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Research Article

Mapping ecosystem service temporal trends: a case study of European wood potential, supply and demand between 2008 and 2018

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Abstract

Wood is one of the key forest Ecosystem Services (ES) of growing ecological, social and economic importance; therefore, we need more precise information about its long-term usage. To achieve this, it is necessary to examine the spatio-temporal aspects of wood ES potential, supply and demand. In this study, we analyse spatio-temporal patterns of wood ES supply and demand at continental, national and regional scales to identify areas of increasing and decreasing supply and demand levels in Europe. In addition, we present background information about the potential of European forests to provide wood ES and its relationship to supply and demand. Our results showed that the overall European wood supply and demand as well as the wood ES potential were characterised by increasing trends. Furthermore, this increase was also regional, particularly in central and northern Europe. This study demonstrates not only the significance of spatio-temporal data in ES mapping, but also the importance of considering a broader range of components of the ES cascade model when assessing change. Our research has shown that potential, supply and demand can all increase in the same area, but also that low supply and demand do not guarantee wood potential growth. In addition, we found that a broad scale assessment helps to identify more general patterns and trends, but analysing data at a more accurate

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scale provides more comprehensive insights for identifying areas that may require targeted action for sustainable forest management.

Keywords

wood ecosystem service (ES), ES potential, ES supply, ES demand, temporal change, spatial distribution

Introduction

Forests offer a range of Ecosystem Services (ES), including soil conservation, climate change mitigation, medicinal resources and recreation (Thorsen et al. 2014). The European forest area has been expanding by 9% since the 1990s and is still growing (Köhl et al. 2020). Maes et al. (2020) also showed that forest loss and gain were mostly balanced in Europe between 2000 and 2018. These findings are due to the forest transition, which represents the combined effects of social, economic, cultural and political actions for forest restoration, as well as natural processes (FAO 2009, FAO and UNEP 2020, Maes et al. 2020, Palmero-Iniesta et al. 2021). Nevertheless, an increase in forest area does not necessarily indicate an improvement in forest quality. In fact, the condition of Europe's forests has been reported to have deteriorated due to the combined effects of human and natural pressures (Maes et al. 2020). One of these pressures is the consumption of wood, which has been steadily increasing for several decades and is projected to rise by 25-45% by 2050 compared to 2020 globally (FAO 2022). Additionally, in Europe, the demand for wood is expected to increase as a consequence of green transition (e.g. Bull (2018)). Growing demand for wood products only intensifies the pressures on forest ecosystems and other services they provide (Verkerk et al. 2014, Chaudhary et al. 2017, Pohjanmies 2018, Blattert et al. 2023).

Protecting, restoring and promoting sustainable use of forests are key issues for many emerging international agenda, scientific reports and policies (e.g. United Nations (2015a), United Nations (2015b), European Commission (2020)). They highlight the urgency for better understanding of varying patterns in using different ES. In response to this need, map-based spatial analysis has been identified as an important method for presenting complex information on the spatial distribution of ES in a practical and easy-to-read form (Burkhard et al. 2012). Thus, mapping of forests and other ES helps to integrate the information on their spatial coverage into policy- and decision-making (Maes et al. 2012). Spatial data and visualisation of any ES potential, supply and demand coverage can be used to evaluate local production and consumption patterns, as well as risks of overconsumption. However, we need more information, not only on the spatial coverage of the ecosystem capacity to provide ES, but also on their supply and demand values and their temporal changes. Including the temporal dimension in ES mapping has an immense potential for discovering the drivers and causes of their overuse or mismanagement (Renard et al. 2015, Rau et al. 2019). A joint assessment of the spatio-temporal trends of forest ES can help to better understand the progress towards their sustainable use.

Forest ES, like all ES, revolve around ecological and socio-economic interactions, meaning that their current state is affected by both ecosystem properties and societal needs (Martínez-Harms and Balvanera 2012). ES supply and demand are differentiated from the stocks of ES potential services (in this study referred to as ES potential), which is defined as the hypothetical maximum yield that is rarely fully utilised (Burkhard et al. 2012, Potschin-Young et al. 2018). In ES mapping, supply and demand are interconnected, but represent different spatial aspects (Potschin and Haines-Young 2011, Rau et al. 2019). Ecologically focused supply illustrates the area of service provision and is defined here as the amount of mobilised service in time and space (Burkhard et al. 2012, Villamagna et al. 2013, Dworczyk and Burkhard 2021). Socio-economically focused demand exemplifies the area of receiving services (Syrbe and Walz 2012, Syrbe and Grunewald 2017, Ala-Hulkko et al. 2019) and is considered in this study as the need to consume a service (Haines-Young and Potschin 2010, Burkhard et al. 2012). Over the years, research on ES has focused more on potential and supply than on demand (Tao et al. 2018, Rau et al. 2019). This may be explained by the fact that different definitions of demand make it more difficult to map (Wolff et al. 2015). However, studies that consider both ES supply and demand are the key in searching for ways to manage them and their rapid socio-economic change simultaneously (Rau et al. 2019) and to explore the balance between supply and demand (Wei et al. 2017, Ala-Hulkko et al. 2019).

In recent years, there has been an increasing interest in studying the spatio-temporal dynamics of ES supply and demand, but, according to Rau et al. (2019), the number of studies considering the temporal patterns of ES have remained limited. Especially when exploring spatio-temporal dynamics of forest ES, local case studies are the most frequently conducted (e.g. Guan et al. (2020), Roces-Díaz et al. (2021), Helseth et al. (2022)). In European and global studies, there has been a greater emphasis on investigating the intensity of wood harvesting (e.g. Verkerk et al. (2015), Chaudhary et al. (2017)) and its drivers (e.g. Levers et al. (2014)).

The provision of wood resources, being an important forest product of economic value, is one of key forest ES (Verkerk et al. 2015, Jenkins and Schaap 2018). Wood ES serve as a source of energy, building materials and a basis to produce various goods (Bull 2018). According to the Common International Classification of Ecosystem Services (CICES), wood ES belongs to the provisioning ES section and is divided into fibre and material producing or energy producing classes according to its final use (Haines-Young 2023). In this study, wood ES represents both classes including fibre, material and energy wood. The purpose of this study is to map the potential, supply and demand of wood ES and analyse their spatio-temporal changes across Europe for the period 2008-2018. Europe was chosen as the study area for this research because it is one of the major suppliers and users of wood resources in the global market (Brack 2018). It is also a good example of a region in which forest cover has increased in recent decades (Köhl et al. 2020), but its quality has not improved, due to high exposure on intensifying anthropogenic and natural pressures (Maes et al. 2020).

