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Mind the income gap: Income from wood production exceed income from providing diverse ecosystem services from Europe's forests

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ABSTRACT

Forests supply multiple ecosystem services, categorized into provisioning (e.g. wood), regulating (e.g. climate change mitigation, biodiversity protection) and cultural (e.g. recreation) services. While European policies have set the target for forest management to supply multiple ecosystem services, the literature emphasises that regulating and cultural ecosystem services tend to be undersupplied, as most management incentives focus on provisioning services.

We conducted a pan-European survey of forest owners and managers on sources of forest income and extrapolated the results with spatially referenced data and machine learning.

We gathered relative income and profitability levels derived from supplying different groups of forest ecosystem services per forest plot. We show that approximately eighty percent of forest income is currently linked to provisioning services. Supplying regulating and cultural services is rarely perceived as profitable. We then identified two clusters of European forest owners and managers. The first, managing predominantly conifer-dominated forests in thinly populated areas of Northern and Eastern Europe, derives nearly all its forest income from wood production. The second, managing forests characterized by broadleaved species, proximity to cities, and with a higher share being designated as Natura 2000, dominates in Western and Southern Europe. In this second cluster, about one-third of forest income comes from regulating and cultural ecosystem services, but at low profitability. We conclude by arguing that recognizing both this spatial divide across Europe and the gap between forest owners' economic incentives to provide preliminary provisioning ecosystem services, and societal

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demand emphasising regulating and cultural ecosystem services, is key for designing customized, effective policies for multiple forest ecosystem services.

1. Introduction

European forests have been shaped by successive historical patterns of human use, reflecting changing management priorities over time and space. For more than a hundred years, the objective of forestry across the continent has predominantly been the sustainable yield of wood, albeit never uncontested, with historical debates relating to the necessity to practice forestry for multiple "functions" (Pistorius et al., 2012) or variants of more "close to nature" forestry already going back to the 19th century in some countries (Hallberg Sramek, 2023). In recent decades, non-material regulating and cultural Forest Ecosystem Services (FES) have received greater attention, even culminating in the observation of a "re-spiritualisation" of forest management in Europe and parts of Asia (Roux et al., 2022). Correspondingly, concepts such as integrative forest management (Sotirov and Arts, 2018; Aggestam et al., 2020), multi-functional forestry (Borrass et al., 2017), climate-smart forestry (Verkerk et al., 2020) and close-to-nature forestry have become popular in European forest science and policy debates (Bolte et al., 2009; Nagel et al., 2017), emphasizing a land-sharing perspective for European forests. Meanwhile, day-to-day management of Europe's forests remains in many cases mostly wood-focused, resulting in a potentially significant trade off with other FES (Turkelboom et al., 2018; European Environment Agency, 2016; Raudsepp-Hearne et al., 2010; Forzieri et al., 2021, Winkel et al., 2022). While there is ongoing debate about current magnitude and possible intensification patterns in forest harvesting in Europe (Ceccherini et al., 2020; Palahí et al., 2021), civil society and general population repeatedly state that they appreciate forests for their cultural and regulating FES (De Groot et al., 2012; Acharya et al., 2019; Torralba et al., 2020a; Grammatikopoulou and Vačkářová, 2021; Bruzzese et al., 2022). This dichotomy of interests and approaches creates a political field of tension in the governance and management of European forests (Winkel and Sotirov, 2016, Sotirov et al., 2021).

EU forest policies have recently increasingly responded to this tension. The EU Green Deal calls for improving supply of regulating FES (European Commission, 2019). The new EU Forest Strategy puts strong emphasis on regulating FES, and specifically climate change (mitigation and adaptation) and biodiversity (European Commission, 2020), the latter being also strongly mirrored in the EU Biodiversity Strategy. Recent debates focused, *inter alia*, on restoring forests for multiple ecosystem services, on "closer-to-nature" management emphasizing forest biodiversity protection (Weiss et al., 2019), and on old growth forest protection (O'Brien et al., 2021). The EU's new Biodiversity Strategy calls upon member states to map, assess and value ecosystem services (Larsen et al., 2022). FES mapping has progressed in the past decade (Maes et al., 2016, Mengist and Soromessa, 2019) and has entered the policy sphere; as with the EU Regulation No.329/2022 (amending EU Regulation No.691/2011) by introducing new environmental economic accounts modules – including reporting on various ecosystem services such as pollination, wood provision, air filtration, local climate regulation and nature-based tourism. Still, we know little about the importance and distribution of FES-related incomes (FOREST EUROPE, 2020; FAO, 2020).

Yet, the latter aspect is of great importance for forests as about 47 % of the European forests are privately owned, and public forests are at least partially managed by profit-oriented public forestry companies (FOREST EUROPE, 2020). Hence, forest income and profitability play a great role in their management. Currently reported forest income data in Europe is build, however, mostly on hard-to-compare, highly aggregated national-level sources, focusing on biomass and selected non-timber forest products, yet failing to account for regulating and cultural FES (Crossman et al., 2013; Knoke et al., 2021). Despite efforts to mainstream multiple FES in national accounting (Grammatikopoulou and Vačkářová, 2021), European forest statistics remain focused on biomass production (Crossman et al., 2013; Knoke et al., 2021). Hence, forest incomes – a key potential economic building block for underpinning ambitious EU forest, climate and biodiversity policies – remain widely obscured.

In this paper we aim to help filling this forest-income lacuna using data collected in an online pan-European survey of forest owners and managers, including spatially referenced forest locations. Thus, our research question is '*How is forest income linked to supplying different groups of forest ecosystem services across Europe*?'. Using survey with forest owners and managers as a starting point, we combined it with forest characteristics (e.g. tree species composition, growth, slope, ownership type, country, protection status, distance to nearest city), and then applied machine learning (Abadi et al., 2016), to extrapolate survey's results to the whole of Europe. We thus gain proxies for forest profitability, income, and its change over the last two decades, disaggregating provisioning, regulating and cultural FES on a 1x1 km spatial resolution. We did not gather information on absolute levels of income and profitability (e.g. XY Euros per ha/yr and X% ROI), but rather relative measures of income and profitability. In the case of income, this means that we asked on the share of total forest-based income related to supplying different groups of FES, and in the case of profitability we asked to what extent can income related to supplying different FES cover the costs of doing so. Assessing the underlying spatial determinants of different FES-specific income components enables us to shed new light on the economic incentives for supplying FES across Europe.

