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Mapping hotspots and bundles of forest ecosystem services across the European Union

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ABSTRACT

Forests cover about 40 % of the European Union (EU), providing a wide spectrum of invaluable ecosystem services to more than half a billion people. In order to protect and harness this crucial asset, EU policies are advancing multifunctional management. This study lays a basis for such an effort by mapping the supply of key forest ecosystem services (FES) across the entire EU: wood, water supply, erosion control, pollination, habitat protection, soil formation, climate regulation and recreation. To further support the operationalization of multifunctionality and targeting of policies, our analysis delineates hotspots, assesses synergies and tradeoffs, and identifies spatial bundles.

We generated maps at 1-km resolution starting from existing datasets through simple modelling (Tier 1). Out of these maps, we denoted the highest supplying pixels (i.e. top 20 %) as hotspots, and performed correlation analysis to detect synergies and tradeoffs. Finally, we used cluster analysis to identify FES bundles. Our analysis shows that hotspots of single FES are spread across the entire EU and that forests of mountain regions and Central Europe (particularly France, Germany, Slovakia) supply significant amounts of multiple FES. The cluster analysis resulted in four bundles: “balanced” in the northeast, “wood & water” in the center, “soil carbon” in the north and “rural-recreational” in the south. While a purely quantitative analysis of the produced maps may be misleading because of the strong links between FES supply and climatic and socio-economic conditions, overlaying hotspots and bundles with administrative layers can be a first step to inform about the role of different countries and regions in securing the sustainable supply of European FES.

1. Introduction

Forest ecosystems provide a wide spectrum of services that human societies enjoy and depend upon. These include tangible goods such as wood and non-wood products, regulating functions such as soil stabilization, carbon sequestration and water retention, and cultural benefits such as recreational opportunities and spiritual values (Saarikoski et al., 2015). Ecosystem services (ES) are interlinked and contribute to the well-being of human communities (MEA, 2005; Haines-Young and Potschin, 2010; FAO, 2015). To ensure continued provision of ecosystem services, forest landscapes need to be managed in a way that pays attention to the different functions of forests and secures their sustainability. As population growth and climate change increase pressure on forest resources worldwide (DeFries et al., 2010; Hanewinkel et al., 2013), the idea of a multifunctional management that seeks to guarantee all functions supported by forests, is receiving a great deal of attention in scientific literature (Wolf and Primmer, 2006; Gustafsson et al., 2012; Langner et al., 2017), technical reports (Sabogal et al., 2013) and policy (UN, 1992; EC, 2013a).

Sustainable multifunctional management is at the core of the European Union’s (EU) forest policy (EC, 2013a; Bouwma et al., 2018), which oversees 1.4 million km^2 of forest area, representing 3% of the world’s forests, and providing benefits to around 520 million people, that is 7% of the world’s population. The EU Forest Strategy, in particular, highlights the importance of “balancing various forest functions, meeting demands, and delivering vital ecosystem services” (EC, 2013a). It supports protection and management efforts aimed at maintaining, enhancing and restoring “forest ecosystems’ resilience and multi-functionality as a core part of the EU’s green infrastructure, providing key environmental services as well as raw materials” for both urban and rural areas (EC, 2013a). Additionally, the EU green infrastructure policy calls for nature-based solutions (NBS) and the enhancement of

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nature and natural processes in spatial planning and territorial development (EC, 2013b), for which forest ecosystems are central. Yet, the integration of these different goals into other policy sectors and across regions and governance levels can be challenging (Winkel and Sotirov, 2016).

In fact, the practical implementation of the different EU strategies promoting the sustainable use of natural processes and capital for ecological and social wellbeing requires an in-depth knowledge of where different forest ecosystem services (FES) are supplied across the EU territory. This can be achieved through mapping (Burkhard et al., 2012; Crossman et al., 2013; Santos-Martín et al., 2019), as advocated by the MAES (Mapping and Assessment of Ecosystems and their Services) initiative (Maes et al., 2013, 2015), and shown by various Pan-European maps of ES produced recently (Schulp et al., 2014a; Stürck et al., 2014; Vandecasteele et al., 2017), some of which specifically focus on ES intimately linked to forests (e.g. biomass production, carbon storage) (de Rigo et al., 2013; Avitabile and Camia, 2018). However, while existing maps convey detailed information about the spatial distribution of European ES, including some of those deeply connected to forest ecosystems, they cannot, if considered separately from each other, respond to some important questions decision-makers might face when adopting the multifunctional approach advocated by EU forest policy.

The first question is which forest areas are the greatest providers (i.e. highest supply per unit area) of ES. These areas, which are generally referred to as ES hotspots (Egoh et al., 2008; Garcia-Nieto et al., 2013; Geneletti et al., 2018), are in fact of crucial importance for ecosystem health and human well-being, and may be given special conservation status. The second question is how the provision of one FES is related to the provision of others, or whether synergies or tradeoffs occur between different FES (Raudsepp-Hearne et al., 2010; Seppelt et al., 2011; Geneletti, 2013), which is a very important information for the design of cost-effective and legitimate policies (Hauck et al., 2013). The third question is whether different forest areas provide similar ensembles of multiple ES, as this would reveal their (ir)replaceability (particularly at a national or sub-national level) and their connection with human-controlled land uses (Bai et al., 2011). Such ensembles, known as ES bundles (Maes et al., 2011; Mouchet et al., 2017a, 2017b), are a direct consequence of synergies and tradeoffs (Bennett et al., 2009; Raudsepp-Hearne et al., 2010), and constitute unique providers of multiple ES, reflecting relevant socio-ecological subsystems (Dick et al., 2010; Raudsepp-Hearne et al., 2010).

The first question, which addresses a major topic in conservation planning (Chan et al., 2006; Schröter and Remme, 2016), can be answered through a variety of approaches. When the goal is to identify hotspots of single ES, this can be achieved by selecting from a map a fixed number of cells with the highest levels of ES supply (Eigenbrod et al., 2010; Bai et al., 2011; Geneletti et al., 2020), imposing some biophysical thresholds (e.g. carbon storage above 40 tons ha^{-1}) (Egoh et al., 2008) or clustering (O’Farrell et al., 2010). When the goal is to delineate hotspots of multiple ES, this can be achieved by overlapping various ES’s hotspots (Garcia-Nieto et al., 2013) or applying more complex measures of occurrence, such as intensity (i.e. number of sites providing a service) or richness (i.e. number of different services per land cover unit) (Plieninger et al., 2013). An example of such analyses for European ES is provided by Schulp et al. (2014), who detected potential hotspots of climate regulation, erosion protection, flood regulation, pollination and recreation, reviewing and comparing maps from various sources to check their accuracy and consistency.

The second question can be answered through correlation-based analysis of ES supply values, whereby a positive correlation highlights a synergy and a negative correlation highlights a tradeoff (Turner et al., 2014; Geneletti et al., 2018; Roces-Diaz. et al., 2018), although synergies and tradeoffs may also be roughly detected through simple map overlay (Swallow et al., 2009).

Maes et al. (2011), for example, used Principal Component Analysis (PCA) to assess tradeoffs among 13 ES at the European level, showing positive correlations among such FES as wood, climate regulation and recreation (in fact, the amount of wood is inherently related to carbon storage) as well as between these and pollination, and between these and erosion control. Results similar to Maes et al. (2011) were drawn by Jopke et al. (2015), who also highlighted how synergies between timber provision and regulating services may be more common in unmanaged rather than managed forests (i.e. in managed forests timber provision is typically inversely related to other services) (Maes et al., 2011).

The third question can be answered through spatial cluster analysis, which may be performed on a limited set of principal components rather than all the original ES variables to ensure orthogonality of the inputs and therefore avoid double counting of correlated ES (Plieninger et al., 2013; Turner et al., 2014; Ferrari et al., 2016; Barò et al., 2017; Schirpke et al., 2019). A thorough analysis and mapping of ES bundles in Europe was carried out by Mouchet et al. (2017a; 2017b), who identified three major clusters (spatial bundles), the first of which predominantly represents FES and overlaps almost perfectly with forested areas. European-level bundles were also mapped by Maes et al. (2011) and Schulp et al. (2014b), yet in these studies bundles were simply intended as either groups of ES associated with one resource (e.g. timber-related ES, health-related ES) or the summation of multiple ES.

While some of the above-mentioned studies have provided valuable insights about European FES, relatively little has been done to specifically address the hotspot, synergy-tradeoff and bundling questions for a significant number of FES over the entire EU (Van der Plas et al., 2018). Our analysis aims to map the supply of key FES across the EU, to delineate FES hotspots, to identify synergies and tradeoffs among FES, and to allocate spatial bundles of FES. The study is comprehensive in scope as we consider the entire EU forested land and analyze a total of eight ES of all categories (i.e. provisioning, regulating, cultural) that are tightly connected to forest ecosystems.

The paper is organized as follows. In the methods section, which comes after a description of the general features of EU forests, we will describe the reasoning behind FES choices, as well as our approach to mapping FES, delineating hotspots, assessing synergies and tradeoffs, and identifying spatial bundles. In the results section, we will report on the spatial distribution of FES, hotspots, correlations among FES, and bundles. Finally, in the discussion section, we will elaborate on our findings and their policy implications, and comment about strengths and weaknesses of the method.