In this study, we provide an insight into wood ES mapping using a Geographic Information System (GIS)-based space-time cube to analyse the distribution and temporal trends of wood ES potential, supply and demand across the European continent. The integration of the temporal dimension in mapping all of the spatial characteristics of ES is under-represented in ES research (Rau et al. 2019) and it concerns all services. Wood ES supply and demand are recognised pressures on forest, related to the human activities (Maes et al. 2020); therefore, assessing their spatio-temporal trends is an important step towards realising the scope for improved understanding of wood ES use. Here, we use annual spatio-temporal wood ES potential, supply and demand data collected and compiled from statistical sources. We explore temporal patterns and changes in ES potential, supply and demand, with statistical analysis and visualisation tools in GIS. In addition, we analyse the effect of scale in ES mapping, comparing studied variables in continental, national and regional levels. The overall goal of this study is to improve our understanding of the importance of temporality and scale in mapping ES, particularly concerning the aspects of potential, supply and demand characteristics to support informed decision-making. The specific research questions of this study are:

1. How does the distribution (and relationship) amongst ES potential, supply and demand vary at different spatial scales (continental, national, regional) across Europe between 2008-2018 and
2. What are the recent spatio-temporal trends in wood ES potential, supply and demand within analysed scales?

We expect to detect increasing trends in wood ES supply and demand and identify the regions of notable changes in trends of these ES components, in different scales.

Mapping, assessing and evaluating ES is essential for their practical application and sustainable management (Wei et al. 2017). Forest ES, especially wood, play an important socio-economic and ecological role in maintaining human well-being. Spatio-temporal evaluation of supply and demand of wood ES can be applied, for example, in answering questions on changes in forest ES usage, estimating the balance between production and actual needs of the population that benefit from ecosystems or identifying potential issues with forest management, analysing whether the trend of resource exploitation goes within the strategic plan of sustainable development (Maes et al. 2012). In this paper, by addressing the matters of wood ES supply and demand variation with the background information on the wood ES potential and studying its spatio-temporal trends, we can gain more information about the temporal changes of studied ES in Europe, which can be used in planning our sustainable future.

Material and methods

Study area and its forest resources

This paper analyses the potential, supply and demand of wood ES, which are elements of the ES cascade model (Potschin and Haines-Young 2011, Potschin-Young et al. 2018, see Fig. 1) at two spatial scales: continental and national. In addition, due to the availability of more accurate data, supply and demand are also examined at a third, regional scale. The statistics at continental scale provide a summary overview on the studied characteristics and are, therefore, expressed in absolute values (the total volume, m^3, of wood available for supply or supplied or consumed per year on a continental scale). In the national and regional analysis, the area of the administrative region or country is taken into account (expressed in m^3/ha/year). The study area covered European countries for which comparable data on potential, supply and demand were available between 2008 and 2018. A total of 24 European Union (EU) countries, as well as Switzerland, were included in the study (Suppl. material 1, Figure S1). At the continental scale, we analysed the whole of Europe as a single region, while at the national scale, we used country borders (Eurostat 2016). At the regional scale, we assessed supply and demand using nomenclature of territorial units for statistics (NUTS 3; n =1061) and local administrative units (LAU; n = 957) from year 2016 (Suppl. material 1, Table S1,Eurostat (2016)). As the geographical size of NUTS 3 regions varies greatly (min. 14.0 km^2 and max. 105,907.5 km^2) across Europe, we combined these two administrative regions to create study units with as similar areal coverage as possible to improve their comparability (min. 0.4 km^2 and max. 21,762.4 km^2 in combined data; Suppl. material 1, Table S1 & Figure S1). The areas we used corresponded well with the statistical data collected in previous ES studies at a European scale (e.g. Ala-Hulkko et al. (2019)).

Forests cover almost 35% of Europe's land area (Köhl et al. 2020), but are unevenly distributed across the continent. Finland and Sweden are the countries with the largest forest cover, whereas in the Benelux Regions, the forest area is the lowest in comparison to other European countries (Köhl et al. 2020, Suppl. material 1, Figure S2). Following Köhl et al. (2020), the majority of forests in Europe are dominated by coniferous species (46%), followed by broadleaved (37%) and mixed (17%).

Mapping wood ES potential, supply and demand indicators

This study uses the ES cascade conceptual framework as the basis for choosing representative data indicators for mapping the potential, supply and demand aspects of wood ES (Haines-Young and Potschin 2010, Potschin-Young et al. 2018, Fig. 1). The idea of a provisioning ES begins with the valuation of a biophysical structure in which humans can potentially use natural resources to achieve or maintain their well-being. However, in the case of wood ES, this potential does not represent the amount of the resources available for supply. The availability of a resource for supply can vary locally depending on environmental, economic or social restrictions (Levers et al. 2014, Alberdi et al. 2016). These restrictions can be related to, for example, the number of areas under protection, environmental conditions for tree growth and issues related to topography or accessibility (Alberdi et al. 2016). Nevertheless, the wood ES potential provides a background information on the total European forest resources and can be used to study the relationship between the available European forest resources and their supply and demand, as well as their changes.

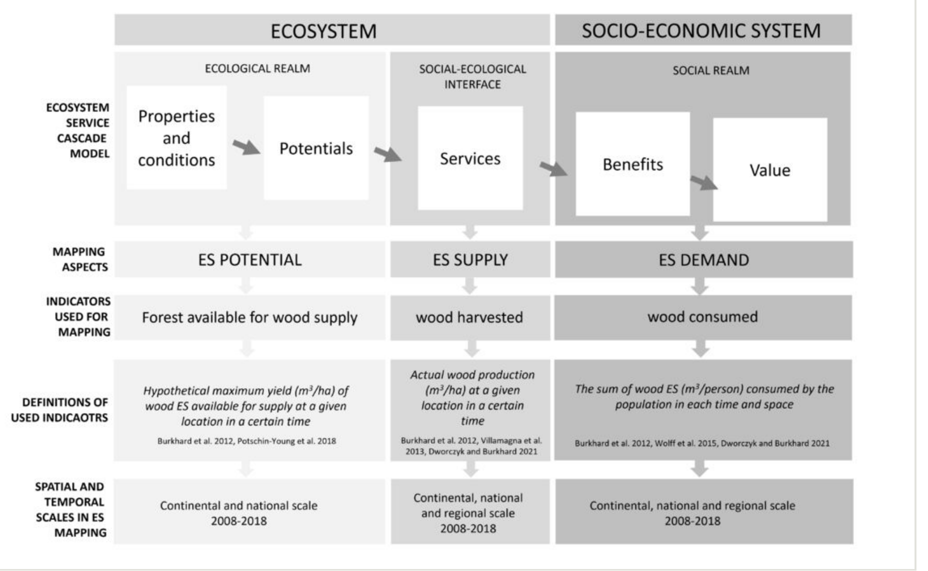

Figure 1.

