCusker, 2021). The data represent the amount of unprocessed wood consumed by manufacturing industries to produce the demanded goods and is defined as "*the sum of wood logs from all sources plus wood that is imported, minus wood that has been exported (…) measured under bark*" (UNECE, 2022). All types of wood are included in the data same as for supply. In this article we use these data as a proxy that corresponds to the sum of demanded wood ES for satisfying populations' needs in each studied area.

To analyze the balance between demand and supply using spatial accessibility method, we calculated the absolute volume (m^3) of demand and supply of wood for each area. Absolute ES supply and demand values (m^3) allocated to the polygons of the administrative regions may at first appear to be larger in the larger polygons. However, applying accessibility analysis to explore supply–demand balance is only possible with absolute ES values. For our analysis, it's necessary to represent the origin and destination as points. Hence, we've transformed the supply and demand polygons into centroids. These centroids correspond to the centers of the statistical region and are all linked to the network, ensuring network connectivity. In this study, we analyzed the average annual supply and demand for years between 2008 and 2018 (Fig. 1) and single year 2018 for comparability reasons (Fig. S3.). Two independent time periods were examined to determine if there is a significant difference between the average annual values of a decade and the single most recent year from the data.

2.3. Mapping service connecting area (SCA) and spatial flow

The transport network represents the service connecting area (SCA) as defined by Syrbe & Walz (2012), and it can be used to analyze the transfer of service (spatial flow) from provisioning to benefiting areas. This study uses European level road and ferry network (Fig. S4.) to quantify the spatial flow. The network data consists mainly of EuroGlobalMap (2016) and partly of Open Street Map (OSM, 2016) in the Balkan Peninsula (see Ala-Hulkko et al., 2019). To estimate the spatial flow of mapped services, wood ES spatial accessibility from provisioning sites to service beneficiaries have to be calculated (Bagstad et al. 2014; Ala-Hulkko et al., 2019). Spatial accessibility assesses the potential for the end user to consume wood ES produced within specified transport threshold. In this study a calculation of spatial accessibility-based supply–demand balance is suggested and tested to map spatial flow of wood ES across Europe for the average annual values between 2008–2018 and independently for the year 2018. Commonly available accessibility