2. Basic features of EU forests

The EU, which currently includes 28 countries, has a total area of 4.3 million km^2 and is home to about 520 million people. Forests – namely, land with a canopy cover above 10 % and an area of more than 0.5 ha (FAO, 2018) – and other wooded land – namely, land with a canopy cover of 5–10 % and an area of more than 0.5 ha or land with a canopy cover above 10 % comprising shrub, bushes, trees (FAO, 2018) – cover around 182 million ha or about 40 % of the EU territory (Eurostat, 2016), with forests alone covering roughly 140 million ha. Larger unfragmented forest areas are mostly concentrated in Central-Northern countries like Sweden, Finland, the Baltic Republics and Poland, as well as in mountain regions, particularly the Alps, the Pyrenees, the Iberian Range, the Carpathians, the Apennines, the Pindus and the Rhodopes (Fig. 1). The more fragmented forest landscapes of the Central and Southern lowlands are associated with a stronger human presence and therefore larger extensions of agriculture and urban and periurban land uses. Nonetheless, at the EU-level, forest cover has been growing at an average 0.4 % annual rate in the last decades owing to afforestation and the abandonment of remote areas (e.g. mountain pastures) by human communities, which has left space for natural succession (Tattoni et al., 2017). Due to the significant latitude and

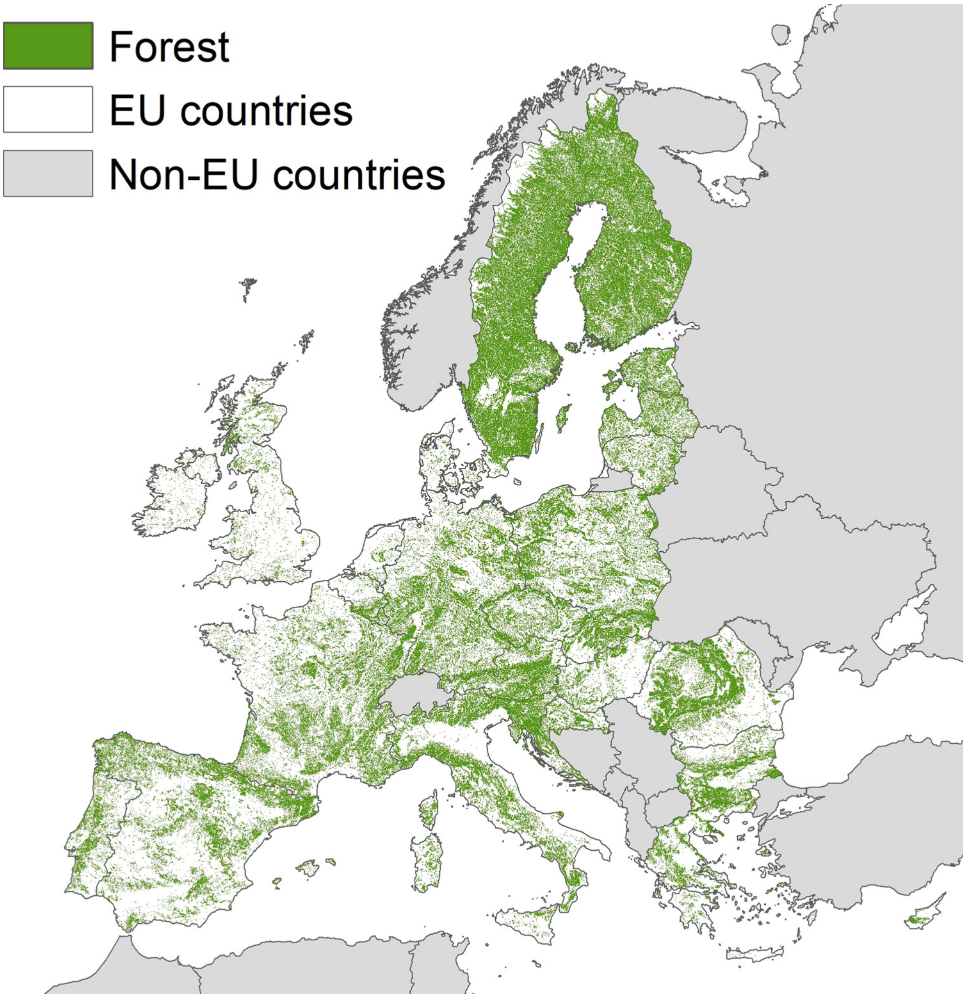


Fig. 1. The EU forest cover as per classes 311, 312 and 313 of the 2012 CORINE land cover.

elevation gradients, forest and vegetation types vary dramatically across the continent: from Mediterranean scrub to boreal forest, from tundra to Alpine woodland (EEA, 2007).

Roughly 60 % of EU forests are privately owned, though the proportion of public vs. private forests varies dramatically both between and within countries. In general, forests are predominantly private (i.e. more than 50 % of forest land is private) in Western Europe, with the exception of Andalusia and Aragon in Spain, Trentino, Abruzzo and Sicily in Italy, South-western and North-eastern Germany, most of Ireland and the northernmost part of Sweden and Finland, whereas they are predominantly public (i.e. more than 50 % of forest land is public) in Eastern Europe, with exceptions in Romania and Estonia (Pulla et al., 2013).

The habitat role of EU forests is crucial: about 9 million ha of the total forest area are undisturbed by humans (i.e. forests where natural forest development cycle is conserved, showing characteristics of natural tree species composition, natural regeneration and minimal evidence of man-made activity) and more than 14 million ha are designated as Natura 2000 sites, that is nearly one fifth of the whole terrestrial Natura 2000 network (EC, 2010; Forest Europe, 2011). Further, most of the areas not included in the Natura 2000 network host species that are protected under EU legislation.

Wood and forest biomass are the main source of financial revenue from forest products and the most important source of renewable energy, respectively. While in the recent past only 60–70 % of the annual increment was being cut, and therefore wood stock was rising, harvest rates may increase by about 30 % by 2020 compared to 2010 (EC, 2013a). Similarly, biomass is expected to provide more than 40 % of the 2020 renewable energy target, meaning that the amount of wood required for energy purposes in the near future will be equivalent to today's total harvest (EC, 2013a). Meanwhile, climate change is having and, according to climate modelling, will have enormous impacts on forest ecosystems, including a modification of species composition, the intensification of fires and other extreme events (e.g. storms) and the diffusion of pests (EEA, 2017). Under these circumstances, sustainable forest management driven by a careful analysis of the potential of different areas to supply various FES is key to guaranteeing long-term benefits to human communities.

3. Methods

The study involved four major steps: mapping of FES; delineation of hotspots; analysis of synergies and tradeoffs; and identification of spatial bundles.

3.1. Mapping of FES

Continental-scale mapping of ES is generally performed at resolutions between 100 m and 1 km through the application of relatively simple models fed by spatially-explicit raster data about land use/land cover (Kienast et al., 2009; Schulp et al., 2014a), elevation (Guerra et al., 2016) or vegetation characteristics (Vandecasteele et al., 2017), as well as point-based information (e.g. meteorological data), which may be used for calibration (Guerra et al., 2016). Such approaches are suited to the large scale of analysis and the strong link between the modelled services and land use/land cover (Maes et al., 2012), and are consistent with Tier 1 level mapping (Grêt-Regamey et al., 2015). In this study, FES were mapped at 1-km resolution, predominantly by direct extraction of relevant information from existing raster datasets generated in previous mapping exercises (mostly, those produced by the European Commission's Joint Research Centre), though some Tier 1 modelling using land use/land cover, forest, soil, elevation and climatic data was also performed to generate new datasets (e.g. water supply) or adapt existing datasets to the scope of the present study (e.g. recreation). Basic raster operations, such as resampling, were performed on some of the existing raster datasets to make them comply with the common resolution requirement.

The selection of FES to map was based on the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2013), as it provides a consistent standardization in the way ES are described and is the classification scheme employed in the EU initiative on Mapping and Assessment of Ecosystems and their Services (MAES) (EC, 2014). Two main criteria were used to select FES: close link to forest ecosystems (i.e. services that are mostly provided by, or significantly associated with, forest ecosystems) and availability of relevant high-quality data for the entire EU. This resulted in selecting two provisioning, five regulating and one cultural FES (Table 1).

The definition of appropriate supply indicators for the selected FES was also based on two criteria, namely the scientific relevance of an indicator for a specific FES and the availability of sufficiently high-quality spatial datasets to map the indicator over the entire EU. The first criterion was assessed by reviewing scientific literature and indicator proposals included in the second MAES report (EC, 2014), which is connected to mapping exercises recently conducted by the European Commission's Joint Research Centre (JRC). The second criterion was assessed by verifying the availability of spatially-explicit datasets generated by peer-reviewed Pan-European studies at high or very high resolution (generally from 1 km to 100 m) that could be used directly or through simple processing to map the indicator. Indicators for the selected FES (Table 1) were mapped at a resolution of 1 km over the EU forested area as per Corine land cover classes 311, 312 and 313, which refer to land occupied by broadleaved forest, coniferous forest and mixed forest, respectively (canopy cover of at least 30 % or a minimum 500 subjects ha^{-1} density).

3.1.1. *Provisioning FES*

3.1.1.1. Wood. The provision of wood was mapped as the overall amount of wood available for timber production using a global dataset of growing stock volume (m^3 per hectare) derived from Earth Observation data in the framework of the European Space Agency's (ESA) GlobBiomass project (Santoro et al., 2018). According to the dataset's metadata, growing stock volume is defined at a 1-km resolution as the volume of all living trees with a diameter breast height (DBH) in excess of 10 cm, measured over bark from ground (or stump) height to top. Small branches, foliage, flowers, stump and roots are excluded from the measurement. Santoro et al. (2018) estimated growing stock volume combining space borne Synthetic Aperture Radar (SAR), LiDAR and optical observations (Landsat-7), and a variety of forest and climatic datasets (used for training) for the year 2010. Models to turn earth observations into biomass values were tuned locally to account for the variability of forest structure across space (Santoro et al., 2018).

3.1.1.2. Water supply. Similar to what was done in previous studies (Mokondoko et al., 2018), we estimated freshwater supply as the amount of water running off each land parcel in the landscape owing to the combined effect of precipitation and evapotranspiration, using the Annual Water Yield model of InVEST 3.3 (Integrated Valuation of Ecosystem Services and Tradeoffs). The model, which is based on an approximation of the Budyko curve (Zhang et al., 2008), does not

Table 1
FES considered in this study, indicators selected to map them and references to the publications describing how the datasets used to map the related FES were created.

Section	Division	Group	ES (Class)	Indicator	Unit	Reference[a]
PROVISIONING	Materials	Biomass	Wood	Growing stock volume	$m^3\ ha^{-1}$	Santoro et al., 2018
	Nutrition	Water	Water supply	Water yield	$mm\ yr^{-1}$	–
REGULATING	Mediation of flows	Mass flows	Erosion control	Avoided soil erosion	$tons\ ha^{-1}\ yr^{-1}$	Maes et al., 2015; Guerra et al., 2016
	Maintenance of biological conditions	Lifecycle maintenance and habitat protection	Pollination	Relative pollination potential	–	Zulian et al., 2013
			Habitat provision	Relative bird species richness	%	Vallecillo et al., 2016
		Soil formation	Soil formation	Soil organic carbon	$tons\ ha^{-1}$	Hiederer and Köchy, 2012
		Atmospheric composition	Climate regulation	Carbon storage	$tons\ ha^{-1}$	de Rigo et al., 2013; Barredo et al., 2012
CULTURAL	Physical and intellectual interactions with ecosystems	Physical and experiential interactions	Recreation	Recreation opportunity	–	Paracchini et al., 2014

[a] No reference is reported for Water supply as this was mapped through modelling with InVEST.

distinguish between surface and subsurface water, but assumes that all water passing through a land parcel will eventually reach an outlet (i.e. a watershed's lowest point or a hydropower plant) via one of these pathways. The effect of soil type, soil depth and vegetation on water yield is accounted for in the model, hence acknowledging the role of forests in the provision of this ES.