The cascade model describes the flow from nature to humans through the division of ES into five steps. The original first two steps, biophysical structure and process and function, have been replaced by properties and conditions and potentials to harmonise these terms with the mapping aspects of ES (see Bastian et al. (2013), Spangenberg et al. (2014)). The relevant mapping aspects of each step in the cascade model are described below the cascade model. The wood ES indicators and their definitions used in this study are quantitative proxies for the mapped ES. The spatial and temporal scales of these indicators are shown at the bottom of the figure.

Supply and demand are independent variables of the ES cascade model and their spatial representation can vary, depending on the type of ES mapped. Here, we have distinguished supply and demand from the potential, representing wood in total, as it is not common for the entire forest cover to be used annually. Consequently, total stocks or biomass cannot be an estimate of the annual wood resources used. Hence, we define supply (frequently referred in literature as ES flow) as the amount of the mobilised service within the ecosystem capable to provide a service at a given location in a certain time (Burkhard et al. 2012, Villamagna et al. 2013, Dworczyk and Burkhard 2021). As mentioned above, the supply in this study does not represent the hypothetical maximum yield of the forest; instead, actual yearly wood production (m^3) describes supply more realistically. Demand is defined as the need for the ecosystem-based service by the end users (Haines-Young and Potschin 2010, Burkhard et al. 2012, Bastian et al. 2013) and serves as socio-economic focused pressure on the ecological structure. Here, finalised demand was estimated by consumption rates as the sum of services consumed by the population in a given time and space (Burkhard et al. 2012, Wolff et al. 2015, Dworczyk and Burkhard 2021). For the provisioning ES such as wood, demand is mainly driven by population size and growth, income level, technological changes, urbanisation, policy-making and the availability of alternative materials (Brack 2018). In this paper, we choose to estimate the demand for wood, from the perspective of an end user, as it is not possible to take into account the supply chain of wood, its processing and the industry effect. The demand is strictly interconnected to service supply in many ES examples. However, it is not equal to supply and serves as an independent element of ES consumption structures. Fig. 1 illustrates the the conceptual background applied in this study together with the mapped elements and use indicators.

Potential data

In this study, we use the data on forest availability for wood supply from Eurostat, based on European Forest Accounts (EFA) questionnaires (Eurostat and European Forest Accounts 2023), as a proxy indicator for wood ES potential. The data include national-level information on forest available for wood supply, defined as forests where there are no restrictions (social, environmental or economic) that would have an impact on current or potential supply of wood (Alberdi et al. 2020, Suppl. material 1 Table S2). We have chosen these data as a proxy for mapping wood ES potential because they are available for the same period as the compiled supply and demand data. It also provides data in units (m^3) that are consistent with the supply and demand data and countries covered in this study. These data give an insight into the hypothetical amount of wood resources available to be used in ES perspective (ES potential). The continental data are a summary of the national data.

Supply data

The data on annual wood production from statistical databases of the studied countries for the period 2008-2018 were used as a proxy indicator to estimate the wood supply across the European administrative regions used in this study (Suppl. material 1, Table S3). Most of the countries had information on the supply at the regional scale. For those without regional supply data available, information was compiled, based on the Eurostat annual roundwood production data (Eurostat 2021). Then, depending on the resolution of original data, the supply was shared between each region using information on the extent of forest cover therein. The annual share of forest in each area was calculated using the CORINE Land Cover (CLC 2006 as a basis of forest cover for year 2008, CLC 2012 as a basis of forest cover for years 2009-2014 and CLC 2018 (as a basis of forest cover for years 2015-2018; European Environment Agency (2022), Suppl. material 1, Table S4). All forest classes (coniferous, broadleaf and mixed) were included in the analysis. The broad scale of this study did not allow us to consider all harvest restrictions. However, to make the calculations more accurate, protected areas with a status that most likely do not allow wood supply were excluded from the forest cover for each analysed year (International Union for Conservation of Nature (IUCN) & United Nations Environment Programme - World Conservation Monitoring Centre (UNEP-WCMC) (2022)). The areas erased from the forest cover included strict natural reserves, wilderness areas, national parks and natural reserves (see detailed Suppl. material 1, Table S5). To ensure comparability between regions, we divided the total supply (m^3) of each region by the area (in hectares) of each administrative unit. Forest area available for wood supply (*Ft*) was calculated as follows:

$$Ft = T - P; Fa = \frac{Ft}{A}$$

where *T* is total forest area (ha) (source: European Environment Agency (2022)) and *P* is excluded protected areas (ha), from which harvest is most likely not possible (source: International Union for Conservation of Nature (IUCN) & United Nations Environment Programme - World Conservation Monitoring Centre (UNEP-WCMC) (2022)). *Fa* represents the share of forest area in each administrative region (NUTS3/ LAU) and *A* is area of the administrative region.

Annual supply in each administrative region (*S*) in m^3/ha was then calculated using following formula:

$$St = W \times Fa; S = \frac{St}{A}$$

where *St* = absolute supply (m^3) in each administrative region; *W* = wood harvest statistical data (see spatial resolution and detailed list of sources from Suppl. material 1, Figure S1 and Table S3). For all annual regional supply maps, see Suppl. material 1, Figure S3. The continental and national supply data are the summary of the regional data within the borders of each country or at the continental level.

Demand data

The UNECE annual estimated national wood consumption data for the years 2008-2018 were used as a proxy indicator of demand (United Nations Economic Commission for Europe 2022). The data represent the amount of unprocessed wood consumed by manufacturing industries to produce processed products. It was calculated by adding imports and subtracting exports from the domestic production (United Nations Economic Commission for Europe 2022, Suppl. material 1, Table S6). The data are the result of a Joint Forest Sector Questionnaire (JSFQ)- collaboration project of Food and Agriculture Organisation (FAO), The International Tropical Timber Organisation (ITTO), UNECE and Eurostat, that aims to collect forest related national data since 1997 (Eurostat 2023). According to UNECE, these data indicate the size of the domestic wood-processing industry. These data allow us to analyse the demand from the perspective of the ES end user. Population size is one of the main drivers of wood demand (Brack 2018). Therefore, the population information for each statistical region (Eurostat 2022, Suppl. material 1, Table S7) were used as a surrogate for local consumption, which was multiplied per capita with the UNECE annual wood consumption data. To ensure comparability between supply and demand data, the value of wood consumed in each administrative unit was divided by its area in hectares. Wood consumption per capita (*c*) was calculated as follows:

$$c = \frac{Ct}{Pt}$$

where *Ct* is total national wood consumption and *Pt* is total national population.