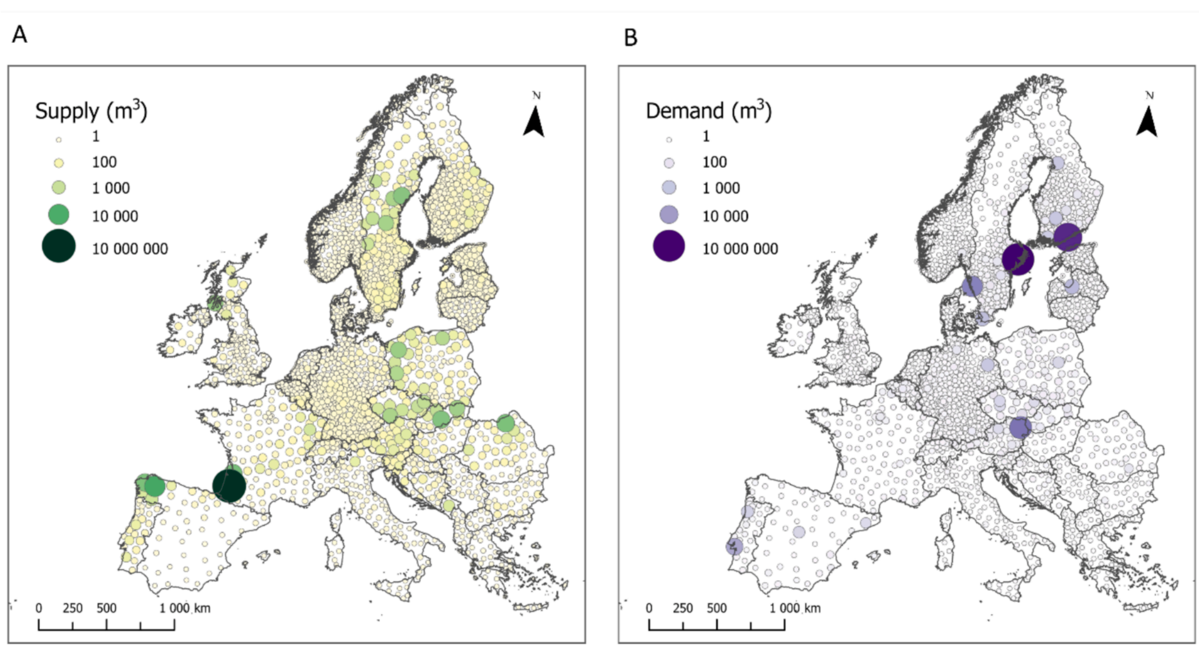

Fig. 1. Average annual wood ES (A) supply and (B) demand estimates (m^3/per 10 years) between 2008 and 2018.

analytical tools lack the capability to perform supply–demand analysis including quantifying supply surpluses and unsatisfied demand, whereas e.g. floating catchment area type of approaches include some of the key components. Hence, an analysis utilizing origin–destination cost matrix and operations was built using Python 3 for Arc GIS Pro 3.0.3. to better account for supply surpluses and unmet demand.

Analysis relates supply and demand to each other within defined catchment area with stepwise iteration starting from smallest cost-distance. In each step of the analysis, supply of the wood is subtracted from the demand. Likewise, also demand is subtracted from supply for the locations connected by shortest cost-distance available during each step (Fig. 2A). The analysis may be described with mathematical notation in the following way.

In the origin–destination cost matrix supply in different locations may be expressed as a row vector,

$$S = [s_1 \quad \cdots \quad s_i] \tag{1}$$

and demand in different locations may be expressed as a column vector,

$$D = \begin{bmatrix} d_1 \\ \vdots \\ d_j \end{bmatrix} \tag{2}$$

and again, least cost path-based travel cost-distance matrix connecting supply and demand locations can be expressed as a $i \times j$ matrix.

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

Now we may express to have supply s_l in location l (in where l can be $1 \leq i$) and demand d_m in location m (m can be $1 \leq j$) and the least cost path between elements s_l and d_l can be expressed as t_{kl}. Next the travel cost-distance matrix T is sorted,

$$T_n = min\{t_{11,\cdots,}t_{ij}\} \tag{4}$$

and the supply s_l is allocated over the lowest cost-distance to demand, so that if supply is larger than or as large as the demand $s_l \geq d_k$ negative change for supply and demand equal to available demand,

$$\Delta s_l = \Delta d_k = -d_k \tag{5}$$

or if the demand is larger than the supply $s_l < d_k$

$$\Delta s_l = \Delta d_k = -s_k \tag{6}$$

The allocation of supply to demand is then continued over to the next lowest cost-distances until the travel cost distance is less than the defined cost distance threshold c.

$$t_{lk} < c \tag{7}$$

The modified vectors S and D will thus represent the supply surplus and unsatisfied demand within the cost distance limit c.

In this study, the transport distance as kilometers is used as a transport cost. Three different thresholds were applied in this study, starting from catchment of 150 km, followed by doubling the distance to 300 km and 600 km respectively (Fig. 2. B). Given thresholds were selected on the basis of the average transport distances of timber by different transport modes (Strandström, 2022; Eurostat, 2023a). These distances spread from regional to international, allowing us to explore whether and when hypothetical wood ES supply and demand balance can be reached.

In addition to the accessibility analysis, overlay analysis was carried out by subtracting demand from the available supply. This method is often used in studying ES supply and demand balance (see e.g., Burkhard et al. 2012; Martínez-López et al. 2019). However, its major problem is that it does not consider the ES spatial flow, but only examines the balance within given region, depending on the scale of the study. Comparing the overlay with the spatial accessibility results enables us to see the differences between the balance within the regions (overlay) and when the service is transported (spatial accessibility).

3. Results

In a situation where spatial flow has not been considered, overlay analysis shows that on average in the period between 2008 and 2018, 1366 (51%) regions had higher demand than supply. This pattern is mainly caused by larger population concentrations separated from forest regions. It can be seen especially in vastly populated areas and regions where the supply is not so high, due to the low availability of forest resources. Again, supply surplus was detected in 1291 (49%) regions, most of them located in Fennoscandia and Central Europe (Fig. 3).