Several inputs are required by the model to run properly. We computed data about average annual precipitation at each location by summing up monthly datasets available in the WorldClim global climate database (http://www.worldclim.org), which provides monthly averages estimated at a 1-km resolution over the period 1970 – 2000. The average annual reference evapotranspiration was obtained from the Global Reference Evapotranspiration Version 2 dataset (Trabucco and Zomer, 2019). The root restricting layer depth, namely the soil depth at which the penetration of roots is inhibited, was obtained from the JRC European Soil Data Centre's (ESDAC) European Soil Database (Panagos et al., 2012; Hiederer, 2013). The plant available water content (i.e. fraction of water stored in the soil that is available for plants) was derived from the relevant map (Available Water Capacity) in the "Topsoil physical properties for Europe" database by ESDAC (Panagos et al., 2012; Ballabio et al., 2016). As the dataset does not cover Cyprus, information for this country was computed from spatially-explicit data of the fraction of clay, sand, silt, gravel and organic matter (from the European Soil Database) using the Soil-Plant-Air-Water (SPAW) Field and Pond Hydrology Model of the United States Department of Agriculture (USDA). Land use/land cover information was directly imported from the Corine land cover, while watersheds were delineated from the European Digital Elevation Model (EU-DEM) using GIS-based hydrological tools. Finally, the maximum root depth per vegetated land use class was extracted from the Forest and Agriculture Organization (FAO) guidelines (Allen et al., 1998) and Schenk and Jackson (2002), whereas the evapotranspiration coefficient (K_c) was extracted from Allen et al. (1998) and Nistor et al. (2017) for vegetated areas, and from InVEST guidelines for urban areas and water bodies.

3.1.2. *Regulating FES*

3.1.2.1. Erosion control. The ability of forests to limit erosion was mapped as avoided soil erosion, namely the amount of soil that is not lost annually owing to vegetation, using the relevant dataset created by the JRC (Maes et al., 2015; Guerra et al., 2016). The dataset, which has a resolution of 100 m, reports the difference between soil loss in the absence of vegetation and soil loss in the presence of vegetation, where loss was computed using the Revised Universal Soil Loss Equation (RUSLE). The latter assumes soil loss to be a function of erosivity (kinetic energy of raindrops), erodibility (susceptibility of soil particles to removal by rain), topography (slope length and degree), vegetation cover, soil conservation and management practice (Renard et al., 1997). Maes et al. (2015) combined Pan-European datasets, geospatial analysis and the LUISA (Land Use Integrated Sustainability Assessment) modeling platform to compute the indicator, whereby the vegetation cover factor was estimated using the relation between NDVI and factors provided in literature (Wischmeier and Smith, 1978), and considering only one forest type (i.e. broadleaved, coniferous and mixed forests merged into one class). We performed a resampling to bring the JRC's dataset to a 1-km resolution.

3.1.2.2. Pollination. Pollination is intimately linked to forest ecosystems as these, and particularly forest edges, support wild pollinator insects (e.g. honey bees, bumblebees), therefore sustaining the yield of neighboring crop fields (Kells and Goulson, 2003). This service was mapped using the JRC's map of Relative Pollination Potential (RPP) (Zulian et al., 2013), which describes the relative capacity of ecosystems, including forest edges, to support crop pollination at a 100-m resolution. The JRC computed the RPP index, which is dimensionless and ranges between 0 and 1, by combining information on floral resources and foraging ranges (to identify foraging sites) with an estimate of nesting sites (to obtain relative pollinator abundance), and correcting this with information on climate and elevation (i.e. accounting for pollinators' reduced activity levels and ability to find nesting sites at lower temperatures and higher altitudes). In order to generate the actual FES indicator, the JRC's dataset was resampled to a 1-km resolution.

3.1.2.3. Habitat provision. The ability of forest ecosystems to provide and maintain habitat for terrestrial species was mapped using the JRC's Habitat Quality dataset (Vallecillo et al., 2016), which reports for each portion of the territory (10 km × 10 km) a value of relative bird species richness, intended as the ratio between local richness and the average richness in the regional context (%). The JRC built the Habitat Quality Index (HQI) starting from occurrences of 148 common bird species included in the European Common Bird Index (EBCC, 2012) (33 of which are considered forest bird species as forest is their predominant habitat for breeding and feeding), whose distribution was mapped using a maximum entropy method with various climate and land use variables as predictors (for the full list of species, refer to Vallecillo et al., 2016). Local species richness, computed as the sum of all species' presence, is then compared to regional species richness, which is estimated considering a radius of 250 km around each location. In order to generate the actual FES indicator, we performed a resampling of the JRC's Habitat Quality dataset, increasing its resolution to 1 km.

3.1.2.4. Soil formation. A common indicator of soil formation is soil organic carbon, as this moderates a wide array of processes and properties including soil aggregation, soil hydrological properties, microbial population, etc. (Lal, 2014), and is related to management and biodiversity (Maes et al., 2018). The amount of organic carbon in the soil was mapped using data from the amended Harmonised World Soil Database, which was created at a 1-km resolution combining spatially-explicit information about soil organic carbon content (%), dry bulk density ($g\ cm^{-3}$), volume of stones (%) and depth of soil layer (m) (Hiederer and Köchy, 2012). We summed up estimates for the topsoil (0 – 30 cm) and the subsoil (30 – 100 cm) to get a more comprehensive information.

3.1.2.5. Climate regulation. Forests contribute to climate regulation through a variety of processes including carbon fixation, moisture production and temperature control. Given the magnitude of the impacts of climate change and the emphasis placed by EU forest policy on climate change mitigation measures (EC, 2013a), the ability of forests to contribute to climate regulation was mapped using the Pan-European dataset of forest above- and below-ground carbon stock produced by the JRC at a 1-km resolution (de Rigo et al., 2013). This was created combining a map of forest types (i.e. coniferous vs. broadleaved), a map of ecological zones and numerical factors of average forest biomass content and carbon fraction by ecological zone (Barredo et al., 2012). JRC scholars generated the 1-km resolution forest map using the 100-m resolution CORINE land cover and considering the "mixed forest" class as a 50 % coniferous-50 % broadleaved land cover; extracted ecological zones from the map of Global Ecological Zones for the Global Forest Resources Assessment (FAO, 2001); and relied on IPCC guidelines to obtain the above-mentioned conversion factors (IPCC, 2006).

3.1.3. *Cultural FES*

3.1.3.1. Recreation. Among various cultural functions of forests, recreation is the most important and economically valuable. The recreation potential of a forested land parcel is related to its intrinsic natural value (i.e. environmental quality, scenic beauty) and its accessibility as, unlike other ES types, cultural services can only be delivered and enjoyed if the beneficiary can actually get onsite. We then assessed the recreation value of forests by reclassifying the Recreation Opportunity Spectrum (ROS) map produced by the JRC (Paracchini

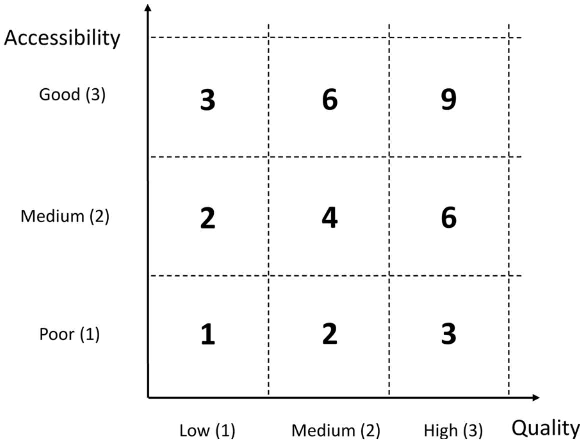


Fig. 2. Scores used to quantify recreation supply as the multiplication of values of quality and accessibility assigned by the JRC to map the Recreation Opportunity Spectrum of European landscapes (Paracchini et al., 2014).

et al., 2014) over the EU at a 100 m resolution. The ROS map is developed starting from the original ROS concept, namely the idea that the combination of physical, social and managerial conditions determine different recreation settings (Clark and Stankey, 1979), to provide an assessment tool for recreation provision in Europe. In particular, the JRC considered nine main recreation opportunities that are given by combinations of three classes of recreation potential/quality (low, medium, high), which is a function of naturalness (i.e. degree of human influence on each land cover class according to literature and management conditions), presence of protected areas (i.e. Natura 2000 sites) and water attractiveness (i.e. bathing water quality, distance from the coast, protected coastline), and three classes of accessibility (poor, medium, easy) summarizing the distance of a site to the closest road and the closest residential area.

In order to convert the JRC's ROS classification into an indicator of recreation supply, we assumed the latter to be proportional to the product of the two ROS variables (i.e. quality and accessibility). Hence, we reclassified the ROS map produced by the JRC according to the scheme of Fig. 2. The reclassified map was then made continuous by running a neighborhood operation assigning each pixel the mean of pixels within a radius of 1000 m. This is consistent with the idea that the supply of recreation opportunities at a specific location is affected by supply at neighboring locations. We finally performed a nearest neighbor resampling to bring the resolution to 1 km.

3.2. Delineation of FES hotspots

We delineated hotspots of single FES from each FES map as the 20 % of forest pixels ensuring the highest supply of the relevant FES (Eigenbrod et al., 2010; Schröter and Remme, 2016).

We then built a map of hotspots of multiple FES by summing up binary maps of single hotspots, which were generated by assigning 1 to hotspot pixels and 0 to all other pixels. As such, values of the output map can range between 0 (no hotspot) and 8 (hotspot of all FES).

3.3. Analysis of synergies and tradeoffs

We analyzed synergies and tradeoffs by assessing pairwise correlations among all FES indicators in search of significant positive (synergies) and negative (tradeoffs) associations, consistent with work by Turner et al. (2014); Geneletti et al. (2018) and Roces-Diaz et al. (2018).

We sampled values of FES indicators at 70,000 random locations at no less than 1 km from each other, therefore covering 5% of all 1 km x 1 km forest parcels. Given likely non-linear relationships and skewness of indicators, the Spearman index was used to quantify the degree of association between indicators.