Annual demand for wood (*D*) in m^3/ha in each administrative region was then calculated in the following equations:

$$Dt = c \times Pa; D = \frac{Dt}{A}$$

where *Dt* = absolute demand (m^3) in each administrative region and is sum of population in each administrative region; *Pt* = area (ha) of the administrative region. The annual demand maps are included in Suppl. material 1, Figure S4. The continental and national demand data represent a sum of regional values withing the country or continental borders.

Analysing spatial distribution, relationships and temporal changes in wood ES potential, supply and demand

In this study, we examine the distribution, relationships and temporal trends of wood ES potential (in continental and national scales), supply and demand (in continental, national and regional scales). In addition to the statistical comparison, most of the analyses are carried out using the space-time cube tool from Esri's Arc GIS Pro 3.0.3. software. We decided to use the space-time cube as it provides useful tools for evaluating variations in data over space and time simultaneously. It combines statistical analysis with map visualisation tools, allowing users to explore dynamic patterns, trends and changes over time within specific geographical areas. This holistic approach supports not only informed decision-making, but also spatio-temporal understanding. It has been used, for example, in examining forest loss or the temporal effects of drought (e.g. Harris et al. (2017), Ahmadi et al. (2022)). The space-time cube, as its name suggests, can be used to analyse temporal changes in space and we performed the analysis at both national and regional levels. At the continental scale, the temporal variation was examined statistically, as we did not find it useful to perform the space-time cube analysis on a single uniform continental polygonal dataset. Therefore, space-time cubes were created from defined potential, supply and demand polygon locations (Esri 2023) corresponding to the administrative areas for which the data were gathered (national (n = 25) and regional (n = 2018)) for annual time intervals between 2008 and 2018. Summary descriptive statistics were calculated for the national and regional levels based on the potential, supply and demand values. These descriptive statistics, including mean, standard deviation and coefficient of variation, calculated as part of space-time cube local outlier analysis, were used to outline the main information on the spatial distribution of European wood ES potential, supply and demand, within the period analysed. Based on these statistics, the geographical locations with the highest and lowest potential, supply and demand levels within the period studied can be identified for different spatial scales.

In addition, with visualisation of the space-time cube, we were able to detect the temporal trends in annual levels of wood ES potential, supply and demand for individual polygons (at national and regional scales). The space-time cube tool also performs a Mann-Kendall trend test, which is a series rank correlation analysis (Mann 1945, Kendall and Gibbons 1990). This analysis was used to identify countries and regions where annual potential, supply and demand values have decreased or increased. This test compares and sums the values over time. To identify statistically significant trends, the sums are compared with the expected sum (zero, no trend). The analysis is carried out independently for each polygon location studied (countries at national scale and administrative regions at regional scale), resulting in detection of an individual trend observed within the analysed period. Potentially detected trends are then indexed with a z-score and p-value, in each analysed polygon. The statistical significance of the trend is indicated by small p-value ($p < 0.01$ = 99% confidence; $p < 0.05$ = 95% confidence; $p < 0.1$ = 90% confidence). Trend direction is detected, based on the z-score. A positive z-score indicates an increase in the values within the period analysed and negative z-score vice versa (Esri 2023).

Additionally, we also calculate the ratios between the potential, supply and demand at the national level, as well as the ratio between total and local supply and demand in regional level. The ratios allow us to explore the relationships between studied variables.

Results

Changes in overall wood ES potential, supply and demand at continental level

The mapping aspects of the ES cascade (potential, supply and demand) considered in this study are dynamic. At continental level, European wood ES potential has been gradually increasing through the period studied (Fig. 2a). The overall values of the total wood ES supply in Europe have increased over time (Fig. 2b). The greatest increase was observed from the year 2015 onwards. The overall demand values have also shown an increasing pattern and the trend of the change is stronger than overall supply (Fig. 2b). Demand has shown a slight upward trend each year since 2009. In Europe, overall supply was higher than demand and supply also grew faster than demand, with a difference of around 16% between the first and last years of the study period, while the difference in demand was around 10%.

Distribution of wood ES potential at national level and supply and demand at national and regional level in Europe

At the national level, our results showed spatial differences in the distribution of wood ES potential, supply and demand across Europe. The availability of wood resources depends on both natural factors (climate and growing conditions) and human activities (land use and forestry). This can be seen from our results, where we found that central and northern Europe have the greatest wood ES potential (Fig. 3). These include Austria, Switzerland, Germany, Finland, Sweden and the Baltic States. The variability of the wood ES potential between years is low in all the countries studied (Suppl. material 1, Figure S5 A1). Due to lack of regional wood ES potential data, it is not possible to assess these aspects within individual countries. However, with the high capacity for supply, the above-mentioned countries are also the largest producers of the studied ES, based on supply mean values at a country level. This means that the countries mentioned above have the largest wood supply compared to potential. However, Poland, Hungary, Ireland and especially Portugal, are also particularly over-supplied compared to potential (Fig. 4a). Regionally, the high supply can be seen in the regions of southern and south-eastern Finland as well as in southern and south-eastern Sweden (Fig. 5a). Relatively high supply values were also detected in southern regions of Germany and across Austria, Slovenia, the French Region of Aquitaine and parts of northern Portugal. The lowest levels of wood supply were characteristic of southern and western Europe and the regions of Lapland in Sweden and Finland. The regions with high wood ES supply values are also characterised by high ratio between total European supply and local regional supply (Suppl. material 1, Figure S7 A). The coefficient of variation for national level supply is generally low (Suppl. material 1, Figure S5 B1). At the regional level, the variability of supply values varies, being highest in regions such as central Finland near the eastern border, south-eastern France, north-western Italy and Sicily (Suppl. material 1, Figure S6 A1). Nevertheless, the distribution of the coefficient of variation is low in most of the studied regions (Suppl. material 1, Figure S6 A2).