To estimate the generalized spatial mismatch between supply and

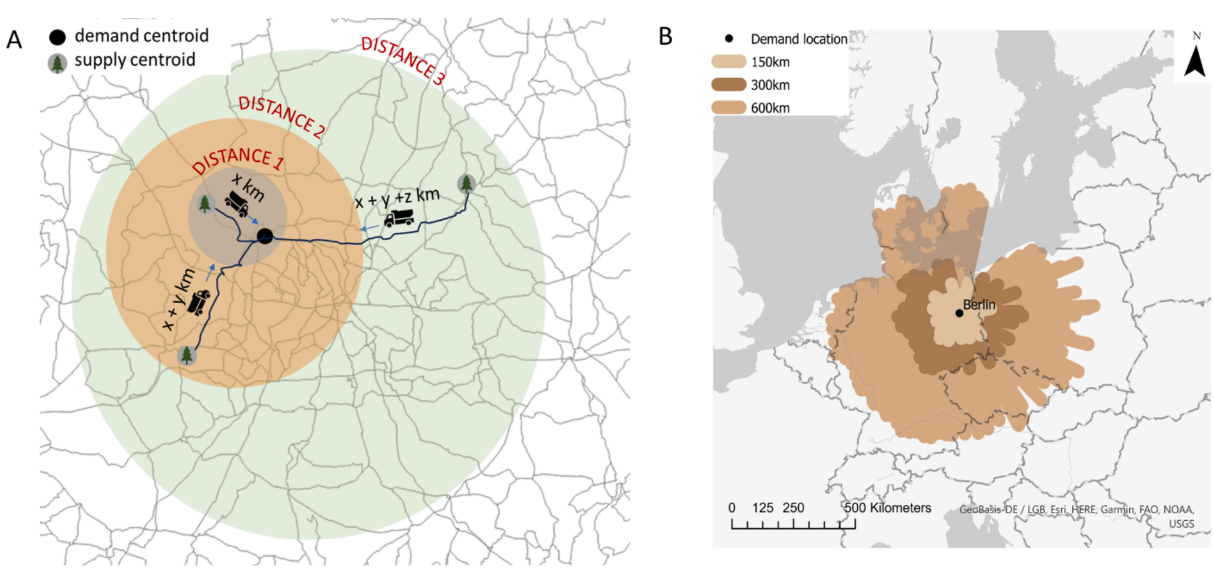

Fig. 2. The areal supply–demand balance method distributes supply to demand point choosing the least cost path (A) within each distance threshold. Potential surpluses of supply can be transferred to unsatisfied demand locations by applying further distance thresholds. Thresholds tested in this study (B) represent regional (150 km), national (300 km) and international (600 km) transport distances.