3.4. Identification of spatial bundles

We identified spatial bundles by means of cluster analysis of FES maps as suggested by Plieninger et al. (2013). Our analysis was run on principal components of FES indicators (instead of raw indicators) as these represent uncorrelated attributes of FES (Plieninger et al., 2013; Ferrari et al., 2016). Principal components were identified through Principal Component Analysis (PCA), which was performed on FES data sampled at the above-mentioned random locations, relying on the Kaiser-Guttman criterion (eigenvalue > 1) to establish the minimum number of components that adequately describe the structure of the data. Loadings supplied by the PCA were used to compute principal component maps, and K-means cluster analysis was run on them, to identify bundles of FES. The ideal number of clusters, i.e. bundles, was determined qualitatively by assessing the dominance of different FES within each cluster, as shown by Turner et al. (2014).

4. Results

The supply of FES varied dramatically across EU forests (Fig. 3). For example, wood provision (measured as growing stock volume) was as high as 450 m^3 ha^{-1} in some forests of the Alps and Southern Germany, but dropped to a mere 5 m^3 ha^{-1} in forest landscapes of the Spanish lowlands. In terms of habitat protection, forests in the Northern Apennines (Italy) supported a bird species richness that is 100 % higher than the regional one (i.e. within a radius of 250 km), whereas some Austrian forests supported bird species that is 60 % lower than that of surrounding areas. Recreational opportunities were exceptional, in terms of environmental quality and accessibility, in many German forests, but much more limited in remote forests of Northern Scandinavia.

Forests constituting a hotspot of wood provision were generally found in the big mountain ranges, particularly the Pyrenees, the Alps, the Apennines and the Carpathians, and at mid latitudes, particularly in France, Germany, Austria, Poland, Czechia and Slovakia. Areas characterized by strong precipitation and medium to high latitude, and particularly northwestern Spain, the Pyrenees, the Alps, Western Croatia and Western Sweden, constituted a hotspot of water supply. The hotspot of soil erosion control, not surprisingly, was found in mountain areas, particularly the Pyrenees, the Alps, the Apennines and the Carpathians, where vegetation strongly reduces soil loss. Pollination potential was particularly high in France and Southern Europe, where the landscape is often characterized by a mix of relatively small forest patches and agricultural areas. Forests providing habitat to particularly large (relative) proportions of bird species were found across the entire EU, but they are particularly concentrated in Central Spain, Southern France, the Apennines, the Slovenian Alps, Central Germany, Bulgaria and Northern Scandinavia. The hotspot of soil formation was almost entirely concentrated in Scandinavia and Scotland. Forests playing a major role in climate regulation were mostly found at mid latitudes in Germany and Eastern Europe, though some patches were spread across Southern France, Southern Sweden and the Baltic Republics. The recreation hotspot was generally associated with mountain areas as well as forest landscapes in France, Germany and Poland.

Table 2 provides an overview of the proportion of each country's forests that is a hotspot for each of the 8 FES. All countries had at least one fifth of their forests as a hotspot of one service and most had more than one third (Table 3). In most countries, forests included hotspots of up to six or seven services. Austria, Slovakia and particularly Slovenia had very large extents of their forests showing these characteristics. The forests of six countries – Belgium, France, Germany, Hungary, Poland and Sweden – included hotspots of all services considered in this study.

The map of Fig. 4 shows, for each land parcel, the number of

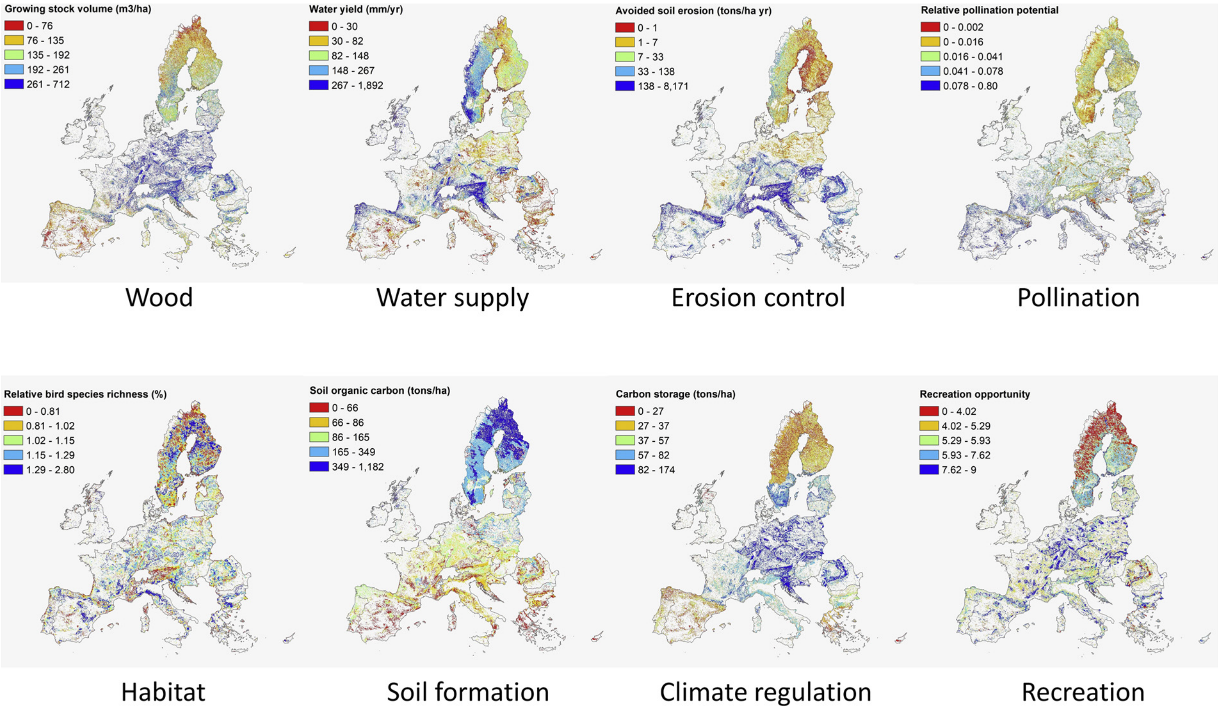


Fig. 3. Maps of the eight FES, shown according to a quintile graphical representation (i.e. each class represents 20 % of EU forested lands). The top quintile (blue color) for a given FES represents the hotspot of that FES. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

services of which it is a hotspot. While about 15 % of all forests were not a hotspot of any of the considered services, over 60 % of them constituted a hotspot of one or two services and nearly one fifth of them were a hotspot of three or four services simultaneously (Table 3). The latter category was mostly represented by forests in big mountain ranges, but also in Northwestern Spain, Southern France, Southern Belgium, Germany, Southern Sweden and Croatia (Fig. 4). Some forested areas in Germany, the Alps and the Tatras supplied large

Table 2
Share of each country's forests that is a hotspot of different FES (as a single land parcel may be a hotspot of multiple FES, columns do not sum to 100 %).

	Share of national forest (%)							
	Provisioning		Regulating					Cultural
	Wood	Water supply	Soil erosion	Pollination	Habitat provision	Soil formation	Climate regulation	Recreation
Austria	54.1	79.3	64.3	11.5	7.8	0.1	55.3	8.8
Belgium	47.6	62.0	14.7	15.2	22.6	0.7	45.8	30.7
Bulgaria	16.3	1.7	22.4	32.9	38.0	0.0	0.1	37.8
Croatia	29.3	44.1	45.9	32.5	3.2	0.1	73.8	14.2
Cyprus	0.1	0.7	32.9	52.9	53.4	0.0	0.0	28.2
Czechia	48.0	13.2	23.5	14.2	19.6	0.2	68.2	20.0
Denmark	19.8	16.1	0.0	6.0	18.1	0.4	19.8	11.3
Estonia	7.2	1.2	0.0	15.6	7.1	18.9	3.2	9.1
Finland	0.1	2.0	0.0	9.1	25.7	66.0	0.6	5.9
France	28.1	25.4	25.7	37.4	21.4	1.0	14.0	29.8
Germany	53.6	23.9	19.5	9.3	18.1	2.1	67.0	57.9
Greece	5.3	13.8	24.7	41.2	25.8	0.0	0.0	16.7
Hungary	20.4	2.4	14.2	36.0	9.8	2.6	2.4	29.8
Ireland	20.3	94.0	11.1	18.4	24.1	36.1	0.0	1.2
Italy	21.9	16.9	64.3	39.0	32.3	0.0	0.1	22.9
Latvia	11.9	2.9	0.0	17.3	0.1	4.7	31.7	16.4
Lithuania	30.7	1.8	0.0	9.2	13.9	3.7	9.1	20.9
Luxembourg	42.5	25.8	26.8	14.0	2.0	0.0	32.4	16.7
Malta	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
Netherlands	35.4	49.7	0.2	16.0	12.0	4.3	21.0	28.4
Poland	46.9	6.2	6.6	8.9	11.0	4.3	51.3	31.0
Portugal	0.0	31.8	26.9	61.6	23.1	0.0	0.0	14.4
Romania	26.7	11.9	38.1	27.0	14.2	0.1	37.7	14.4
Slovakia	46.2	25.7	61.9	16.3	7.7	0.0	61.6	44.7
Slovenia	48.8	80.2	74.2	24.1	37.1	0.1	84.9	31.9
Spain	3.7	21.4	40.5	52.3	29.8	0.1	0.0	26.6
Sweden	4.0	26.2	1.7	1.8	15.9	50.9	6.9	3.7
UK	54.1	79.3	64.3	11.5	7.8	0.1	55.3	8.8

Table 3
Area and share of EU forested areas that are a hotspot of various numbers of FES (i.e. area and share of forest land parcels that are among the top 20 % suppliers of 0, 1, 2, etc. FES). The first row reports figures for forested areas that are no hotspot, whereas the last row only reports zeros because no forest land parcel is a hotspot of 8 FES.

Number of FES	Area (km^2)	Share (%)
0	218,145	15.629
1	507,606	36.369
2	383,340	27.465
3	193,882	13.891
4	73,747	5.284
5	17,414	1.248
6	1559	0.112
7	36	0.003
8	0	0.000

amounts of five services simultaneously, whereas Slovenia includes the largest continuous extents of forest guaranteeing major supplies of six services (Fig. 4).

The analysis of synergies and tradeoffs showed that all 28 pairwise correlations between FES were significant (almost all of them at the 0.001 level), as shown in Table 4. The highest correlation coefficients ($|\rho| > 0.5$) highlighted a strong synergy between wood and carbon, and a marked tradeoff between erosion control and soil formation. A moderate synergy was observed also between climate regulation and recreation. Tradeoffs occurred between pollination and soil formation as well as between soil formation and climate regulation.