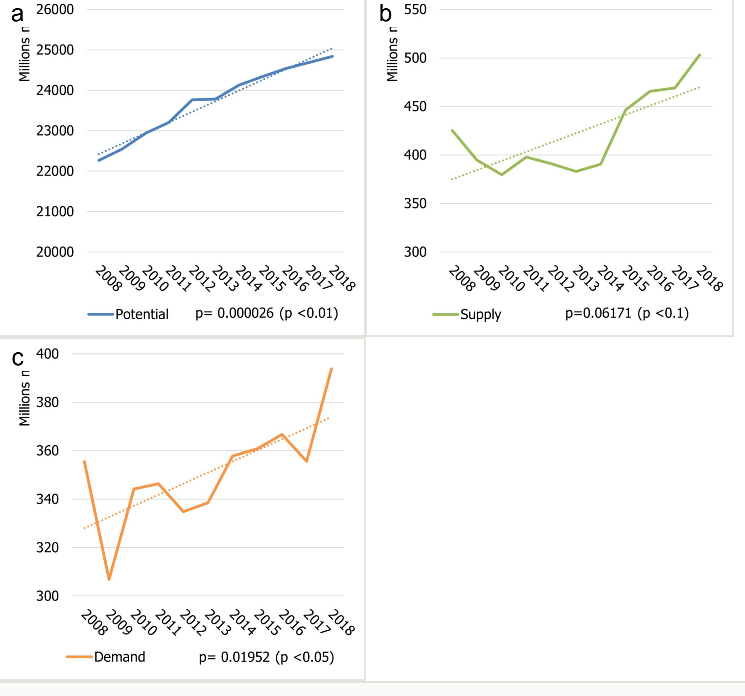

Figure 2.

Amount (sum, m^3) of wood ES potential. The Mann-Kendall test was used to calculate the significance of each trend. Note that the y-axes in Figures A to C are scaled differently.

a: supply
b: and demand
c: across European continent between 2008 and 2018

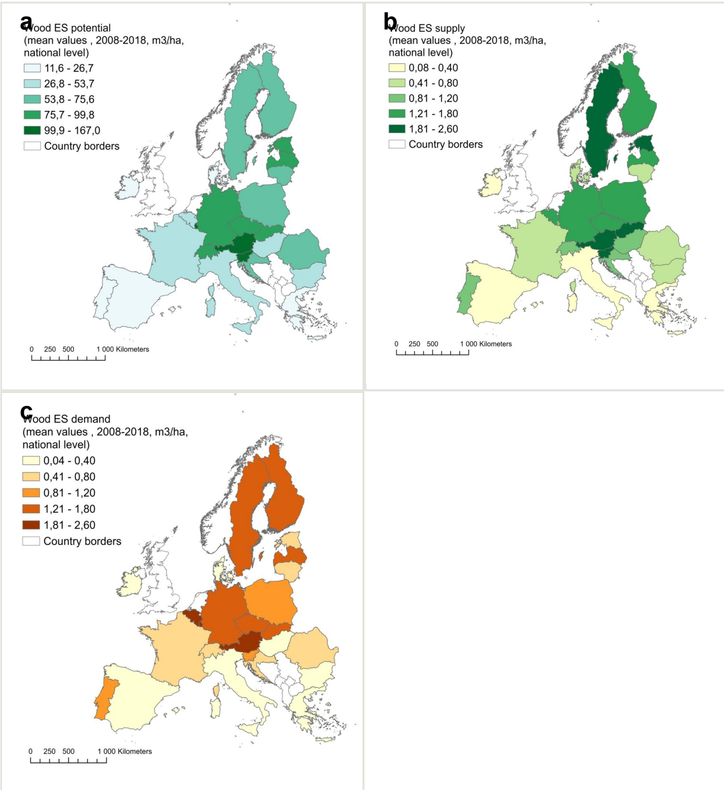

Figure 3.

The distribution of mean values of wood ES.

a: potential
b: supply and
c: demand at national levels between 2008 and 2018.

National level wood ES consumption is also concentrated in central and northern Europe, although it is also high in countries such as Belgium and Portugal (Fig. 3c). This can be seen both from the mean ES demand values and the ratio between national potential and the demand (Fig. 4b). A closer look at the wood ES demand at regional level shows that it is concentrated in large population centres (Fig. 5b) and in areas where the wood industry plays a significant economic role which matches the conceptual approach of this study. Commonly, the densely populated metropolises have accumulated high needs for consumption of analysed wood ES. In general, the areas with the highest levels of demand were the southern regions of northern (Finland and Sweden) and central (e.g. Germany, Poland and Czech Republic) Europe, as well as major European cities and capitals such as Paris, Lisbon or Riga. This phenomenon is even more clearly visible when looking at the ratio between the total European demand and the demand of single regions (Suppl. material 1, Figure S7 B). The coefficient of variation for demand at national level is generally low (Suppl. material 1, Figure S5 C1). Regionally, the variation in demand values is higher in the single regions, with overall low variability across most of the regions (Suppl. material 1, Figure S6 B).

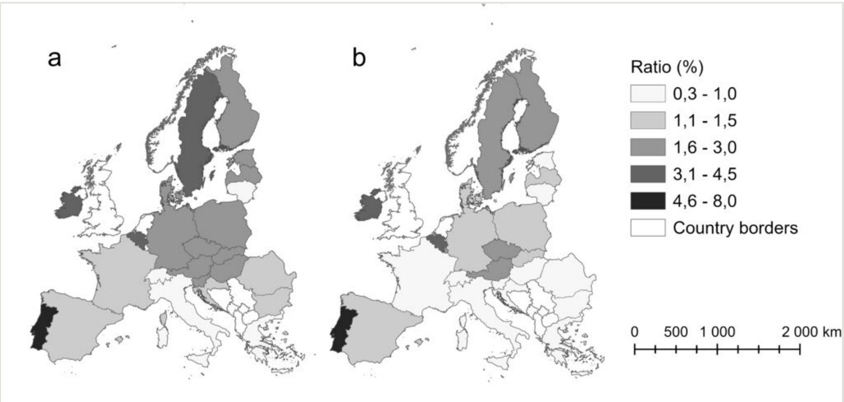

Figure 4.

The comparison between (a) mean potential and supply and (b) mean potential and demand between 2008 and 2018 at national level. This ratio (in %) expresses how much of supply (or demand) is contained in comparison to the potential.

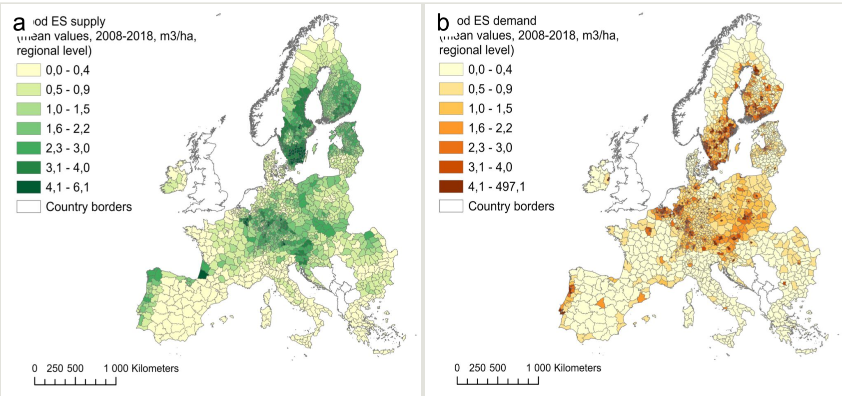

Figure 5.