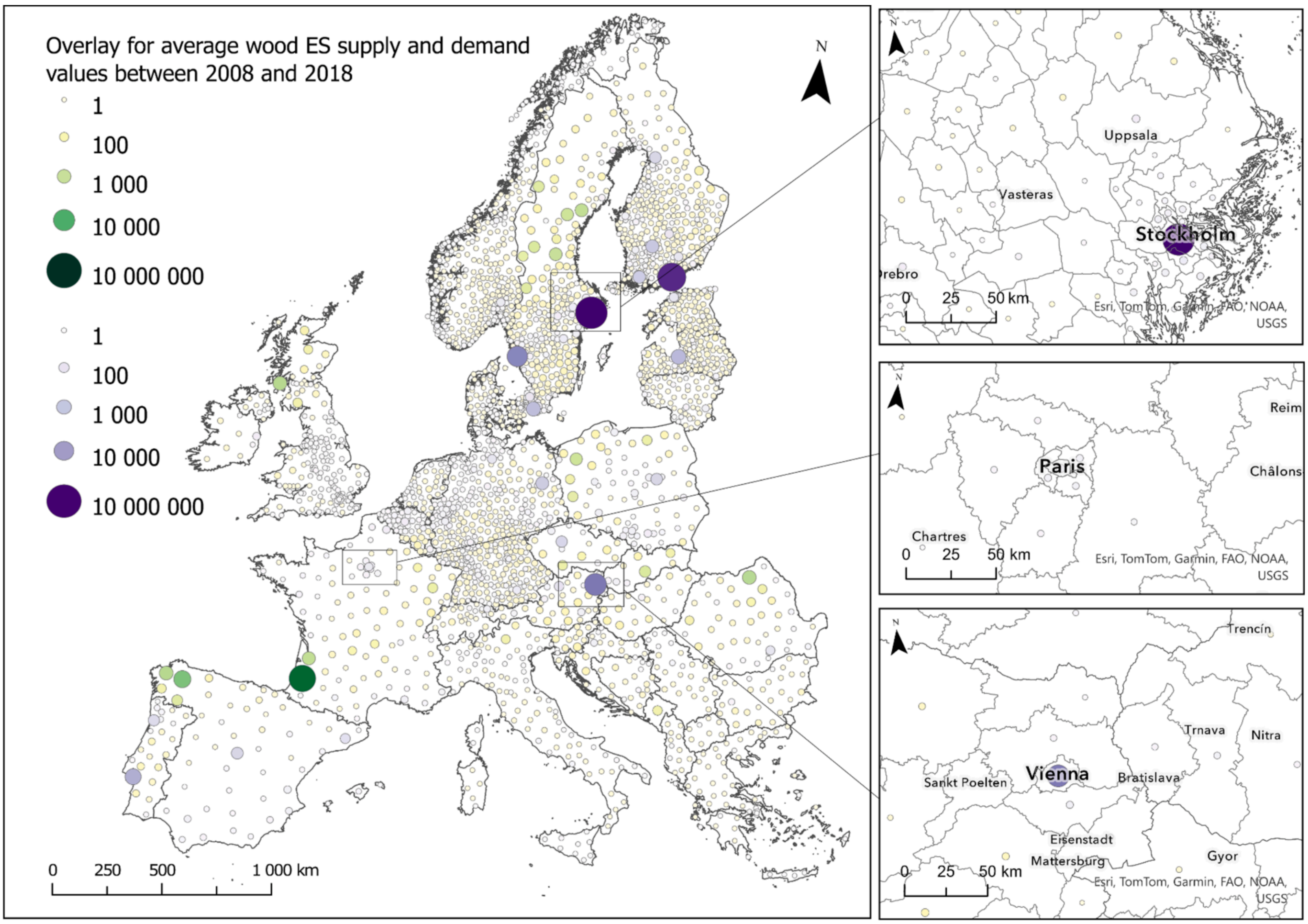

Fig. 3. Overlay analysis results for average annual supply and demand values between 2008 and 2018 (m^3 per 10 years). Overlay represents subtraction between supply and demand. The results of overlay analysis for the single year 2018 can be found from Supplementary materials, Fig. S5. Note that the size of administrative boundaries may affect the visual result (see the spatial resolution and the administrative units used in this study in supplementary material Fig. S1).

demand, we tested various transport distances to determine the distance the supplied wood ES would need to be transported, without the structure of industry and logistics, to meet the average demand of its consumers in Europe (Fig. 4). Most of the wood demand in rural areas can be met by nearby transport (within 150 km) and locations with clear supply surpluses at this distance threshold are in areas rich in forest resources, including central Fennoscandia, central and eastern Europe (Fig. 4 A). The remaining demand is mostly concentrated in large population centers and less accessible regions such as some of the Mediterranean islands, northernmost parts of Lapland, rural areas located in regions with low wood ES provision. Continentally, after transporting wood in catchment of 150 km substantial supply surplus can be noticed (Table 1.). In addition, our results show that more than three-quarters of total demand can be met by supplies transported within a short distance of 150 km (Table 1).

Increasing the transport threshold distance to 300 km is already enough to balance supply and demand in Central Europe (Austria, Poland, Czechia). However, unsatisfied demand is still visible, for example in London, Stockholm, southern Finland, and southern Spain (Fig. 4B). By increasing the transport threshold distance to a relative long 600 km, the average annual regional demand in Europe is almost fully satisfied (Fig. 4C). At the same time, supply surplus is left across vast number of European regions (e.g., central Fennoscandia, central Europe, south-west France). On average, the percentage of satisfied demand increases from 63% (without interregional transport) to 77% when local spatial flow is taken into account. The demand for the wood increased continuously up to 89% as the transport distance increased, finally reaching almost 98% of the demand within the last tested catchment of 600 km (Table 1). This indicates that the wood ES consumption needs for entire continent can be met within reasonable transport distance.