Four principal components, explaining 72.8 % of the total variance, were retained for the analysis of bundles. In fact, while the first three components would have been formally sufficient (eigenvalue > 1), the fourth one was also included for having an eigenvalue very close to 1 (0.94) and significantly contributing to the explanation of variance (+12 %). The first component was strongly related to wood, climate and recreation, reflecting a tradeoff between erosion control and soil formation (Table 5). The second component captured the tradeoffs between pollination and wood, and pollination and climate regulation (Table 5). The third and fourth components were strongly associated with water supply and habitat provision, respectively (Table 5).

A qualitative analysis of the outputs of cluster analyses run with different numbers of clusters (K) suggested the most meaningful classification (i.e. best characterization of each cluster) was obtained with $K = 4$ (Fig. 5). The first cluster or bundle ("Balanced"), which was characterized by an average or above-average supply of five out of eight FES (i.e. wood, habitat, soil, climate, recreation), primarily occurred in forests that are concentrated in the Northeastern part of the continent (particularly Poland, Baltic Republics, Southern Sweden and Southern Finland), and covered an area equivalent to around 31 % of EU forests. The second bundle ("Wood & water"), which was characterized by markedly above-average supply of wood, water supply, erosion control (this one three times the EU average) and climate regulation, occurred in the forests of mountain regions and central Europe (particularly France, Germany, Czechia and Slovakia) (total area = about 24 % of EU forests). The third bundle ("Soil carbon"), which was characterized by strongly above-average values of soil formation but lower-than-average values of everything else (except water), occurred in the far North (Sweden and Finland) (total area = about 23 % of EU forests). The fourth bundle ("Rural-recreational"), which was characterized by markedly above-average values of pollination potential combined with average recreational values, was predominantly found in non-mountainous Southern Europe (total area = about 21 % of EU forests).

Table 6 expresses the occurrence of the four bundles in each country as percentage of forest area. While little over a third of countries had two of the bundles occurring in at least one quarter of their forests, Romania was the only country to have three. Among countries with two

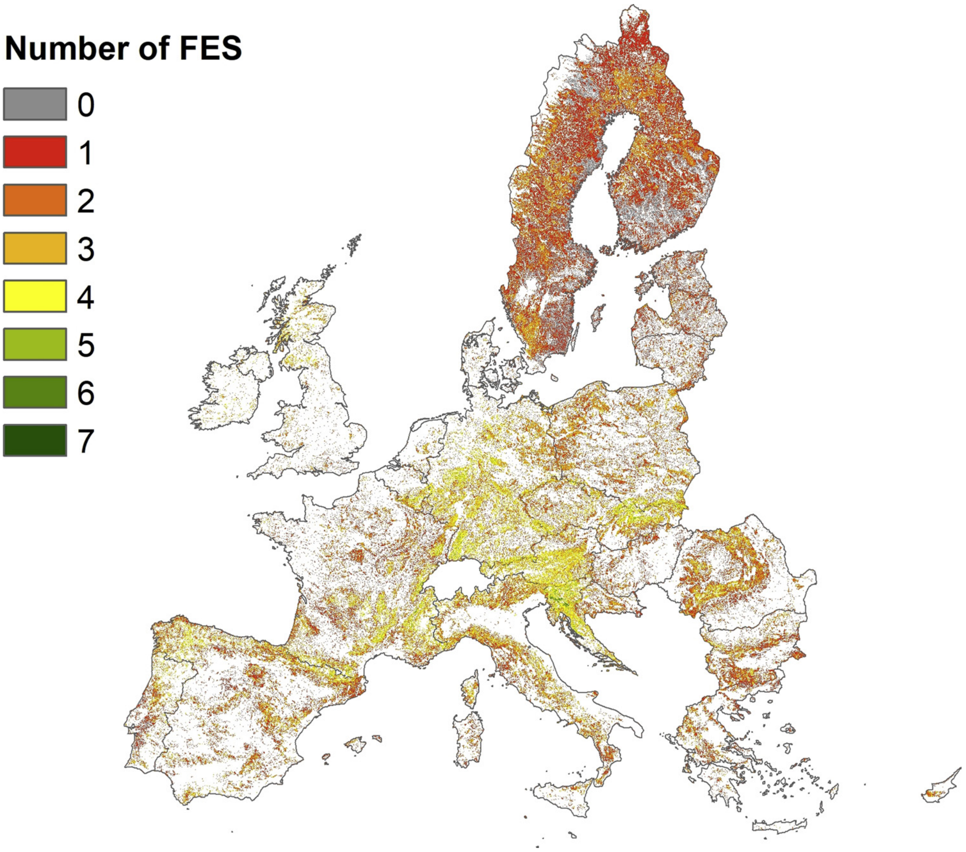
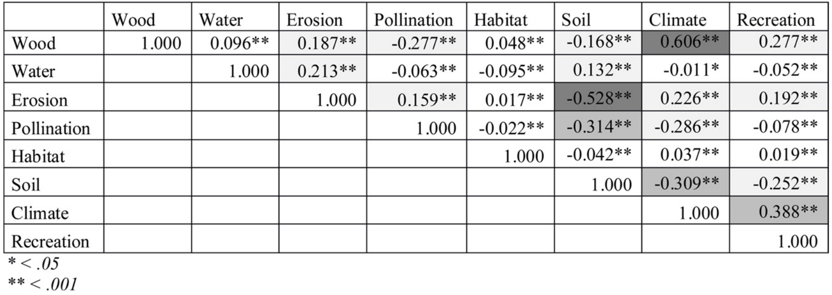


Fig. 4. Number of FES of which each forest parcel is a hotspot (i.e. a top 20 % supplier).

Table 4
The internal (vertical and horizontal) lines can be eliminated from the table, similar to what done in Table 5. Just for style purposes...... Pairwise Spearman correlations (and significance level) between all FES. Different shades of grey highlight strong ($|\rho| > 0.5$, *dark grey*), moderate ($0.3 < |\rho| < 0.5$ *medium grey*) and weak ($0.1 < |\rho| < 0.3$, *light grey*) correlations.



	Wood	Water	Erosion	Pollination	Habitat	Soil	Climate	Recreation
Wood	1.000	0.096**	0.187**	-0.277**	0.048**	-0.168**	0.606**	0.277**
Water		1.000	0.213**	-0.063**	-0.095**	0.132**	-0.011*	-0.052**
Erosion			1.000	0.159**	0.017**	-0.528**	0.226**	0.192**
Pollination				1.000	-0.022**	-0.314**	-0.286**	-0.078**
Habitat					1.000	-0.042**	0.037**	0.019**
Soil						1.000	-0.309**	-0.252**
Climate							1.000	0.388**
Recreation								1.000

* < .05
** < .001

*p < 0.05.
**p < 0.001.

Table 5
Principal component loadings (i.e. weights of the linear combinations defining principal components as a function of original variables).

	PC1	PC2	PC3	PC4
Wood	0.379	−0.424	0.098	−0.013
Water supply	−0.017	−0.212	0.768	0.359
Erosion control	0.404	0.321	0.392	0.185
Pollination	−0.065	0.627	0.077	0.077
Habitat	0.106	−0.061	−0.450	0.883
Soil formation	−0.480	−0.426	0.025	0.020
Climate regulation	0.498	−0.303	−0.072	−0.114
Recreation	0.446	0.047	−0.183	−0.193

well represented bundles (i.e. each occurring in at least 25 % of forests), Czech Republic ("Balanced" and "Wood & water"), Hungary ("Balanced" and "Rural-recreational"), Italy ("Wood & water" and "Rural-recreational") and Slovakia ("Balanced" and "Soil carbon") showed a relatively balanced distribution of them (i.e. less than 15 % difference).

To evaluate the administrative relevance of our bundle analysis, we classified NUTS3 regions according to the most common bundle in their forests (e.g. if the main bundle in region X is "Wood & water", then X is considered a "Wood & water" region). The resulting map (Fig. 6) would give an idea of the FES identity of each region and therefore the regional niches administrations should focus on to ensure the supply of specific FES. A few countries had all of their sub-national administrative regions predominantly characterized by the same bundle (e.g. Portugal, Baltic Republics), several had their regions split between two bundles (e.g. Sweden, Finland), and some between three (e.g. France, Hungary) or even four bundles (e.g. UK).

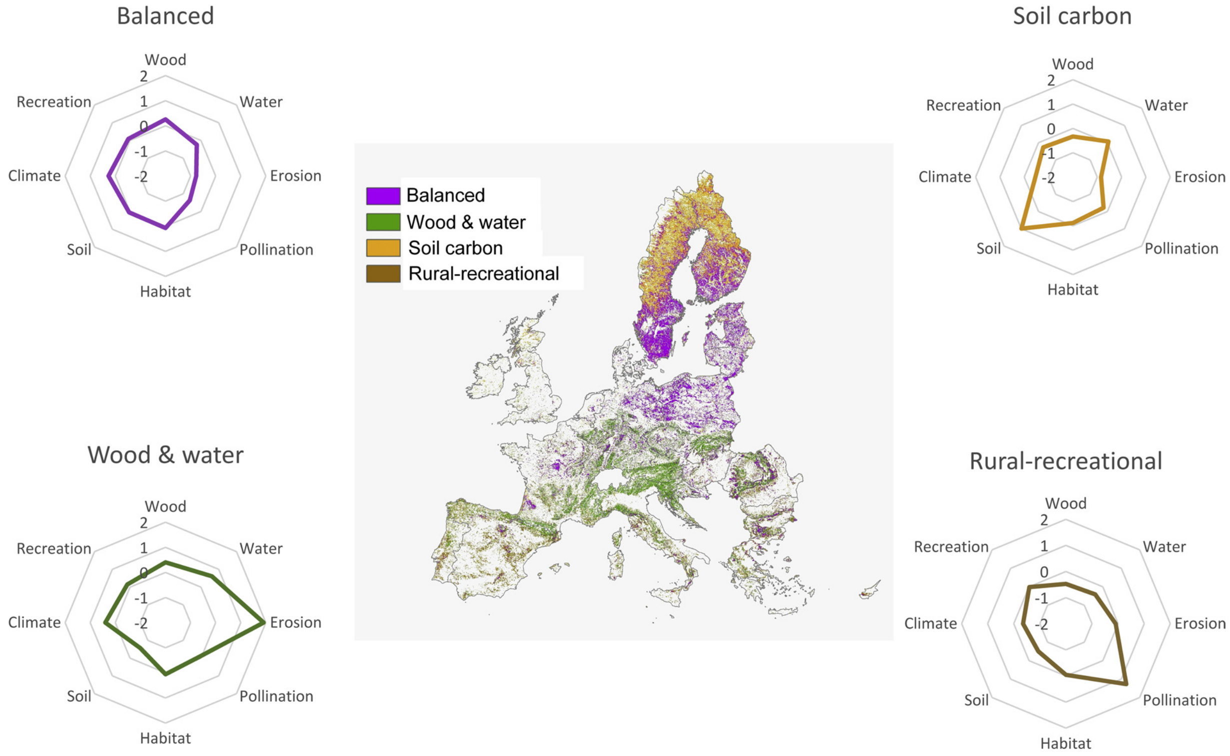


Fig. 5. Spatial distribution of the four bundles (map) and occurrence of different FES in each bundle (radar graphs). Graphs were built by comparing the average supply value of a given FES within the bundle and the average supply of the same FES across the whole EU (i.e. a value of 0 means that average supply within the bundle is equal to the EU average, a value of 1 means that average within-bundle supply is 100 % higher than EU average, etc.).