2. Material and Methods

2.1. Data collection

The primary data source for the present analysis was a survey focused on the relative importance of FES income, its change and relative profitability, targeting forest owners and managers in Europe (Torralba et al., 2020b). It was disseminated during May-August 2019 through the European State Forest Association (EUSTAFOR), the Confederation of European Forest Owners (CEPF), the European Landowners Association (ELO) and the European Federation of Municipal and Local Community Forests (FECOF). Through their respective membership networks, this distribution covered all major types of forest ownership in Europe. The questionnaire was first reviewed among an interdisciplinary team of 18 researchers, and then pre-tested with selected forest owners and managers associated with the above-listed forest organizations. The survey was subsequently translated into 19 European languages. The survey was administered in an on-line format (See Supplementary Table S2). Respondents were also asked to provide geographic information about a forest plot they own and / or manage, which was then to be identified by a point location on a map. The background map was a Bing satellite image with overlaid Open Street Map objects. A minimum zoom level of 1:25,000 was enforced to ensure a precise location. Respondents were also instructed that if they owned or managed multiple patches of forest, they should locate the biggest one on the map.

Respondents were asked which self-assessed *share* of their forest income comes from provisioning (wood biomass, game, wild forest products), regulating (watershed protection, air quality regulation, climate change mitigation, biodiversity protection and habitat provision) and cultural (emotional, spiritual and cultural values, sports and outdoor recreation, education and healthcare) FES. Importantly, we *did* *not* ask for their absolute forest income and profit sizes. The survey pre-testing, which included these sensitive, more intrusive questions, revealed a strong drop in response rates. Survey questions were administered through a visual analogue scale, ranging from 'no income at all' to 'entire income from the forest' – separately for each of the three FES groups. The same type of instrument was used in subsequent questions. The next question asked about the relative change in income occurred during the last 20 years for each FES category (scale from 'has strongly decreased' to 'has strongly increased'). Finally, respondents were asked how profitable it was for them to supply different FES. By profitability, we meant the ratio between total FES-specific forest income (including from subsidies, tax deductions, etc.) and the costs of providing them, which was explained in the survey. Solicited answers were again not in monetary terms, but expressed on a slider scaled from 'not at all' to 'very profitable'. Responses were coded and results normalized to a 0–1 scale. We additionally asked about the size of the forest, type of ownership and management status (see Supplementary Table S2 for survey content and Supplementary Figures S2-S5 for responses on these variables). A total of 1,530 responses were collected (i.e. those who have answered the whole survey in more than two minutes and had answered at least seven out of nine income and profitability questions). We then selected only those responses where respondents had clicked on a map to show where the centre of their forest is; this brought the sample size to 948. This sample version was regarded as the largest sample version on which analysis could be performed (as the respondents needed to answer the survey's questions with a refence to a specific forest that they own and/or manage). This data version with 948 responses had 19.1 % of missing data on income and profitability variables; i.e. about a fifth of the questions were not answered by the respondents. We then further narrowed down the sample by filtering out responses where the distance between the point-location selected by the respondents and the nearest point-location in the forest biomass map of living forests (Barredo et al., 2012) is larger than 750 m (i.e. disregarding out-of-forest responses). This further decreased the sample size to 516 – a drop-out rate of 66 % in relation to all of the collected responses or 45 % in relation to all respondents who have pointed to their forest on a map. Different versions of the survey's data were tested based on the distance to the nearest actual known forest; with the cut-off distance ranging from 500 m to 1 km (with 50 m increment). The distance criterion of 750 m was selected as the estimates produced from this data generated smallest mean average error.

This was the sample that was used to extrapolate the survey's findings to the European level. The sampled point-locations of respondents' forests are situated in 27 different European countries with wide geographical coverage (Supplementary Figure S1). Missing data for income and profitability items were subsequently estimated by Multivariate Imputation by Chained Equations (MICE; Van Buuren and Groothuis-Oudshoorn, 2011). A detailed description of this process is provided in Appendix A2.

The next step was to collect a spatially explicit data set on forests in Europe. These variables include growing stock, tree species composition, terrain ruggedness and slope, distance to the closest city and Natura 2000 protection status. This data (see Appendix A1) was collected based on different sources on a 1x1 km raster grid in a LAEA (Lambert Azimuthal Equal-Area) projection. Counting in the coordinates, the dataset covered 94 variables. Forested parcels were identified as pixels with positive non-zero value for above-and-below-ground biomass (Barredo et al., 2012). Only pixels that had no missing data across all listed variables were retained (86.9 % of the data). The data set included 33 out of 51 European countries, excluding by default Andorra, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Cyprus, Georgia, Iceland, Kazakhstan, Malta, Moldova, Monaco, Russia, San Marino, Ukraine, Turkey and Vatican City. Turkey and Russia were deliberately excluded, as most of their surface area is outside of Europe. This led to a data set with 1,458,941 observations, representing 1.46 million km^2 of forests. Excluding Russia, total European forest area is 2.27 million km^2 (FORESTS EUROPE, 2020); so this study covered 64.31 % of Europe's forests.

The survey data extrapolation, which is presented in the results section, is performed onto this area of 1.46 million km^2. As next step, we assigned these spatially explicit variables to the forest point-locations selected by respondents, based on the variable values of the closest point-location in the forest data grid. Summary depiction of all the variables used in analysis is presented in Table 1. For details, please see Supplementary Table S1 and S2.

2.2. Data analysis

A key underlying assumption of our study is that forests sharing similar characteristics (e.g., biomass, tree species composition, distance to the closest city, same protection status, same country, etc.) will tend to have similar composition and relative importance of income and profit from different FES. For example, if the task is to estimate forest-income related variables of a certain forest point-location in North Italy, greater weight in this estimation will be given to data associated to point-locations from the survey that are in close vicinity to the targeted location, have approximately the same distance to the nearest city, are occupied by same tree species with similar growing stock, slope, terrain ruggedness and ownership status. Also, the opposite is true; for estimating income-related variables of this forest in Northern Italy, little or no weight will be assigned to survey responses with 'dissimilar' forests (e.g. a flat-land Scotch pine and birch forest in Eastern Finland). Hence, we use 'forest characteristics' as proxies through which forest income, income change and profitability can be estimated, using the survey responses as calibration for the extrapolations. The entire methodology, from collected and compiled data to the results, is presented in Fig. 1.