However, even though the variation of supply and demand values in the data used in this study is low (see Poturalska et al., 2024b), the values of reaching satisfaction for wood ES demand can vary slightly between years. For example, considering only the 2018 supply and demand values, demand satisfaction was about +2 % higher than the average annual demand for all studied transport distances (Table 1). The supply surplus in 2018 is also around 3–4% higher than the 10-year average across all distances. The spatial distribution of areas with supply and demand surpluses for year 2018 (Fig. S6) follows the average annual supply and demand areas for 2008–2018. Thus, the result indicates that while supply and demand in a single year (2018) will differ from the annual average of 2008–2018, the regions with the highest wood ES supply and demand are in the same parts of Europe (see Fig. 4 and Fig. S6). Additionally, there are significant supply surpluses within the largest transport threshold distance, as shown in Table 1. Approximately 20% of the average annual wood ES supply between 2008 and 2018 remains after transport of 600 km. The supply surplus in 2018 was higher than the average, reaching almost 25% across the study area (see Table 1.).

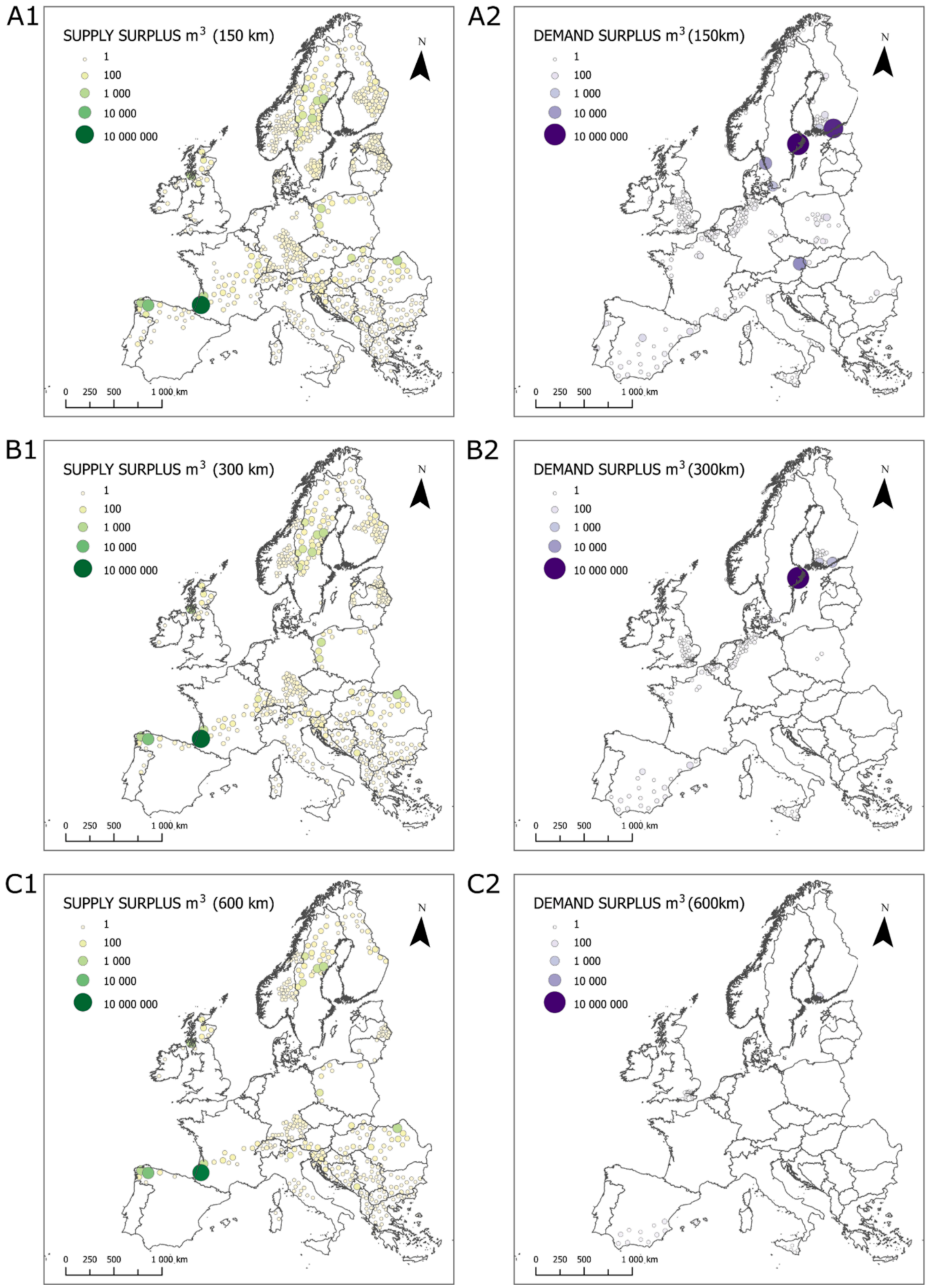

Fig. 4. Wood ES supply and demand surpluses after accessibility analysis for distances of 150 km (A), 300 km (B) and 600 km (C) for average annual supply and demand values between 2008 and 2018 in cubic meters (m^3 per 10 years). The visualization of calculations for tested single-year values (2018) are available in supplementary material (Fig. S6).

Table 1
The comparison between overall European wood ES unsatisfied demand and supply surplus (%) in each transport distance threshold (km) for solely 2018 and average period between 2008 and 2018.

Transport distance (km)	% Unsatisfied demand 2018	Supply surplus 2018	Average annual unsatisfied demand 2008–2018	Average annual supply surplus 2008–2018
0 (within the region)	34,8	58,5	36,8	55,1
150	21,5	40,1	23,4	37,4
300	9,5	31,0	11,5	27,7
600	0,8	24,4	2,2	20,1

The threshold related to the overlay analysis is 0 km (within the region), and the thresholds related to the spatial accessibility analysis are 150, 300 and 600 km.

4. Discussion

In this study, wood is an example of ES that is a crucial resource provided by forest ecosystems. This study represents the spatial flow of the service from wood ES supply to demand sites through spatial accessibility. It improves the understanding of the balance between wood ES supply and demand in Europe by considering the properties of connecting area (SCA) where pathways of spatial flow occur. These properties have an impact on the delivery and potential use of ES. Thus, spatial flow is a key factor to consider when evaluating the transfer of services between the supply and demand of ES at various spatial scales (Syrbe & Walz, 2012; Bagstad et al., 2013; Ala-Hulkko et al., 2019; Huang et al., 2022). This study used spatial accessibility to model carriers that deliver wood products from providing areas to beneficiaries via transport networks and provide information on supply and demand availability and proximity.