Table 6
Shares of each country's forests characterized by the occurrence of each of the four FES bundles (columns sum up to 100).

	Share of the forest (%)			
	Balanced	Wood & Water	Soil carbon	Rural-recreational
Austria	11.7	78.2	2.8	7.3
Belgium	18.1	63.7	7.7	10.5
Bulgaria	24.3	28.4	2.6	44.7
Croatia	16.8	5.0	8.4	69.8
Cyprus	27.8	55.9	1.6	14.6
Czechia	38.4	45.8	3.9	11.8
Denmark	42.7	8.5	23.7	25.0
Estonia	61.7	1.4	22.0	14.9
Finland	15.6	20.8	7.4	56.1
France	8.5	22.2	4.5	64.7
Germany	33.2	0.5	59.0	7.2
Greece	20.2	57.0	6.4	16.5
Hungary	35.0	20.0	6.3	38.7
Ireland	6.4	11.6	65.6	16.4
Italy	11.7	49.8	3.2	35.4
Latvia	66.0	4.2	16.6	13.2
Lithuania	13.6	65.8	3.8	16.7
Luxembourg	65.1	4.6	17.5	12.8
Malta	0.0	0.0	0.0	100.0
Netherlands	47.2	12.4	30.5	9.9
Poland	65.0	14.0	8.1	12.9
Portugal	5.6	15.4	10.3	68.7
Romania	26.8	37.8	3.3	32.1
Slovakia	42.2	1.6	50.8	5.4
Slovenia	9.7	86.0	1.0	3.3
Spain	20.9	65.3	1.6	12.2
Sweden	13.4	22.0	39.8	24.8
UK	20.9	45.1	5.9	28.2

5. Discussion

5.1. Hotspots at country level

Our analysis shows that about half of the EU forested areas supply large amounts of multiple FES simultaneously, that is about half of EU forest land parcels are top 20 % suppliers of more than one FES. In particular, mountain and central European forests, typically characterized by large extensions of conifers, show remarkably high values for wood production, water supply, erosion control, climate regulation and recreation. These observations are consistent with findings by Schirpke et al. (2019). The other half of European forests provides FES in either an intermediate generalist multifunctional fashion, i.e. low relative quantities of any FES, or in a specialist fashion with large relative quantities of only one FES. French and Southern European forests show high values for pollination, whereas forests characterized by high potentials of soil formation are almost entirely concentrated in Scandinavia owing to the presence of soils with significant organic matter concentrations.

Most countries include hotspots of multiple FES and some have large or very large shares of their forests constituting a hotspot of one or multiple FES. Given such shares and the size of their forested areas, countries like Austria, Germany and Slovakia then play a very important role in the provision and maintenance of European FES (for example their contribution to climate regulation or habitat protection at the continental scale). On a smaller scale, Slovenia is equally crucial as it holds a unique natural feature in the form of large tracts of forests simultaneously supplying very high quantities of six FES.

From a management point of view, it is worth observing that the proportions of different forest types (e.g. broadleaved vs. coniferous) and the degree of naturalness of the existing forests (e.g. human disturbance, area of plantations) vary considerably both within and

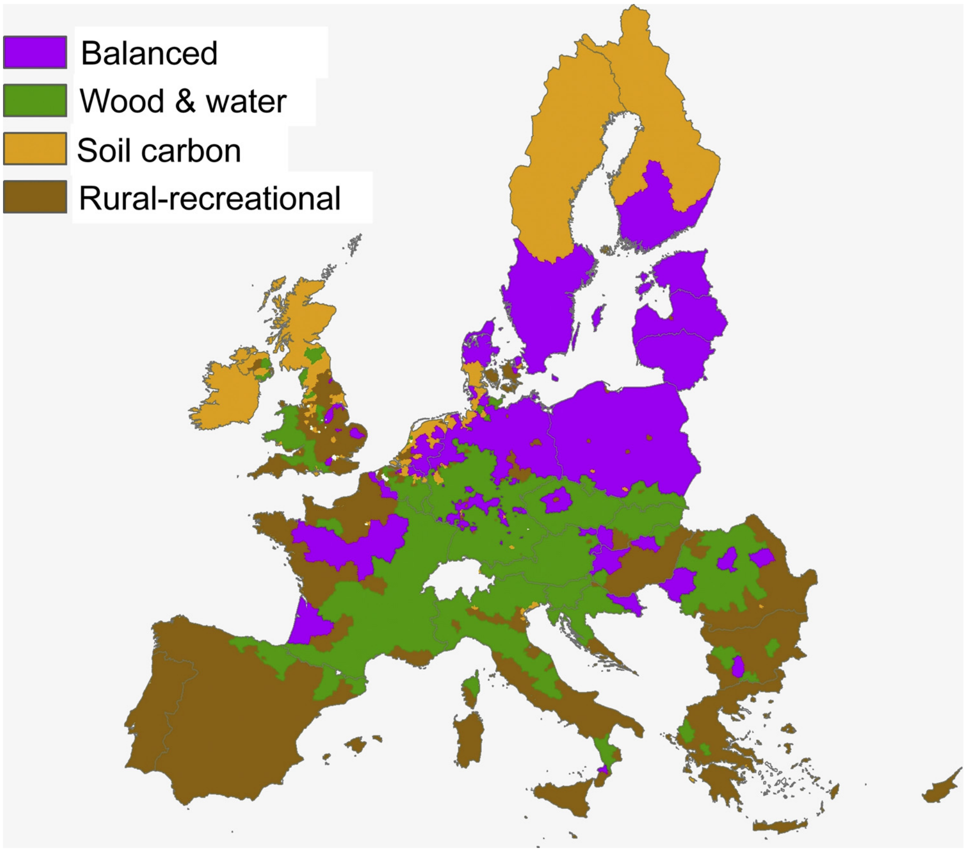


Fig. 6. Most common bundle occurring in the forested areas of each NUTS3 region.

between countries, eventually determining, among other things, the types of available recreational opportunities or the possibility to actually extract provisioning services. For example, looking at countries whose forests include hotspots of all services, France and Hungary both have a majority of broadleaved forests but very different shares of plantations (about 10 % vs. more than 40 %); Belgium and Germany present a relatively balanced mix of broadleaved and coniferous forests (in Germany conifers are mostly in the South and the East) although Belgium has over 60 % of its forests as plantations and Germany has none; Poland and Sweden have a predominance of coniferous forests and little plantations (as a percentage of overall area), but almost 10 % of Sweden's forests are undisturbed (EEA, 2016).

5.2. Analysis of synergies and tradeoffs

Our findings do not align with earlier observations of predominant tradeoffs between provisioning and regulating FES and synergistic relationships between regulating FES (Lee and Lautenbach, 2016). Instead, we find a mix of synergies and tradeoffs across all FES interactions. Consistent with the identification of hotspots of multiple FES, we discover various synergies among wood provision, erosion control, climate regulation and recreation. This was expected in many ways as biomass and carbon stock are inherently related, and the presence of dense forests is associated with erosion control (especially on steep slopes) and recreation opportunities. This result is also in line with what was found by Maes et al. (2011), although they also observe synergies between pollination and other FES that we do not detect. In fact, we observe pollination to be positively related to erosion control, but negatively related (or unrelated) to everything else. This seems reasonable as pollination is almost solely supported by forest edges close to crop fields, that is fragmented forest landscapes where the supply of other FES (particularly wood provision and carbon storage) tends to be lower. Further, other studies have found tradeoffs between crop production and regulating services (Raudsepp-Hearne et al., 2010; Jopke et al., 2015).

Our analysis shows soil formation has a synergistic association with water supply, consistent with Jopke et al. (2015), but it is negatively related or unrelated to everything else. This may be explained by the fact that soil organic carbon content is very high in northern forests where the difference between precipitation and evapotranspiration is also very high (and therefore water yield significant), but considerably lower anywhere else.

Habitat protection is the only FES that does not show significant correlations with any other FES. This is different from what observed in other studies, which showed, for example, strong correlations with carbon sequestration and storage (Lin et al., 2018), and is possibly related to the fact that the indicator adopted to map this FES measures a ratio of local to regional species richness rather than a purely local variable (e.g. species richness, degree of fragmentation).

In general, the discrepancy between our results and those of previous studies with respect to associations between some FES may also be due to the impact of forest management on the provision of FES and how management approaches vary both within and between different study areas. For example, the decision to undertake selective logging (e.g. close-to-nature silviculture) in some regions of Europe like the Alps (Brang et al., 2014) helps to maintain mature and dense forests that, while ensuring high values of wood supply (on a per unit area basis), curb the removal of soil by water on erosion-prone slopes.

5.3. Bundles of forest ecosystem services

Our correlation analyses allowed the identification of bundles of FES. These show spatial patterns that are particularly connected to latitude, elevation and ruggedness. The "balanced" bundle is predominantly associated with low elevation flat areas of northeastern continental Europe and Southern Scandinavia, as well as with fragmented land-ownership and intensively managed forests. These forests rank high in terms of wood supply, habitat protection, soil and climate regulation, and recreational value (Saarikoski et al., 2017). However, their position on mostly flat terrain and their contiguous structure limit their role for erosion control and pollination support.

The "wood & water" bundle is deeply associated with mountain areas, particularly at mid to low latitudes, and the hilly part of Southern France, Germany, Czechia and Slovakia. High values of biomass production and carbon storage (wood) as well as water supply and erosion control (water) make this a remarkably multifunctional bundle, guaranteeing average or above-average levels also on all other services except soil formation. This reaffirms the key role of mountain regions as ES providers (Crouzat et al., 2015; Schirpke et al., 2019) owing to both natural features (e.g. tree species, remoteness) and management approaches, and calls for their conservation or very careful management, particularly considering adaptation needs in the face of climate change (Mina et al., 2017). Among various concrete measures managers can think of in this respect are: the shift to close-to-nature silviculture, which allows a constant forest cover to be maintained (Tudoran and Zotta, 2020); a reduction in the reference age for tree harvesting, in response to a stronger annual tree growth; the increase of species mix to foster resilience; and the improvement of the thinning sequence to reduce fire risk (Yousefpour et al., 2017). Anyway, ecological conditions vary dramatically across European mountain forests and adaptation measures should vary accordingly. While our analysis suggests that all measures enhancing biodiversity may have a positive effect, the intensification of extreme events (e.g. storms) at the local scale calls for ad hoc adaptation measures and a more dynamic forest and biodiversity management (Jandl et al., 2015; Werners et al., 2016).