The estimation was done in the R programming environment (R Core Team, 2017), package *keras* (Kalinowski et al., 2021). This is an R interface to Keras (Chollet, 2015), a deep learning application programming interface written in Python, running on top of the machine learning platform TensorFlow (Abadi et al., 2016), through which we have implemented a deep learning model designed for this analysis. The details of the machine learning-based extrapolation procedures are presented in Appendix A3. After the forest income and profitability-related variables were estimated for Europe's forests, we performed statistical analysis to find how these variables relate to one another and to other spatially-explicit forest variables. We first grouped Europe's forests based on the forest income and profitability-related variables

Table 1
Summary representation of all the variables used in the study.

Type	Variable group	Notes
Dependent	Income	For provisioning, regulating and cultural FES Scale: from 'no income at all' to 'entire income from the forest' (0–1)
	Income change	For provisioning, regulating and cultural FES Scale: from 'has strongly decreased' to 'has strongly increased' (0–1)
	Profitability	For provisioning, regulating and cultural FES Scale: from 'not at all' to 'very profitable' (0–1)
Independent	Coordinates	In meters, LAEA projections; country (0/1)
	Land characteristics	Average annual rainfall (mm yr^{-1}); slope (degrees); soil bearing capacity (0–1); terrain ruggedness (meters); reference evapotranspiration (mm yr^{-1})
	Forest characteristics	Biomass and carbon (tons km^{-2}), separately above and below ground; growing stock volume (m^3 ha^{-1}); increment (ton ha^{-1} yr^{-1}); percentage share of a tree species from land area (for 20 tree species, coded 0–100); dominant tree species (0/1)
	Relation to people	Accessibility (travel time in 2000 and 2015); population density; share of private forest ownership; Natura 2000 protection status (SPI, SCI & SAC, joint for all classes)

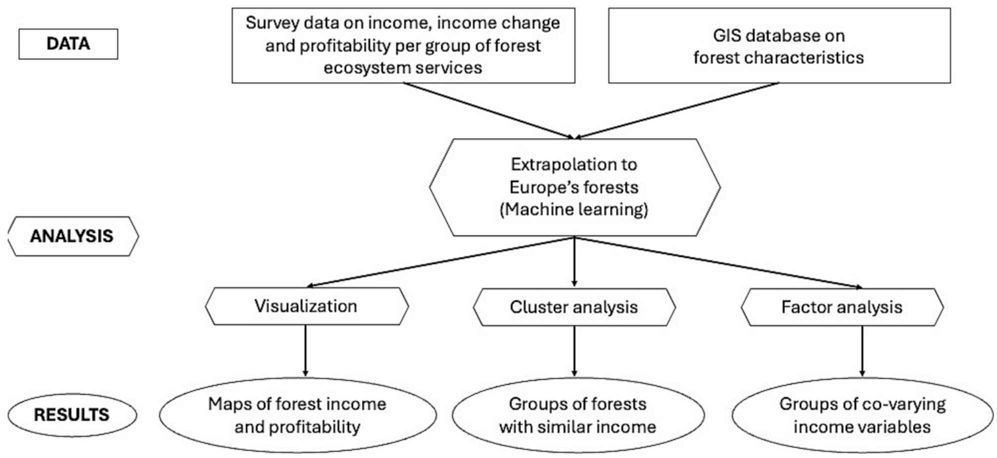

Fig. 1. Methodological workflow (.
Source: own figure). Cluster 1 is blue, labelled as 'wood-focused management' area; cluster 2 is yellow, labelled as 'management for supplying multiple FES' area. The clustering procedure is based on forest income, income change and profitability per FES group. Dominant cluster affiliation per NUTS3 are shown

through clustering procedure appropriate for large datasets, and then used Kruskal-Wallis one-way analysis of variance to see if there are significant difference between these two clusters or not, with respect to variables that describe them. After this, we wanted to see if there is some small set of underlaying variables that could potentially group the nine forest-income and profitability related variables. To that end, a maximum-likelihood factor analysis was performed. We then looked at detailed descriptive statistical analysis of the nine forest-income and profitability related variables. We found that their distributions are not normal, on both national and sub-national (i.e. NUTS-3) levels. We also found that average variability of point-locations within NUTS-3 level is smaller than what the mean average error of point-location estimation is. This led us to use average (median) values on NUTS-3 level for these nine forest-income and profitability related variables when presenting the results of the study (for example, as seen in Fig. 2). Detailed explanations of the statistical procedures are presented in Appendix A4, and the results of all mentioned statistical procedures are shown in the Supplementary material.

3. Results

3.1. European forest incomes

Across Europe, most forest income reported resulted from provisioning FES, i.e. forest products (median or $\mu_{1/2}$ 83 % with inter-quartile range or IQR 24 %). Income shares from regulating and cultural FES were much lower ($\mu_{1/2}$ 18 % with IQR 9 % and 20 % with IQR 13 %, respectively). In the last twenty years, on average, the income share of provisioning FES slightly increased ($\mu_{1/2}$ 0.54 with IQR 0.30 – zero meaning strong income decrease, one a strong increase). For regulating FES, the share was unchanged ($\mu_{1/2}$ 0.50 with IQR 0.17), while for cultural FES it slightly decreased ($\mu_{1/2}$ 0.45 with IQR 0.21). Provisioning FES were perceived as moderately profitable ($\mu_{1/2}$ 0.53 with IQR 0.37– zero means unprofitable, one highly profitable); regulating and cultural FES were predominantly perceived as unprofitable ($\mu_{1/2}$ 0.24 with IQR 0.14 and $\mu_{1/2}$ 0.15 with IQR 0.10; see Supplementary Table S3).

3.2. Spatial patterns

The average share of provisioning forest income in Europe increased markedly when moving on a South-West to North-East spatial gradient (Fig. 1a). Regulating and cultural income shares were somewhat higher in Eastern than in Central and Western Europe (Fig. 1b,c). Over the last two decades, median provisioning income shares decreased in South-Western, yet increased in North-Eastern Europe (Fig. 1d). Going in a West-to-East direction, regulating and cultural FES also increase their income shares (Fig. 1e, f). The profitability of supplying provisioning FES (Fig. 1g) increased from South-West to North-East of Europe. For regulating and cultural FES (Fig. 1h,i), a profitability increase from West towards Eastern Europe could be observed, mirroring the pattern for forest income shares. At country level, Croatia had the highest increase in income derived from regulating ($\mu_{1/2}$ 0.80 with IQR 0.14) and cultural ($\mu_{1/2}$ 0.68 with IQR 0.09) FES.