4.1. Mapping the spatial flow of ES: advantages of accessibility methodology

The evaluation of the balance between ES supply and demand has been a topical research problem for quite some time, but the overlay analysis commonly used for evaluating this balance (e.g., Burkhard et al., 2012; Nedkov & Burkhard, 2012; Field & Parrott, 2022), does not adequately answer the questions of provisioning ES supply and demand mismatches. This is especially evident when it comes to ES that are used in a different location from where they are produced (Bagstad et al., 2014; Syrbe & Grunewald, 2017). In practice, it is difficult to define proper regional division for overlay analysis, whereas distance-based approaches may provide more comparable results for spatial and temporal analyses. This is indisputable in the case of a provisioning ES, such as wood, where the SPA and the SBA do not match perfectly and where the transport of the service is required, the overlay does not give correct outcome (Dworczyk & Burkhard, 2021). In this study, the results of overlay analysis (Fig. 3.) demonstrate the in-situ situation with regions of production or consumption concentration. Even though overlay analysis gives an insight into the volumes of supply and demand within the regions, it does not account for the spatial contexts of ES delivery.

On the other hand, the accessibility analysis and incorporating the spatial flow of wood ES enables a more accurate examination of the balance between supply and demand. Spatial accessibility framework for European wood ES is focused to analyze a service that is mainly produced in different regions than consumed. The production sites are in northern and central regions of the continent, while the benefiting areas are those with higher population density (Fig. 4). The supply is related to the potential of the ecosystems to provide ES, and the demand data is an estimated indicator of the populations' consumption needs. The supply and demand indicators are related to each other's, which is also important in ES cascade model (Syrbe & Grunewald, 2017; Dworczyk & Burkhard, 2021). Wood ES demand is connected to the production size (supply) and other factors such as economic development and industrialization level (Kayo et al., 2015). For example, in countries where the forest resources have higher potential, and therefore supply (such as regions in Finland, Sweden or Central Europe), the demand tends to be higher too, and it is also visible in our data (Kayo et al., 2015; UNECE, 2022 & Fig. 1.).