The distribution of the mean values of wood ES.

a: supply and

b: demand at regional levels between 2008 and 2018.

Temporal changes in wood ES potential, supply and demand in national and supply and demand in regional scales

Temporal changes in supply and demand, as well as the potential of wood ES available for supply at national level, have been substantial during the period studied. While the wood ES potential has grown throughout most of the European countries (Fig. 6a), the changes in wood ES supply and demand were more country-specific (Fig. 6b, c). Greatest up-trends (at 99% confidence level) for supply were characteristic for countries such as Poland, Sweden, Spain and Denmark. The upward trend in demand was observed in countries such as Latvia, Estonia, Portugal and Hungary.

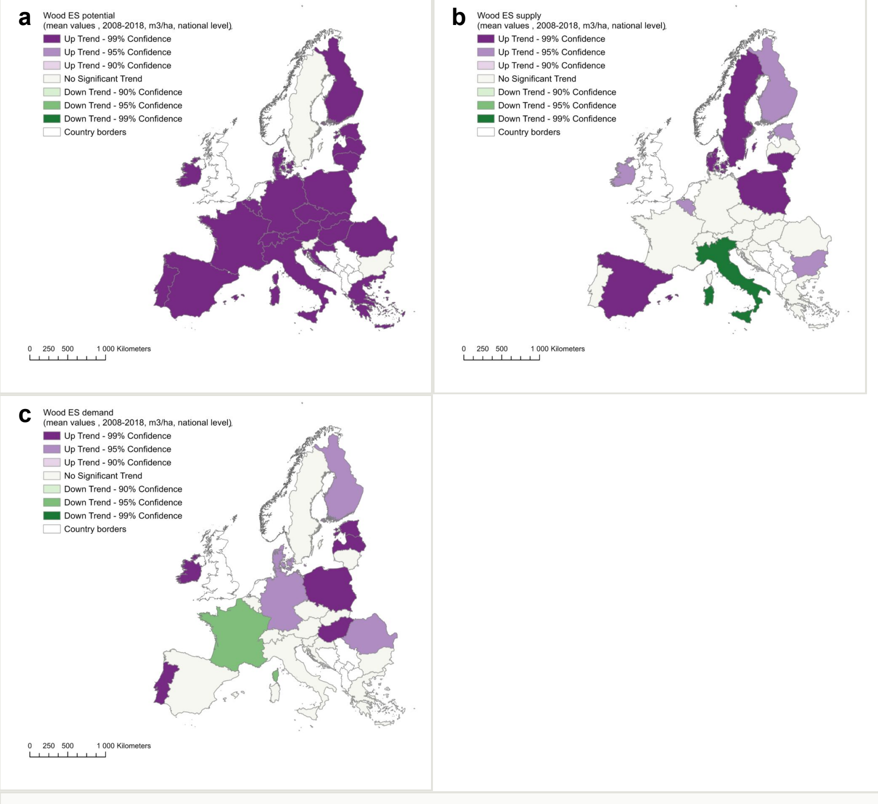

Figure 6.

National-scale temporal trends in wood ES. Confidence levels of the trends were used to indicate in which countries the trends were the strongest.

a: potential
b: supply and
c: demand between 2008 and 2018 using space-time-cube analysis.

At a more specific regional level, the result of the space-time cube analysis also showed an increasing trend in supply and demand across many European regions (Fig. 7). The increasing supply patterns between 2008 and 2018 were dominant in a large number of the analysed regions. These includes various regions, in particular in central and southern Sweden, Poland, Ireland, in certain regions in France and in the north and west of Spain. Decreases in supply were detected in single regions, including southern Spain, northern Italy, southern Sweden and a few regions in France, Germany and Greece. Interestingly, some of these regions were also important supply hubs (Fig. 5). This includes, for example, a few regions in southern Sweden and French Aquitaine.

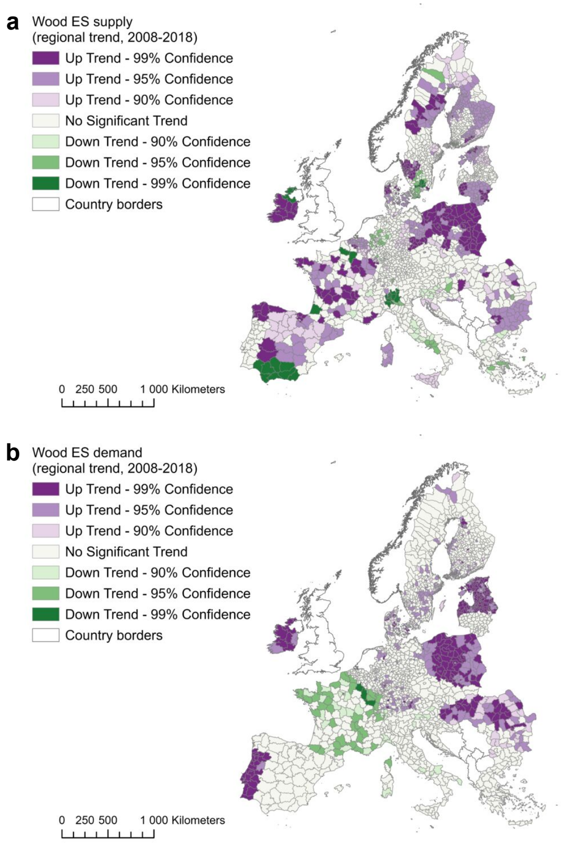

Figure 7.

Regional scale temporal trends in supply, and demand of wood ES between 2008 and 2018 using space-time-cube analysis. Confidence levels of the trends were used to indicate in which regions the trends were the strongest.

a: supply

b: demand of wood ES between 2008 and 2018 using space-time-cube analysis

Trends in demand have generally increased, but differed from supply patterns. As shown in Fig. 7b, increasing demand trends were detected in countries such as Estonia, Latvia, Poland, Romania, Bulgaria, Ireland and Portugal. Rising demands were also noticeable in northern Europe and southwest Germany. On the contrary, consumption in France decreased within the period studied.