3.3. Structural features

Using factor analysis, we explore the relations between nine forest income and profitability-related variables. Two highly explanatory factors account for 76.6 % of the variance (factor-loading threshold of 0.9). Variables of income change and profitability of provisioning FES are associated with factor 1, while income and profitability of regulating and cultural FES are associated with factor 2 (see Table 2, Appendix Fig. A1, Supplementary Table S5 and Supplementary Figure S7). Hence, our data on income and profitability per FES group can be summarized into two factors (underlaying variables) of different economic focus: 'forest products (provisioning FES)' versus 'intangible (regulating and cultural) forest FES. Using the CLARA method, we were able to select two corresponding forest clusters (Fig. 2): about equal halves belonging to Cluster 1 (807,042 km^2) and Cluster 2 (651,899 km^2). Cluster 1 was more present in the Central, North-Eastern and Northern Europe (e.g. Germany, Poland, Sweden, Finland, Austria, Latvia, Denmark), Cluster 2 in South-Eastern, Southern and Western Europe (e.g. Croatia, Greece, Bulgaria, Romania, Italy, France, Spain, Belgium, Netherlands, Ireland). The two clusters were statistically different at $p < 2x10^{-16}$ for all independent variables (Supplementary Table S6), except for changing income shares of regulating FES ($p = 0.0028$). Forests in Cluster 1 had higher shares of forest income coming from provisioning FES than forests in Cluster 2 (Table 2). The same was true for the profitability of provisioning FES which was significantly higher in Cluster 1. The opposite applied to income shares from regulating and cultural FES. Notably, the share of forest income from provisioning FES increased over the last two decades for Cluster 1 yet decreased in Cluster 2. Shares of forest income derived from supplying regulating and cultural FES did not substantially change in the last twenty years in either of the clusters).

These findings suggest Cluster 1 represents forests where management is financed by provisioning FES, while Cluster 2 holds areas where management economically relies more on multiple FES. Cluster 2 forests were located in areas with higher population density and closer to cities, in climates characterized by higher evapotranspiration and rainfall,

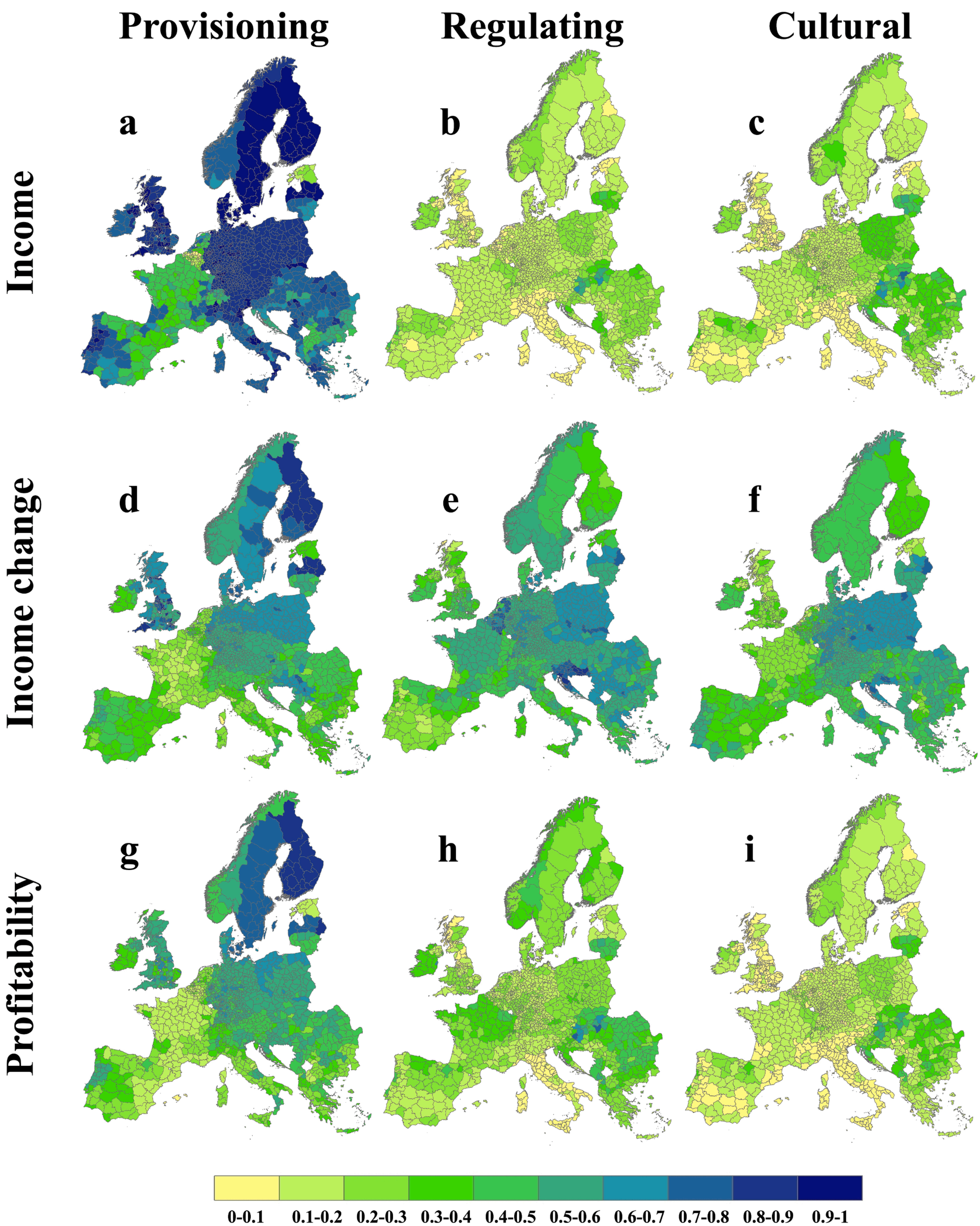

Fig. 2. Share of forest income, income change and profitability (.
Source: own figure). Columns represent provisioning (**a**, **d**, **g**), regulating (**b**, **e**, **h**) and cultural (**c**, **f**, **i**) FES. The first row (**a**, **b**, **c**) refers to share of forest income attributed to supplying each of the three FES groups (0-'no income at all', 1- 'entire income from the forest'). The second row (**d**, **e**, **f**) refers to relative changes in forest income over the last 20 years (0-'has strongly decreased', 1-'has strongly increased'). The third row (**g**, **h**, **i**) refers to profitability of supplying different FES groups (0-'not at all', 1-'very profitable'). Median values per NUTS3 region are presented

Table 2
Clusters of forests in Europe and their forest income and profitability per FES group.