The distances applied in this study describe spatial flow occurring in different scales, and they have been chosen to depict actual transport distances of wood ES across Europe, but also examine how far the service needs to be transported to meet all continental demand. Based on the accessibility analysis, European supply can meet the measured needs of wood ES of the entire population on a continental basis. The delivery of the service already within the distance of 150 km, allows about 75% demand satisfaction on average (Table. 1, Fig. 4) and reach nearly full satisfaction within 600 km transport distance. This result indicates good spatial accessibility of the resources, for consumption of the domestic population, within relatively short transport distance. Although the spatial accessibility of wood ES in theory tends to be good across Europe, the question is how well people can actually use the services and how far products are actually transported for people. Economic competition can affect the affordability of the service, that fluctuates in time and is dependent on the changing wood market (Nepal et al. 2021), that is prone to crises, socio-economic or environmental shocks events and regional shifts (Hlásny et al., 2021; Lock et al., 2021; van Kooten & Schmitz, 2022). In addition, satisfying European wood ES demand through longer transport distances can be directly connected to higher carbon emissions depending also on selected transport mode. Optimizing the delivery of wood ES from areas of high production to areas of high demand can reduce transport costs, but also the amount of greenhouse gas emissions emitted during transport. This is important because there is a growing need to reduce greenhouse gas emissions from all human-made sources, including the transport sector, to mitigate future climate impacts (Greene et al. 2011; IPCC, 2023). Therefore, good spatial accessibility does not guarantee sustainable and equal economic accessibility for all who need the service in certain areas.

4.2. Critical reflections and future directions

Europe is characterized by very good spatial accessibility of wood ES and that it produces substantial wood ES surpluses. Still wood ES provision can be impacted by several factors, like the impact of the global markets. Despite the internal factors mentioned above, such as economic accessibility to the resources of the domestic population, the competition within the study area, the global demand for wood, which is not considered in this study, can pressure the European production, and therefore European forest ecosystems. Factors such as changes in international prices caused by for example trade restrictions, interdependency of production stock quantity, policy implications and most importantly global population growth are having impact on the whole wood market (Mathieu & Roda 2023). According to the FAO forecasts the population-driven global demand for wood will grow 37% by the year 2050 (FAO, 2022). In addition, rapid changes and trade wars may provoke shocks on the global wood market. This may cause quick fluctuations of prices, weakening the economic accessibility of wood, meaning that even if spatially accessible wood wouldn't be affordable. Some of the wood ES produced within Europe is directed to markets outside the continent, as Europe plays an important role as a wood ES exporter (Lock et al., 2021). Although European countries produce a huge amount of wood, not all of it is consumed domestically, which is visible also in overall supply and demand levels from our data. Taking into account the global supply and demand of wood ES would provide a better perspective, but the available data sets are still limited.

However, this study opens the focus on the European scale, with the main aim of analyzing how total wood consumption is balanced against the general availability of wood supply in the context of spatial accessibility. The amount of surplus of harvested wood raises questions in the larger sustainability framework, as forests serve in multiple functions and provide various services besides wood (Lerink et al., 2023). Some studies have also argued that the large exploitation of European wood ES, for global trade, can potentially cause a negative impact on European forest ecosystems and the services they provide (Pohjanmies et al., 2021, Pötzelzberger et al., 2021; Lerink et al., 2023). Moreover, the character of the internal demand is changing and e.g. bioeconomy is already increasing the demands for wood as a sustainable energy resource, and it is predicted that this trend will continue in the next decades (European Commission, 2021a; Fritsche et al., 2021; Lerink et al., 2023). In addition, we do not include specialized types of wood production and consumption, types of industry and the actual logistics in the supply chain. The supply chain of wood ES is an example of a highly complex system, through which the service gets before reaching the consumer, however in the end of the process, people benefit from the final product of that supply chain (Burkhard et al., 2014).