The "soil carbon" bundle is the most geographically clustered of all as it is almost entirely concentrated at high and very high latitudes, and particularly in Northern Scandinavia, Scotland and Ireland, three regions characterized by very high content of soil organic matter and peatlands (Xu et al., 2018). The "rural-recreational" bundle mostly occurs in Southern Europe, particularly at low to mid elevations on undulated terrains, where forests are fragmented and interspersed with agricultural fields (Schulp et al., 2019). These are contexts that may have significant habitat value and, being easily accessible from urban centers, recreational value as well, therefore offering unique cultural opportunities (Tieskens et al., 2017). They have been the target of initiatives aimed at securing multiple ES, in particular under the EU Common Agricultural Policy (van Zanten et al., 2014).

Although our analysis seeks to be sensitive to the administrative regions, to support decision-making, the scale and resolution of analysis may have emphasized the ecological factors in the connection between bundles and socio-ecological sub-systems (Dick et al., 2010; Raudsepp-Hearne et al., 2010). This means that the ecological context and the embedded natural processes and conditions, rather than specific management strategies, influence the set of FES provided by a given forest parcel. Yet, the socio-economic connections to forests cannot necessarily be distinguished from the ecological conditions. For example, peatland areas are barren and uniform, and they have also been a target of intensification, e.g. through drainage (Kareksela et al., 2015). Multifunctionality appears to be connected to the intensive economic use of forests in Southern Scandinavia, providing many ecosystem services but not at high per unit area levels (Triviño et al., 2015; Saarikoski et al., 2017). A stronger connection between management and FES is possibly visible in the "wood & water" and "rural-recreational" bundles. The former reflects active decisions of preserving, or the excessive costs of eliminating, the forest cover on steep slopes, whereas the latter coincides with forest clearings executed to enable cultivation that have created edges hosting pollinator insects and multiple bird species. Clearly, such considerations should, by no means, encourage irresponsible management actions (e.g. extended forest clearings) aimed at increasing the provision of one or multiple FES (e.g. pollination and recreation) as bundles are intimately connected to specific socio-ecological conditions and the "artificial" enhancement of one FES may hinder, or even dramatically reduce, the delivery of other FES (Jackson et al., 2015).

The identification of bundles is particularly valuable when combined with data about political and administrative jurisdictions (Fig. 6) because it may inform about the complementarity and irreplaceability of various regions in terms of the FES they supply. In this respect, the maps may guide the definition of transboundary actions aimed at preserving, or sustainably managing, regions whose unique ensemble of FES (e.g. combination of wood, carbon storage and water supply) generates benefits that span across nations. Further, it they may be used to support local management, helping administrators identify contexts within a region where the actual supply and flow of FES are not consistent with the bundle's characteristics and hence targeted actions (e.g. reforestation, thinning, improved harvesting schedules) may be adopted to bridge the gap. As already anticipated, this approach, which may be based on comparisons between similar and/or nearby countries, (e.g. Portugal actively guiding the natural regeneration of currently deforested and abandoned mountain pastures to enhance the "wood & water" bundle, which is present in adjacent Spain) should be carefully considered, and management actions should be tailored with existing FES provision as the starting point.

The combination of FES and administrative maps can serve as the first step for decision-makers to recognize the niche potential of their region as FES provider based on the abundance of either particular FES or bundles of FES (Primmer and Furman, 2012; Hauck et al., 2013). This could possibly allow them to establish innovative governance mechanisms for managing and securing FES (e.g. cooperatives of forestry operators, or partnerships between forest owners, tourist operators and administrations), and for developing new business opportunities relying on them (e.g. selling of wooden products made up of timber from protected forests). It is worth observing, however, that the accuracy of the information provided by maps like that of Fig. 6 heavily depends on the administrative level considered, whereby coarser subdivisions may lead to rough assessments (e.g. all of Portugal's regions as providers of one bundle only) and conversely finer subdivisions may unveil the peculiar FES properties of different territories.

More in general, knowledge about FES bundles indicates the key areas where the potential of nature-based solutions (NBS) for risk management and the reduction of socio-environmental vulnerability is higher and where improvements to the green infrastructure may be needed (Paavola and Primmer, 2019). This knowledge can thus enhance more integrative land-use planning and territorial development that take sustainability and ecological concerns into consideration as called upon in the Green infrastructure policy (EC, 2013b).

5.4. Limitations of the study

The basic limitation of this work is related to the very large scale of analysis, which imposed a relatively coarse map resolution and raised the challenge of selecting indicators that, while being meaningful at such a resolution, might be assessed consistently over the entire EU. Although the adopted 1-km resolution is rather common in continental-scale ecosystem service studies (Avitabile and Camia, 2018; Vandecasteele et al., 2017), it is certainly far from providing a detailed description of landscape features, including forest cover, particularly on heterogenous terrains (e.g. mountains). The supply of all FES may have been inaccurately quantified in fragmented forest landscapes because of the difficulty of adequately describing forest edges, and similarly the assessment of water yield and erosion control may have been biased in undulated landscapes, where a 1-km digital elevation model cannot capture the complexity of the real terrain.

Among all FES, water supply is the only one that was assessed through ad hoc modeling rather than the use of existing datasets. While the selected indicator (i.e. water yield) provides an accurate quantification of water runoff for every forested cell (Mokondoko et al., 2018), it can hardly extrapolate the very role of forests in supplying drinkable water. In fact, it mostly measures the difference between precipitation and evapotranspiration, possibly overestimating supply in northern forests and underestimating it in southern forests. Pollination and recreation were assessed using non-dimensional indicators, which were the only option for these FES at this scale of analysis, but definitely not the best option for figuring out the pollination and recreational values of different locations.

While we believe that the selected indicators represent one of the best options currently available to map FES at the European scale, we also recognize that some of them may be disputable: not just because of their level of detail, but also for capturing only one aspect of the FES whose supply they are intended to describe. Examples include growing stock volume, which merely describes recent non-use of forests but partly neglects forest productivity (e.g. an analysis of MODIS satellite data on Net Primary Production may have provided such information); relative bird species richness, which solely focuses on one kind of wildlife and is provided at a rather coarse resolution; and recreation opportunity, which does not really explore the multiple elements determining the cultural value of a forested land parcel (e.g. spiritual importance). Nonetheless, they provide a rather detailed picture of FES spatial patterns and constitute a reliable basis for the subsequent analyses of hotspots and bundles, which can be improved once better data become available.

In general, all indicators are deeply affected by climatic and ecological conditions, which, in the case of a territory as diverse as the EU, vary enormously. Subsequently, a purely quantitative analysis of the maps produced in this study may be rather misleading: two forested pixels in very different contexts may supply strikingly different amounts of a specific FES not because one is "better" than the other, but because one is intrinsically characterized by a larger content of that FES. For example, forests in northern Europe grow in peaty soils that have much higher organic content than Mediterranean soils. In the former case, the loss of a moderate quantity of organic content does not alter the system significantly and can be recovered in a relatively short time by forest ecosystems, whereas in the latter case a moderate loss of organic matter needs a long time to recover. Therefore our work highlights that there is a real need for maps that account for the relative importance of the intrinsic characteristics of specific ecosystems and consider how these are related to the supply (and value) of different FES (e.g. taking into account recovery time and ecological features).

Additionally, the selected indicators do not explicitly account for management conditions, which in fact may have a major influence on how the forest can supply different FES. For example, the intensity of logging over time may alter the density of a forest area, and therefore its ability to supply wood and to store carbon on a per unit area basis, its habitat quality and even its recreational potential. However, in the framework of the growing awareness of climate and environmental issues (Verkerk et al., 2020), forest management techniques in Europe are gradually moving towards sustainable forest management, although some differences at national level still remain (Brang et al., 2014).

Given the above-mentioned limitations of the selected indicators, the outcomes of our subsequent analyses may be biased in various ways. The growing stock volume indicator may overestimate the value of less accessible areas (e.g. steep slopes) at the expense of more accessible ones (e.g. low-elevation semi-flat areas), therefore altering the detection of synergies and tradeoffs with such services as water supply, erosion control and recreation. The habitat quality indicator, solely based on bird regional diversity, may provide a skewed interpretation of habitat provision by forests, which may be the reason of lack of correlations with all other FES. The soil formation indicator, which only accounts for soil organic carbon content, has determined such a gap between Scandinavia and the rest of Europe that may explain why this FES is negatively correlated with climate regulation (which tends to be low in Scandinavia on a per unit area basis) and negatively or poorly correlated with many others.

A major limitation of the hotspot analysis is that, being conducted on a cell-by-cell basis, it could detect areas of high per unit area supply, but discarded areas of moderate supply and large size (and therefore high overall supply). This resulted in, for example, Scandinavian forests being almost completely dismissed as wood provision hotspots just because they generally have medium per unit area biomass content compared to Alpine or Central European forests. A solution to this issue might be represented by indicators accounting for both per unit area supply and the extent of contiguous forest cover within a basin, although this would end up in an analysis of the flow of FES rather than their supply (Haines-Young and Potschin, 2010).

Moreover, by just identifying hotspots as areas supplying the largest amounts of one or multiple FES, we systematically neglected the value of areas supplying fair amounts of various FES, hence representing interesting trade-off options. Managers might want to avoid this issue by adopting optimization models, which would allow them to identify a given number of cells (i.e. land parcels) that comprehensively maximize the supply of a wide portfolio of FES (Orsi et al., 2011; Bugalho et al., 2016).

Being the interactions among ecosystem services intricated and almost infinite, we must admit that our synergy-tradeoff analysis might have captured only a limited amount of these relationships. Moreover, given the size of the study area, measuring direct correlations between different services without controlling for regional variations, may hinder the detection, or the accurate quantification, of associations that actually exist. One of the meaning and the importance of this kind of work, however, is exactly to try to produce a clearer picture of those relationships using a trials and errors approach.

The size, shape and attributes of bundles, being the result of clustering, were inevitably characterized by a certain degree of arbitrariness. Although, after several tests, we judged four to be the best number of bundles, equally acceptable results could have been obtained with three or five clusters. This consideration is very important if bundles are to be used to design national or EU policies because different number of bundles might affect the possibility to detect areas with peculiar characteristics within a seemingly uniform region.