Discussion

Recognition of the spatial distribution of ES potential, supply and demand is one of the key issues in the maintenance of their sustainable use (Burkhard et al. 2014, Syrbe and Grunewald 2017, Ala-Hulkko et al. 2019). As pointed out in several previous studies (e.g.

Burkhard et al. (2012), Rau et al. (2019)), the potential, supply and demand of ES are inseparable. Therefore, it is recommended to systematically explore them together. This demonstrates the need for a better understanding of the service state, production and consumption. Incorporating the temporal dynamics of ES mapping has the potential to detect their changes over time and identify their drivers and impacts on ecosystems (Rau et al. 2018, Rau et al. 2019). Our study approach is an example of spatio-temporal analysis of wood ES, based on indicators from the ES cascade model. It highlights that exploring ES supply and demand, also in relation to the ES potential, in space and time is beneficial for a better understanding of these characteristics under rapid socio-economic changes. It adds up to the existing assessments of wood ES, such as the EU ecosystem assessment (Maes et al. 2020), exploring the trends of wood ES potential, supply and demand in more detailed, annual perspective. In addition, looking at analysed variables from three different spatial levels aims to acknowledge the importance of scale when mapping ES.

In this study, we found that the values of all evaluated elements of the ES cascade for the wood ES have increased over the period studied (Fig. 6). The wood ES potential has gradually increased in Europe over the last few decades, aligning with the previous findings of Cook and Eurostat (2021) andBlattert et al. (2023). In contrast, the supply and demand of wood ES are more complex. The natural fluctuation in volume is due to the supply and demand variables, which are largely influenced by the market and the global population's requirements for wood ES (Brack 2018, Bull 2018). When it comes to ES potential, changes are naturally slower, but the amount of wood available for supply is growing year by year across Europe, probably due to the implementation of forest transition as well as forest protection policies (Palmero-Iniesta et al. 2021).

Our results show that both supply and demand were affected by the economic crisis of 2008, dropping down in 2009 and steadily recovering later on, which supports the evidence from the previous observations (Maes et al. 2020). Supply, which was mostly concentrated in Finland, Sweden and parts of central Europe (Fig. 3b), has increased gradually, with more significant rise taking place from years 2014 and 2015 onwards (Fig. 2b). This is consistent with the previous studies showing rise in wood production since 2015 in Europe (Henrard and Forti 2016, Maes et al. 2020, Blattert et al. 2023). The distribution of supply is also visually consistent with Verkerk et al. (2015) wood production statistics for the overlapping years and for the wood harvest intensity patterns (Levers et al. 2014). The mentioned regions have biogeographically high potential amount of wood ES (Palmero-Iniesta et al. 2021, Fig. 3a).

Although the increase in the mean values of demand did not experience the same sudden change as that of supply (Fig. 3c), the overall increase was noticeable. The demand was mostly concentrated across vastly populated areas and in the administrative regions of countries with high consumption per capita, such as Finland and Sweden (Figs 3c, 5b). As we considered the demand of wood ES from the perspective of the end consumer, it is logical that the distribution of the demand is partly collided with high population density. However, as the population is one of the main drivers of the demand (Brack 2018), we think it represents well the locations of end consumption of the ES mapped in this study.

Perhaps the most striking of our findings was that the supply and demand of wood ES increased in most administrative regions of Europe (Fig. 7). The analysed timeframe represents a relatively short period when it comes to the development of wood ES supply and demand levels. Although the total stock of forest resources in Europe has increased in recent decades (Fig. 2a, D'Orangeville et al. 2018, Blattert et al. 2023), climate change-related pressures are increasing and the quality and condition of European forests are declining (Maes et al. 2020). Therefore, the growing wood production and consumption may still affect the goals of sustainable forest management, forest biodiversity conservation or trade-offs between different ES in both continental and regional level. This may indicate that the use of European forest resources has intensified in the period studied.

Potential drivers and consequences of wood ES supply and demand upward trends

There are various drivers of supply and demand of wood ES, both socio-economic and environmental. Levers et al. (2014) have defined those main drivers for wood harvest, referred to in this study as wood ES supply, and include: share of plantation species, terrain ruggedness, the potential of forest available for supply, forest cover and accessibility (environmental drivers), as well as country specific policy, environmental law and bio-economy factors (socio-economic drivers). An example socio-economic driver might be the forest transition, due to which the wood ES potential grows and so is the supply (Fig. 2a). Locally, the supply can be intensified in case of extreme weather events or species diseases, for example, expansion of bark beetles (Palahí et al. 2021). The demand is mostly driven, in addition to population, by other socio-economic factors such as urbanisation, changes in income and policy, development in technology and availability of alternative resources (Brack 2018). For example, the promotion of renewable energy sources in Europe during the green transition is expected to increase the demand for wood ES as a fuel (Jonsson 2013, Bull 2018). Socio-economic shock events (e.g. economic crises, wars, border closing) may cause changes in the demand for wood ES, as it affects the economic ability of the population to afford the services. An example of such an event is visible in our demand data (Fig. 2c) where we can still see the effect of low demand for wood ES after the economic crisis of 2008. Listed drivers likely have an impact on spatio-temporal variety in supply and demand values and the upward trends of ES cascade elements analysed in this study.

Our results, possibly driven by the above-mentioned factors, can directly or indirectly affect forest management, biodiversity or trade-offs between other forests ES. Forest management issues are strongly associated with economy, as the provision and consumption of studied wood ES is highly dependent on economic factors (Jenkins and Schaap 2018, Muys et al. 2022). In addition, the rising position of wood in the context of bioeconomy is making it more important than ever before (Jonsson 2013, Bull 2018). The upward trend observed in our wood ES supply, demand and potential data can possibly be associated with the growing bioeconomic importance of wood ES across Europe in the period studied. Some studies suggest that this trend in wood ES exploitation has continued for a long time and has placed wood ES above the need for the supply of other types of forest ES which can potentially affect their supply (Jenkins and Schaap 2018, Pohjanmies et al. 2021, Dasgupta 2021). Even though some studies suggest that, due to climate change, forests are predicted to grow faster and harvesting may have positive effect on the carbon balance (D'Orangeville et al. 2018), the growing wood ES supply can have a long-term impact on, for example, the habitat quality, connectivity of European forest ecosystems and can reduce the capacity to supply many other ES, such as cultural forest ES or provision of non-wood products (Mitchell et al. 2014, Pohjanmies et al. 2021). As forests are one of the most effective carbon sinks that play an important role in mitigating climate change (Palmer 2021), which is currently one of the greatest challenges facing humanity, the steady increase in wood ES potential could be a positive signal for climate change mitigation efforts. However, the growth of wood ES supply and demand levels at the same time may have an impact on the goals of increasing the amount of carbon sinks. In this study, we have only focused on one forest ES, but to obtain a more complete picture of the state of ecosystems and their ability to provide multiple services, more attention should be paid to analysing the trade-offs between different ES over time (Chaudhary et al. 2017, Pohjanmies et al. 2021).