There are various elements that could be applied to deepen the approach starting with industry and logistics continuing with national border policies and including economic barriers and incentives. In general, European countries are connected by several free trade agreements and the transport of the wood ES, as well as other goods is relatively easy, compared to other parts of the globe (Eurostat, 2023b). Thus, a good spatial accessibility indicates well a good access via infrastructure and proximity of services to demand.

Hence, future developments of this study could focus on how to include logistics, different types of forest industry, or manufacturing processes when considering supply and demand mismatches of wood ES. Similarly, the inclusion of temporal data would be beneficial as the above issues related to service provision and consumption are subject to constant change. Exploring mismatches in various shock scenarios, such as the absence of a free trade zone or its closure, could help to predict the future mismatches resulting from shock events, such as border closing due to epidemics, across continents. In addition, specific regional landscape diversity measures could be taken into account in future studies.

Nevertheless, the application of spatial accessibility methods should be used more often in mapping supply–demand mismatches of other types of ES (like in e.g., Ala-Hulkko et al. 2019). However, decisions on which accessibility method to choose should be adjusted to the service type (e.g. provisioning, regulating or cultural) and the supply and demand data analyzed. In the case of cultural services, for example, the direction of spatial flow occurs in an inverse manner (from the service demanding area to the SPA) compared to the provisioning services. In addition, it is not the ecosystem service itself that moves through the network, but people (e.g. Ala-Hulkko et al. 2016, Dworczyk & Burkhard, 2021). In this case, spatial accessibility needs to consider, for example, the attractiveness of destinations and the people willingness to travel (Páez et al., 2012).

Accessibility analyses can potentially be used to examine trade-offs between ES supply and demand, as accessibility can consider the spatial balance between supply and demand in situations where the use of a service involves mobility (spatial flow). Looking at multiple ecosystem services together provides valuable insights into whether certain areas are experiencing overproduction or unmet demand for ES, and whether these patterns overlap geographically.

Accessibility analysis is, in principle, ready to be applied to different types of areas and at different scales (from local to global), given the availability of network analysis tools and accurate geospatial data on transport networks, supply and demand. However, further studies are needed at different geographical scales. Additional ES supply and demand data are necessary to further research and test this method, while also incorporating socio-economic aspects of service supply and demand, both temporally and spatially. These data and assessments are crucial for implementation of policy strategies and plans, such as for example EU forest strategies or resilience plans (European Commission, 2021a), providing a more accurate means for support sustainable decision making.

5. Conclusions

Spatial accessibility is a framework to be used in mapping supply and demand mismatches of ES. This methodology incorporates the spatial flow of ES in the mapping process and enables exploration of whether a balance between supply and demand can be achieved, and at what distance threshold this can occur. The methodology for assessing spatial accessibility is more effective in identifying mismatches in ES than overlay analysis. Overlay analysis does not consider the spatial flow of goods and only provides a perspective of the supply–demand relationship "in-situ". Our study found that in Europe, the balance between supply and demand of wood ES can generally be achieved within a 600 km distance. Additionally, our results show that there are also supply surpluses for global trade even after satisfying European domestic demand. Estimating surpluses or overconsumption can be a valuable tool for policy and management planning. Spatial accessibility methodology should be applied more often in mapping the ES supply and demand mismatches, which are dependent on the network or transport systems. Explicitly defining the spatial connections between ES supply and demand adds accuracy in mapping ES spatial mismatches.

CRediT authorship contribution statement

Anita Poturalska: Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Ossi Kotavaara:** Writing – review & editing, Software, Methodology, Conceptualization. **Terhi Ala-Hulkko:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization.

Funding

This work was supported by the University of Oulu, Kvantum Institute funding and Transformative Cities- project. Transformative Cities has received funding from the European Union – NextGenerationEU instrument and is funded by the Academy of Finland under grant number 352943.

Declaration of competing interest

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

Acknowledgements

We are thankful to Ph.D. Tuomas Kortelainen for his valuable comments and contributions to the notation and evaluation of the equations.

The analysis was performed with Arc GIS Pro 3.0.3 and Python 3.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113116.

Data availability

The data are available open-access and the information about data availability is given in the manuscript.

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