		CLUSTER 1		CLUSTER 2	
Cluster area (km^2)		807.042		651.899	
Dominant region of Europe		Central, North-Eastern and Northern		South-Eastern, Southern and Western	
QUESTION	ES GROUP	$\mu_{1/2}$	IQR	$\mu_{1/2}$	IQR
Forest income share per FES group (from 0 (0 %) to 1 (100 %) of forest income	Provisioning	0,94	0,10	0,67	0,33
	Regulating	0,15	0,06	0,18	0,13
	Cultural	0,16	0,08	0,20	0,19
20 year's change in forest income per FES group (from 0 – has strongly decreased to 1 – has strongly increased	Provisioning	0,67	0,14	0,37	0,20
	Regulating	0,50	0,18	0,51	0,15
	Cultural	0,45	0,21	0,45	0,19
Profitability of supplying different FES groups (from 0 – not profitable at all to 1 – very profitable)	Provisioning	0,71	0,21	0,31	0,25
	Regulating	0,23	0,09	0,29	0,20
	Cultural	0,14	0,07	0,18	0,18

often on steeper slopes with rugged terrain and more frequently hosting Natura 2000 sites. They also hosted more broadleaved species, while Cluster 1 forests hosted more conifers. Differences in shares of private ownership, forest biomass and increment remained marginal across these two types (Supplementary Table S6). An equivalent dichotomy is found when we split forests to state and privately-owned forests. State forests have a significantly higher share of income, income change and profitability of supplying regulating and cultural FES than do private forests, while the share of forest income, income change and profitability of supplying provisioning FES being higher in private than in state forests (Supplementary Table S5). But despite these differences in forest income across Europe, vast majority of forest income (about four fifths) is linked to supplying provisioning FES.

4. Discussion

4.1. Contextualizing results

Our analysis leads to several findings that are novel at the European continental scale and are of potentially high policy relevance. First, we have shown that provisioning FES constitute the by far dominating share of European forest incomes driving profitability, as reported by landowners and managers. Our results represent an important contrast to previous studies that showed increasing social demand for regulating and cultural FES (Winkel et al., 2022; Mann et al., 2022) – and our finding that this demand has not substantially changed levels of forest income linked to supplying these FES; a clear and remarkable economic mismatch. This mismatch persists between, on the one hand, low *de facto* economic incentives for non-material FES supply creating meagre incomes for forest owners and managers and, on the other, high societal demands for these FES for which currently little economic value exists, be it in terms of marketed FES, subsidies, or bilaterally negotiated Payments for Ecosystem Services (PES).

Second, within this overall pattern, there are significant regional differences visible in our dataset. Specifically, two business models for forest management can be distinguished across Europe: one focusing overwhelmingly on supplying provisioning FES ('wood model'), and one with a diversified portfolio generating income also from regulating and cultural FES ('multi-source model'). Europe's forests divide about equally into the two types, with the first type being present mostly in Northern and partially Central Europe, and the latter type being dominant in Southern and Western Europe. Related to that, forest management overall was reported to have become less profitable in Central and Southern Europe, while profitability has been rising in the North, being heavily centred around wood production. These are interesting patterns that we cannot explain further based on our dataset. One explanation may be shifting productivity in forestry due to climate change – this is as our findings fully square with past model predictions for the profitability of wood production vis-a-vis a changing climate, predicting a decline of profitability for Southern and Central Europe (Hanewinkel et al., 2013). An alternative, possibly also related explanation is that northern forest producers have more benefitted from the EU's internal market than their Southern counterparts, which could inter alia also be related to (partially criticized) patterns of intensive forestry in these regions (Levers et al., 2014; Ceccherini et al., 2020). Such an interpretation would correlate well with the political positioning of the respective countries vis-à-vis EU forest policy, where e.g. Finland and Sweden are leading a group of countries promoting a wood-producing perspective and free market arguing against EU-wide environmental regulation of forests, whereas other countries emphasize more the diversified environmental benefits from forests (Winkel and Sotirov, 2016; Sotirov et al., 2021). Yet, further research would be needed to investigate such patterns further.

Third, and perhaps surprisingly, results showing trends over time at the overall European level and at the level of Cluster 1 (Central, North-Eastern and Northern Europe) show little to no diversification trend of income streams in forest management; but rather the opposite – despite the recent policy emphasis on supplying the regulating and cultural FES groups at the EU level. Seemingly, existing non-product markets and subsidy schemes have jointly not been able to deliver the hoped-for push towards diversification; on the contrary, some subsidy schemes have at least partially reinforced a focus on specialized wood production (Geitzenauer et al., 2017). Yet, some exceptions to this outlook also exist, such as Croatia: here our reported strong increase in income from regulating and cultural FES can be linked to green tax reforms promoting sustainable supply of regulating and cultural FES; from 2005, the national forest law set aside 0.07 % of all private revenues (Lovrić and Lovrić, 2013).

In Slovenia, which trails behind Croatia as a country with second-highest share of forest-based income stemming from supplying regulating and cultural FES, the state subsidizes 30–100 % of forest management activities related to supply of regulating and cultural FES (Poljanec et al., 2019). This exemplifies the potential for institutional-legislative reforms to foster FES-specific income flows (Varumo et al., 2019), and also the appropriateness of clustering these countries to Cluster 2, which is characterized by mixed-income streams for forest management. Finland and Sweden stand-out as examples for Cluster 1 assignment, as they have highest shares of forest-based income related to supply of wood (96 % and 94 %). For the Finnish case, external validity of this percentage could be tested by comparing the sum of direct and indirect subsidies and tax cuts (National Audit Office of Finland, 2023) to the stumpage earnings of forest owners (Natural Resources Institute of Finland, 2023); by which the share of stumpage earnings in the combined income of stumpage earnings and subsidies and tax-cuts is 92 %. For Sweden, the equivalent value is 99 % (Haeler et al., 2023; Skogsstyrelsen Statistikdatbas, 2024).

Fourth, it seems important to keep in mind that income and profitability may not directly link to the provision of FES through forest owners and managers. Both private forest owners and public forest managers are known to also follow non-profit motivations when managing their forests (Hugosson and Ingemarson, 2004; Ficko and Boncina, 2013). Thus, the implicit assumption of the study that forest income and profitability are variables through which supply of FES is affected is not universally true. Although significant portion of forests in Europe is managed by private owners with active (wood) management interest (Weiss et al., 2019), the share of new, more urban, forest owners is increasing across the continent. These owners have a greater tendency to provide regulating FES (Matilainen et al., 2019) and propensity for including management objectives that are not wood-related, such as non-timber forest products, recreation and eco-services (Weiss et al., 2019). This means that a more differentiated perspective will be necessary to investigate the impact of the income and profitability gap for cultural and regulating vis a vis provisioning FES on forest management practices and FES supply.