Strengths, limitations and future directions for the research on ES potential, supply and demand

Provisioning ES, such as wood, are typically used on a cyclical time scale. Forests, depending on species, can grow for several decades before being harvested. For this reason, the analysed example of ES is also not static and depends on temporal variation (Bastian et al. 2012, Rau et al. 2018). As forest harvesting usually takes place after decades, depending on geographical conditions, the supply of ES rarely peaks. As forests grow, the potential of ES increases continuously, while the supply temporarily remains more or less at zero until the final harvest. Therefore, forest landscapes are characterised by regular growth and harvest phases, which need to be taken into account by using temporal data when studying provisioning ES (Burkhard et al. 2014). Our study shows that there have been changes in forest use over the studied decade in many European regions. We can discuss the general impacts of these changes on forest quality or provision of other services. However, in this study, we did not consider factors such as differences in tree species, length of the growth, monocultures and country-specific forest management techniques (Palmero-Iniesta et al. 2021), that can have an impact on regional dynamics of wood ES potential, as well as supply and demand. In addition, supply data are based in official harvest statistics, which rely on the information compiled in studied countries, where the methods for collecting the data might be different. Our data consist of only the information about officially reported harvest. For example, illegal logging was not acknowledged in our data and that may have had an impact on wood ES supply levels. When it comes to demand data, we acknowledge that there might be different ways of understanding the demand for wood, for example, by including the forest industry chain into consideration. However, here, we focus on the ES concepts and analyse the demand from the perspective of the end consumer.

Further studies at different scales could be performed to explore more precise patterns of potential, supply and demand of wood ES. In addition, we only mapped the spatial characteristics of potential, supply and demand at the sites, without considering the spatial flow from the producing to benefitting areas (but see, for example, Ala-Hulkko et al. (2019)) or the effect of global wood market (e.g. trade processes related to transportation and storage) and global consumption patterns. Additionally, even though we considered national trends in wood ES potential and wood ES supply and demand, we did not measure the sustainability level of these indicators. It is often an issue in ES studies to measure what level of service use is sustainable. In this study, we discovered upward trends for all mapped elements of ES cascade. This might influence sustainable use of the resources, but more specific investigations are beyond this work. It should also be kept in mind that there is a wide variety of ways to measure and map ES indicators and although efforts have been made to develop harmonised measurement methods, it may still be difficult to compare the results of different studies (Saarikoski et al. 2015, Boerema et al. 2016).

Despite all the limitations mentioned, the results of this study present a summary of how wood ES potential, supply and demand have been allocated across Europe and how they have changed over time. Such an assessment provides an overview of current changes and the situation of wood ES in Europe and responds to the need to map a wider selection of different mapping aspects of the ES cascade model. Our study adds to the previous EU level assessments of wood ES potential, supply and demand. For example, Maes et al. (2020), although using different definitions of wood supply and demand, similarly found increasing trend in these ES characteristics, supporting our conclusions. Moreover, the methods we used proved to be an effective way to illustrate the temporal patterns of wood ES use across Europe. By analysing changes in potential, supply and demand of ES over time, identified trends lead to a more accurate assessment compared to a single year's analysis (see Burkhard et al. (2014), Maes et al. (2020)). In addition, understanding how spatial scale affects ES characteristics is crucial, as found patterns may vary with changing spatial resolution and extent (e.g. Qiu et al. (2018), Shi et al. (2023)). To acknowledge this phenomenon, we mapped the trends in three different spatial scales across Europe. In the case of ES analysed in this study, the increasing trends of production and consumption are not only visible in those countries and regions that play an important role in wood ES provision, but are also noticeable across the vast number of analysed areas. Even though we have only analysed a period of a decade, we can see a growing trend in the wood ES potential as well as supply and demand patterns. These trends may indicate changing patterns of forest use, that can further affect other ES provided by forests, their biodiversity and habitat quality.

Identifying changes in different scales is important, but regional level information is particularly valuable as it provides insights into how forests have been used over the long-term and helps to target interventions more specifically to areas of intensive forest use. The establishment of conservation plans for the areas where supply and demand are not in long-term balance, together with an assessment of biodiversity, could be a step towards achieving the goal of the EU’s Biodiversity Strategy 2030 (European Commission 2020) and help maintain the capacity of forest ecosystems to provide multiple services. Furthermore, different regions may require different policy strategies to conserve forest resources (Blattert et al. 2023). Nevertheless, more studies on other ES and their trade-offs are needed to develop a complete picture of the state of total ES production and consumption. In addition, more detailed and not too broad scale data on both the supply and demand, as well as the potential of forest ES, are needed to create a comparable system from which we can see the pros and cons of their increasing and decreasing trends.

Conclusions

The main objective of this study was to analyse the potential, supply and demand for European wood ES over a decade. Using GIS-based tools and statistics, we examined both the spatial and temporal variation of wood ES at the national and regional levels, as well as across Europe. Our findings indicate that the major concentration of wood ES potential, supply and demand is in central and northern Europe. Throughout the study period, wood ES potential has consistently increased at both the European and national levels. However, there has been more regional and temporal variation in supply and demand between years. The most noteworthy observation was that, despite the increase in potential, there has also been growth in demand and supply. Such a trend could eventually have implications not just for forest ecosystems, but also for the provision of other forest ES. The study demonstrates that it is essential to continuously assess and map ES over time to draw conclusions about the state of ES and trends in their use, as well as about the main drivers causing the changes. Additionally, the importance of scale is exemplified in our research. We found that, while a broad scale helps to recognise large patterns, analysing data at the regional level offers more comprehensive insights into identifying the corresponding areas that might require targeted action for protection or sustainable forest management.

Data availability

The data for this study are available as open access from the Zenodo repository at https://doi.org/10.5281/zenodo.11047093 (Poturalska et al. 2024).

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Author contributions

T.A-H drafted the original idea together with A. P., which was further developed by A. P. Both A.P and T.A-H. contributed to the study design. A. P. collected all the data, did the analysis and led the writing process with contributions from all authors.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary material

Suppl. material 1: Mapping temporal variations in ecosystem services: a case study of European wood supply and demand between 2008 and 2018 doi

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Data type: tables and images
Brief description: The supplementary materials contains the additional information about the data sources, resolution as well as the supplementary results.
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