In general, however, our results underline remarkable dichotomies in the management of Europe's forests: between specialized wood and diversified non-wood benefits, between the wood-focused income sources of forest owners and diversifying societal demands, and between biophysically and demographically different regions of Europe, showcasing fundamentally distinct realities of forest production. We identify a need to customize and diversify the forest income base towards regulating and cultural FES, especially as progressing climate change will make these services more critical in increasingly vulnerable forests across Europe (Schröter et al., 2005; Lindner et al., 2010). Unless the marked income and profitability gaps are progressively being bridged by innovative policies and markets, these essential forest service functions will continuously remain under-supplied vis-à-vis expanding societal demands.

4.2. Caveats and omissions

Interpretation of our results requires us to duly consider various data limitations.

First, our sampling frame is not fully aligned with the target population of European forest owners and managers – which is not fully registered, and thus essentially unknown. The patchy available forest-owner information is thus also not continentally scalable for systematic sampling. Facing this obstacle, our sampling strategy was top-down, using multiple European and national forest owner and manager umbrella associations for widely disseminating our survey. This likely skews the sample towards more active forest managers and owners and away from more passive and less commercially oriented forest owners. Rectifying this would require different sampling strategy; either general household survey or a stratified 'grid' of case-study areas. Given the low share of forest owners and managers (especially state-owned forest managers) in the overall society, the former approach would be impractical as the incidence rate is lower than what polling agencies would accept, while the latter would be prohibitively expensive to execute and would be more suited for a more qualitative research design. In terms of how big sample size would be needed in a survey distributed with a simple random sample to get the same level of accuracy (i.e. 95 % confidence level, where the mean average error of 0.16 has the same meaning as margin of error at 16 %) at a national level – we'd need 38 random respondents per country, totalling to 950 respondents for 25 countries. This is comparable to sample size of this study.

Moreover, related to the sampling strategy, our sample is not equally distributed across Europe: response rates were higher in Central and Northern Europe than in Eastern and Southern Europe, increasing the level of uncertainty for our results in the latter region (Supplementary Figure S1). On a practical example – two forests in Germany (where we have larger sample) and Romania (where we have smaller sample) may have similar characteristics (which we accounted for) and the model estimates similar income per FES group; but actual income per FES group may be different due to different potential tax subsidy systems, implemented business models and user's preferences. The latter group of preferences we did not account for, and thus the model's validity is lower in Romania than in Germany. Some validity-tests to assess how representative the sample is (See Supplementary Figures S2-S5) can be found by comparing it to UNECE-FAO (2020) report on forest ownership: amongst our respondents, individual and family respondents cover about four fifths of all private-forest respondents, and the majority of state-forest holdings are above 500 ha. These parameters of our sample fits well to the situation as reported by UNECE-FAO. Where the two differ is in the share of private holdings below 50 ha; in our sample 50 % of all respondents are in this category, while the value reported by UNECE-FAO is about 90 %. This may indicate that our sample is skewed towards larger-scale enterprises which are presumably also those more commercially oriented; an expected bias given the selected sampling strategy. Another way of looking at this data comparison would, however, be to say that half of the private forest area in Europe is covered by forest holdings larger than 50 ha; and our sample gives equal weight to forest holdings smaller and larger than 50 ha (thus being representative in terms of private forest holding size but not with respect to distribution of private forest owners).

Second, we faced a large mean error (0.16) in our data extrapolation, limiting our interpretation particularly at country level. Our analysis is thus valid for the big-stroke income and profitability-related patterns and trends across Europe, while more fine-grained data would be needed for country-level or locally rooted assessments. We also used biomass map from Barredo et al (2012) – while it would be more suitable if we have used the newer Corine Land Cover 2018 (Büttner et al., 2021). This omission also had an effect on the drop-out rate; i.e. we excluded some responses who pointed to a forest which was far from we considered to be a forest (based on Barredo et al., 2012), thus omitting some new reforested and afforested areas. Another omission is the fact that we did not use data on intensity of forest management (Nabuurs et al., 2019). While some independent variable used in this paper are the same as the ones used in this one, the analysis would still benefit from its inclusion. We can hypothesize that data on actual forest management strategies would be highly explanatory variable; but such spatially explicit data aggregated on EU level does not exist. One potential future data source is LULUCF reporting, which from 2027 onwards will have to be spatially explicit.

Third, we have measured income and profitability as relative variables reported by forest owners and managers, and not as absolute numbers, reflecting a decision based on the questions' sensitivity. This introduces the bias of forest owners and manager's perceptions of forest income and profitability. Remediating that would require in-depth analyses comparing perceptions and actual forest income and profitability, which is clearly beyond the scope of a European scale analysis. Yet, we are also confident that perception biases may have levelled off in our dataset – i.e. that some respondents may have over-, and others underestimated income shares. This remains, however, uncertain given the nature of our dataset. In general, the performance of the study's model would have benefited from a larger, more equally distributed sample and from inclusion of more and newer independent variables.

5. Conclusions

The economics of forest management investigated in this paper may indicate a critical constrain for the sustainable provision of multiple FES in Europe. This is especially true for areas where wood production is highly profitable (e.g. Northern Europe); compared to the provision of intangible regulating and cultural FES (e.g. in Southern and Western Europe). The European-wide profitability and income gap in relation to regulating and cultural FES compared to provisioning ones need to be bridged by policy to align the forest products-and-services mix with changing societal demands. This changing demand has been recognized by the European Commission (2023), and is actively promoting alternative income streams so that the FES that Europe's forests supply are more aligned to their societal demand.

Still, this challenge varies in degree across Europe, and needs to be met by EU and member state policies for better addressing objectives such as biodiversity conservation and carbon mitigation in forestry. One obvious policy is to incentivize forest owners and managers to specifically supply regulating and cultural FES – something already advocated in the new EU Forest Strategy (European Commission, 2021), e.g. through PES (Wunder et al., 2018). Such incentives can potentially be customized and supported nationally, they would need to remain compatible with the World Trade Organization (WTO) framework and be harmonized with the EU's Common Agricultural Policy. Yet, PES alone will not be sufficient to address the challenges at hand. As indicated above, forest owners and managers do follow various objectives for their forests, and profitability may not always be decisive for their decision making. Varying values and levels of individualism may pose a challenge to policy makers (Matilainen et al., 2019; Živojinović et al., 2015). Policy instruments must consider that forest management decision and motivations governing them differ across forest ownership categories and individual forest owner types. In other words, grounding implementation of a given policy instrument to a local context has higher chance of creating win–win situations than defining them top-down from the onset (Howe et al., 2014). For public forests, PES may not be suitable at all in situations where profitability is not the key objective of management operations.

Finally, to fully tackle the income and profitability gap across Europe, PES systems will need to be embedded in a larger systematic transition of the institutional framework (Thompson and Harris, 2021) forest owners and managers operate in: EU forest policymaking is characterized by long-lasting controversies and ideological polarization between conservation and forest production interests (Sotirov et al., 2021). This is due to underlying reasons featuring Europe's disparate economic geographies, as mirrored well in our results. Based on findings from different FES focused projects in Europe, Winkel et al (2022) identified four policy pathways to align FES supply to demand: (i) a pan-European forest PES system (see above); ii) better spatially explicit FES monitoring; (iii) improved policy integration across objectives and implementation instruments; and (iv) enabling bottom-up participatory forest planning. Hence, a broader instrument mix will be needed in future EU forest policy to ensure that FES supply meets demand across the continent. Achieving this will remain challenging given diverging interests and ideologies involved.

CRediT authorship contribution statement

Marko Lovrić: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mario Torralba:** Writing – review & editing, Validation, Resources, Investigation, Data curation. **Francesco Orsi:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Davide Pettenella:** Writing – review & editing, Validation, Resources, Funding acquisition, Conceptualization. **Carsten Mann:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Davide Geneletti:** Writing – review & editing, Validation, Resources, Funding acquisition, Conceptualization. **Tobias Plieninger:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Eeva Primmer:** Writing – review & editing, Supervision, Methodology. **Monica Hernandez-Morcillo:** Writing – review & editing, Validation, Investigation, Conceptualization. **Bo Jellesmark Thorsen:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Thomas Lundhede:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Lasse Loft:** Writing – review & editing, Validation, Methodology, Data curation. **Sven Wunder:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Georg Winkel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

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Appendix A

A1. Data sources.

Summary representation of data generated in the study and description of used variables and data sources is presented Supplementary Table S1. The data that supports the findings of this study are available in Zenodo repository with the identifier https://doi.org/10.5281/zenodo.6912731. It contains the coordinates of forest point-locations, associated values of dependent variables on income and profitability and all other forest data that was used in the study. It also has an Excel file with various detailed results of the analysis.

A2. Missing data

The objective of the MICE procedure is to input the missing data in such a manner that the relationships between all the variables in the dataset are maintained. It works under the assumption that the variations within the missing data can be observed by the existing data (i.e. that the variability of missing data that is not explained by collected variables is randomly distributed). The MICE model operates on iterative multiple-regression models. The first step is to calculate the means of the columns with missing data, and then these mean values provisionally replace the missing data. Then, these mean values are deleted on the first variable that had missing data. Multiple regression is performed to estimate the values of the missing data on this first column. The procedure is then repeated on all subsequent variables that have missing data. Performing this procedure once on all variables that have missing data is called one cycle, which results with one estimation of missing values and of corresponding regression coefficients per variable. Default setup of the procedure is to iteratively perform five cycles – which is what we did. The default estimation method is classification and regression trees (*cart*) method; and we have applied it. Then the mean values of the regression coefficients from five cycles are used to make the final regression coefficients, which are then used to make the final estimation of the missing data (i.e. five distributions of missing data are pooled to a single one). In terms of removing interval variables that are highly co-linear (i.e. keeping just the above-and-below ground biomass variable from the variables that describe biomass and carbon volume above and / or below ground); this was based on a cross-correlation matrix (where the values were above threshold for very high correlation, i.e. 0.78) and on Variance Inflation Factor, which showed multicollinearity (with values higher than 5;

Gareth et al., 2014).

Spatially explicit co-linear variables that were used for the estimation of profitability and income-related variables were removed. As the variables above-and-below ground biomass, above-and-below ground carbon, above-ground biomass and above-ground carbon proved highly co-linear, only the above-and-below ground biomass variable was kept in the estimations. Country-affiliations of forest point-locations were presented with 'one-hot-encoding'; i.e. each country affiliation was coded as a separate binary variable (0 / 1 or point is not in this country / point is in this country). We removed the binary variables of country association for countries from which we had no responses and for countries where we had less than 10 responses in the survey's data. We did the same with binary variables stating dominant tree species for which there were no positive values in the sample (e.g. binary variable for Black Locust; *Robinia pseudoacacia*, being the dominant tree species in a point-location was removed as the survey's sample data had no responses for forest areas where Black Locust is the dominant tree species). The estimation thus consisted of 73 independent variables. All variables were separately normalized (0–1 range).

A3. Machine learning procedure

Deep neural network model was counstructed. It consisted out of an input layer, two hidden layers, two dropout and one output layer. The output layer consisted of all nine profitability and income-related variables. The rectified linear unit activation function was selected for the hidden layers and the sigmoid activation unit was selected in the output layer, which is scaled to the 0–1 range. Mean absolute error was selected for the loss function and as the output metric. Adaptive Moment Estimation (ADAM) was selected as the optimizer. Epochs were set to 500 with a call-back function for early stopping as based on a valuation loss criterion. A 20 % of the sample was used as validation data. Hyperparameter tuning is based on number of neurons in the first hidden layer (50, 60, 70, 80, 90), in the second hidden layer (25, 30, 35, 40), in the first and second dropout layer (0.1, 0.2, 0.3, 0.4, 0.5, 0.6) and on the learning rate (0.00001, 0.0001, 0.001, 0.01). The full sample of model configurations was run where the best configuration was set by the smallest valuation mean absolute error. The best run configuration was 80 neurons in the first hidden layer and 40 neurons in the second one, with a 0.5 dropout rate in the first dropout layer and a 0.3 dropout rate in the second, using 0.001 as the learning rate. This resulted in a 0.1660 valuation mean absolute error, with a training mean absolute error of 0.1665. The estimation procedure was also implemented on various samples where some of the data quality requirements were different; that the respondents needed to answer between 4 and 9 questions on income and profitability and that the minimal distance to the nearest forest is between 500 and 1000 m. The sample with 750-meter distance criterion and the condition of answering seven or more income and profitability questions resulted with smallest mean absolute error.

A4. Statistical analysis

The CLARA clustering method based on Euclidian distance was performed on all dependent variables (nine income and profitability variables). It is designed to cluster large datasets, implemented through packages *cluster (*Maechler et al., 2021) and *facto-extra (*Kassambara and Mundt, 2020). It was done on five random samples of the size of 30,000 data points. The number of clusters was defined by the silhouette method. The two-cluster solution was selected, with the mean average silhouette across the five samples of being 0.573 (highest among the 1–10 solutions). Kruskal-Wallis one-way analysis of variance was used to test if there were significant differences between clusters when it comes to independent variables (e.g. growing stock or distance to nearest city); as the variables were not normally distributed. A maximum-likelihood factor analysis was performed on the dependent variables with oblique rotation that permits the factors to be correlated with one another. Only the first three factors are shown, having an eigenvalue higher than 1. When disaggregating the data by country, the dependent variables are predominantly not normally distributed (in the dependent variable by country cross-tabulation, 93.7 % of *p*-values in the Jarque-Bera two-sided test are smaller than 0.05). When the dependent variable data is disaggregated to NUTS3 regions, on average (across all dependent variables) 43.3 % of the regions has normally distributed data. As less than half of dependent-variable data per region (NUTS3) are normally distributed, interquartile range (IQR) is selected as the data dispersion (variability) measure. Also called mid-spread, it represents the range of the middle 50 % of the data or the range of values covered in the interval between the 25th and the 75th percentile. Mean IQR for all dependent variable across all NUTS3 regions is 0.08. As this range is smaller than the mean average error of the estimation procedure, the 1x1 km results have been aggregated to NUTS3 level for the depiction in Fig. 2 and depicted in 10 equal classes, representing the 0–1 range of values of the income and profitability variables. This aggregation is based on median value per region, as the majority of NUTS3 data is not normally distributed. We also chose not to normalize the income and profitability related variables to a 0–1 range per forest point location, as this would diminish the visibility of the estimation error. The downside of this transparency is that direct comparisons of income and profitability variables across FES groups are obfuscated, e.g. we can say that forests of Cluster 2 (See Appendix Fig. A1) generate about a third of its income from supplying regulating and cultural FES, but there would be less validity in discussing exact ratios of values. Cross-tabulation of dependent variables across ownership categories is presented in results and in Supplementary Table S5. Ownership is coded on an 0–1 interval scale, where 0 represents full state and 1 full private ownership in the 1 km^2 of the data grid. For this purpose, data points where variable ownership is ≤ 0.2 are classified as state-owned and ≥ 0.8 are classified as private forests. Kruskal-Wallis and pairwise Wilcox tests were used to see if there are significant differences between ownership categories in dependent variables or not. Significant differences between the two categories were found for all dependent variables with $p < 1 \bullet 10^{-16}$.

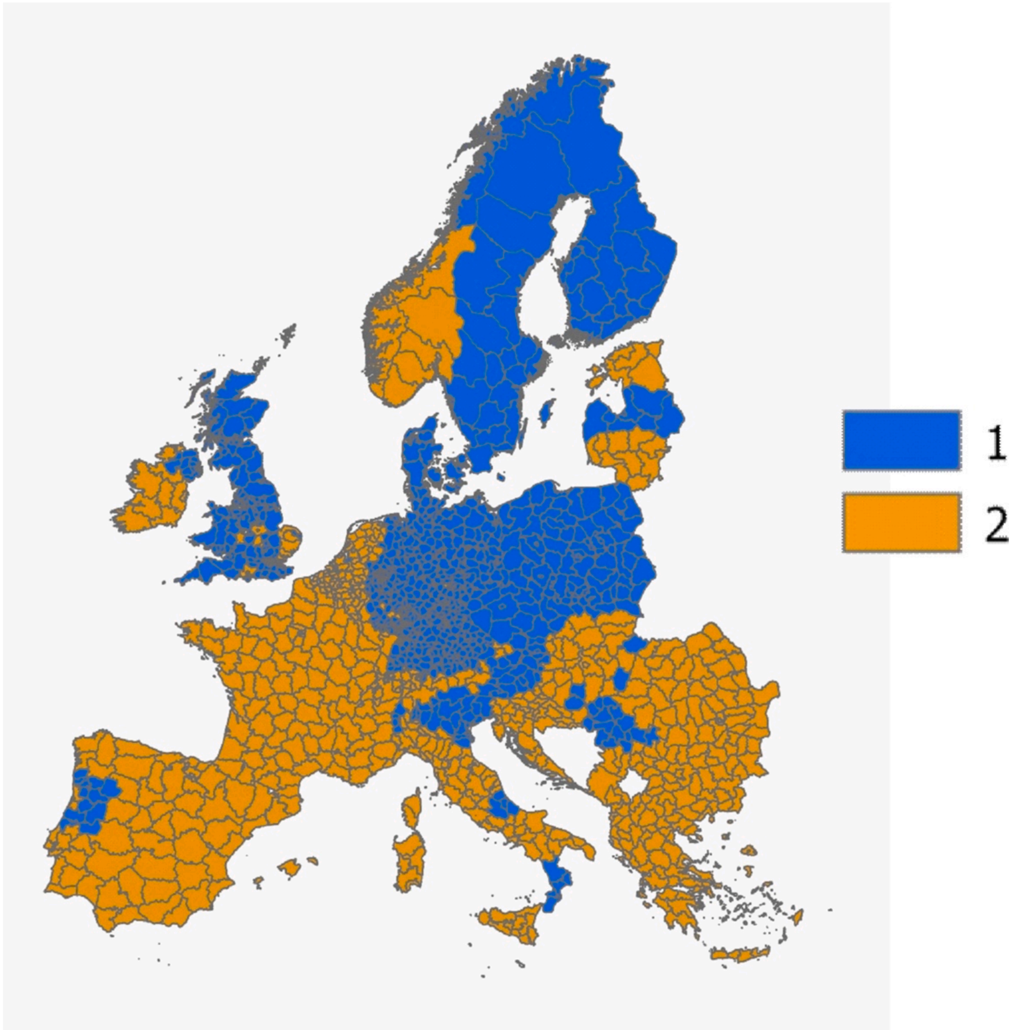

Fig. A1. Clusters of forests in Europe.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2024.101689.

Data availability

All results and independent variables are published on Zenodo. Code and survey data were shared with reviews. Access to code can be requested from authors. Survey data is sensitive and cannot be shared.

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