Finally, our mapping exercise, like any other, represents a static picture of an evolving system, which may change considerably from one year to the next one because of natural processes and management actions, such as forest expansion, urbanization or clear cutting. While our result describes the EU forest situation as of 2010–2012, new mapping initiative should be undertaken to support policy-making in the future, especially in the light of ongoing climate change.

6. Conclusions

This study combines existing and newly created spatially-explicit datasets to improve our current knowledge about the supply of forest ecosystem services (FES) at the EU level. The analysis identifies key areas supplying large amounts of FES (hotspots), assesses synergies and tradeoffs between FES, and identifies FES bundles across the EU and within country members. While the indicators selected to do so may not fully capture the complexity of FES supply across Europe –at least not over time – the results of our study do provide a reliable picture of FES spatial patterns that can inform EU and national forest policies about conservation and management actions potentially securing and improving sustainable FES provision. The analysis of bundles, in particular, could help administrative regions safeguard and valorize unique ensembles of multiple FES and develop niche innovations and governance mechanisms to support FES provision, for example for the management of risks or the improvement of green infrastructures.

CRediT authorship contribution statement

Francesco Orsi: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Marco Ciolli:** Methodology, Writing - review & editing. **Eeva Primmer:** Methodology, Writing - review & editing. **Liisa Varumo:** Methodology, Writing - review & editing. **Davide Geneletti:** Conceptualization, Methodology, Writing - review & editing, Supervision.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome.

Avitabile, V., Camia, A., 2018. An assessment of forest biomass in Europe using harmonized statistics and inventory plots. For. Ecol. Manage. 409, 489–498.

Bai, Y., Zhuang, C., Ouyang, Z., Zheng, H., Jiang, B., 2011. Spatial characteristics between biodiversity and ecosystem services in a human-dominated watershed. Ecol. Complex. 8 (2), 177–183.

Ballabio, C., Panagos, P., Montanarella, L., 2016. Mapping topsoil physical properties at European scale using the LUCAS database. Geoderma 261, 110–123.

Barò, F., Gomez-Baggethun, E., Haase, D., 2017. Ecosystem service bundles along the urban-rural gradient: insights for landscape planning and management. Ecosyst. Serv. 24, 147–159.

Barredo, J.I., San-Miguel-Ayanz, J., Caudullo, G., Busetto, L., 2012. A European map of living forest biomass and carbon stock. Reference Report by the Joint Research Centre of the European Commission. EUR – Sci. Tech. Res. pp. 25730.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.

Bouwma, I., Schleyer, C., Primmer, E., Winkler, K.J., Berry, P., Young, J., Carmen, E., Špulero, J., Bezák, P., Preda, E., Vadineanu, A., 2018. Adoption of the ecosystem services concept in EU policies. Ecosyst. Serv. 29, 213–222.

Brang, P., Spathelf, P., Larsen, J.B., Bauhus, J., Bončína, A., Chauvin, C., Drössler, L., García-Güemes, C., Heiri, C., Kerr, G., Lexer, M.J., Mason, B., Mohren, F., Mühlethaler, U., Nocentini, S., Svoboda, M., 2014. Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. Forestry 87 (4), 492–503.

Bugalho, M.N., Dias, F.S., Briñas, B., Cerdeira, J.O., 2016. Using the high conservation value forest concept and Pareto optimization to identify areas maximizing biodiversity and ecosystem services in cork oak landscapes. Agrofor. Syst. 90, 35–44.

Burkhard, B., Kroll, F., Nedkov, S., Müller, 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indic. 21, 17–29.

Chan, K.M., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. PLoS Biol. 4 (11), e479.

Clark, R.N., Stankey, G.H., 1979. The Recreation Opportunity Spectrum: A Framework for Planning, Management, and Research. General Technical Report PNW-98.

Crossman, N., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Paolomo, I., Drakou, E.G., Martin-Lopez, B., McPhearson, T., Boyanova, K., Alkemade, R., Egoh, B., Dunbar, M.B., Maes, J., 2013. A blueprint for mapping and modelling ecosystem services. Ecosyst. Serv. 4, 4–14.

Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F., Verkerk, P.J., Lavorel, S., 2015. Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. J. Appl. Ecol. 52 (5), 1145–1155.

de Rigo, D., Barredo, J.I., Busetto, L., Caudullo, G., San-Miguel-Ayanz, J., et al., 2013. In: In: Hrebicek, J. (Ed.), Continental-Scale Living Forest Biomass and Carbon Stock: a Robust Fuzzy Ensemble of IPCC Tier 1 Maps for Europe 413. ISESS 2013, IFIP AICT, pp. 271–284.

DeFries, R.S., Rudel, T., Uriarte, M., Hansen, M., 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nat. Geosci. 3, 178–181.

Dick, J., Andrews, C., Beaumont, D.A., Benham, S., Brooks, D.R., Corbett, S., Lloyd, D., McMillan, S., Monteith, D.T., Pilgrim, E.S., Rose, R., Scott, A., Scott, T., Smith, R.I., Taylor, C., Taylor, M., Turner, A., Watson, H., 2010. A comparison of ecosystem services delivered by 11 long-term monitoring sites in the UK environmental change network. Environmetrics 22, 639–648.

EBCC, 2012. Species Classification 2012. European Bird Census Council.

EC, 2010. Green Paper. On Forest Protection and Information in the EU: Preparing Forests for Climate Change. COM(2010)66 Final. European Commission, Brussels 1.3.2010.

EC, 2013a. A new EU forest Strategy: for forests and the forest-based sector. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission, COM(2013)659def.

EC, 2013b. Green Infrastructure (GI): Enhancing Europe's Natural Capital.

Communication from the Commission to the European Parliament, the Council, the European Economic and social Committee and the Committee of the Regions. European Commission, COM(2013) 249final.

EC, 2014. Mapping and Assessment of Ecosystems and Their Services: Indicators for Ecosystem Assessments Under Action 5 of the EU Biodiversity Strategy to 2020. 2nd Report – Final. February 2014. .

EEA, 2007. European Forest Types. Categories and Types for Sustainable Forest Management Reporting and Policy. 2nd edition. Technical report No 9/2006 May 2007.

EEA, 2016. European Forest Ecosystems: State and Trends. EEA Report No 5/2016. European Environment Agency ISSN 1977-8449.

EEA, 2017. Climate Change, Impacts and Vulnerability in Europe 2016. EEA Report No 1/2017. European Environment Agency.

Egoh, B., Reyers, B., Rouget, M., Richardson, D.M., Le Maitre, D.C., van Jaarsveld, A.S., 2008. Mapping ecosystem services for planning and management. Agric. Ecosyst. Environ. 127 (1-2), 135–140.

Eigenbrod, F., Armsworth, P.R., Anderson, B.J., Heinemeyer, A., Gillings, S., Roy, D.B., Thomas, C.D., Gaston, K.J., 2010. The impact of proxy-based methods on mapping the distribution of ecosystem services. J. Appl. Ecol. 47 (2), 377–385.

Eurostat, 2016. Agriculture, Forestry and Fishery Statistics, 2016 edition. Statistical Books, European Union.

FAO, 2001. Global Ecological Zoning for the Global Forest Resources Assessment 2000 - Final Report. Food and Agriculture Organization of the United Nations, Forestry Department, Rome.

FAO, 2015. Global Forest Resources Assessment 2015. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2018. Global Forest Resources Assessment 2020: Terms and Definitions. Food and Agriculture Organization of the United Nations, Rome.

Ferrari, M., Geneletti, D., Cayuela, L., Orsi, F., Rey Benayas, J.M., 2016. Analysis of bundles and drivers of change of multiple ecosystem services in an Alpine region. J. Environ. Assess. Policy Manag. 18 (4), 1650026.

Forest Europe, 2011. State of Europe's forests 2011: Status and trends in sustainable forest management in Europe. Ministerial Conference on the Protection of Forests in Europe, United Nations Economic Commission for Europe (UNECE). Forests and Agriculture Organization (FAO).

Garcia-Nieto, A.P., Garcia-Llorente, M., Iniesta-Arandia, I., Martin-Lopez, B., 2013. Mapping forest ecosystem services: from providing units to beneficiaries. Ecosyst. Serv. 4, 126–138.

Geneletti, D., 2013. Assessing the impact of alternative land-use zoning policies on future ecosystem services. Environ. Impact Assess. Rev. 40, 25–35.

Geneletti, D., Scolozzi, R., Esmail, B.A., 2018. Assessing ecosystem services and biodiversity tradeoffs across agricultural landscapes in a mountain region. Int. J. Biodivers. Sci. Ecosyst. Serv. Manage. 14 (1), 188–208.

Geneletti, D., Cortinovis, C., Zardo, L., Adem Esmail, B., 2020. Planning for Ecosystem Services in Cities. Springer.

Grêt-Regamey, A., Weibel, B., Kienast, F., Rabe, S.E., Zulian, G., 2015. A tiered approach for mapping ecosystem services. Ecosyst. Serv. 13, 16–27.

Guerra, C.A., Maes, J., Geijzendorffer, I., Metzger, M.J., 2016. An assessment of soil erosion prevention by vegetation in Mediterranean Europe: current trends of ecosystem service provision. Ecol. Indic. 60, 213–222.

Gustafsson, L., Baker, S.C., Bauhaus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer, D.B., Lõhmus, A., Martinez Pastur, G., Messier, C., Neyland, M., Palik, B., Sverdrup-Thygeson, A., Volney, W.J.A., Wayne, A., Franklin, J.F., 2012. Retention forestry to maintain multifunctional forests: a world perspective. BioScience 62 (7), 633–645.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. In: Raffaelli, D., Frid, C. (Eds.), Ecosystem Ecology: A New Synthesis. BES Ecological Reviews Series. CUP, Cambridge.

Haines-Young, R., Potschin, M., 2013. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012. Report to the European Environment Agency, Nottingham, UK.

Hanewinkel, M., Cullmann, D.A., Schelhaas, M.J., Nabuurs, G.J., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Chang. 3, 203–207.

Hauck, J., Görg, C., Varjopuro, R., Ratamäki, O., Maes, J., Wittmer, H., Jax, K., 2013. "Maps have an air of authority": potential benefits and challenges of ecosystem service maps at different levels of decision making. Ecosyst. Serv. 4, 25–32.

Hiederer, R., 2013. Mapping Soil Properties for Europe – Spatial Representation of Soil Database Attributes. Publications Office of the European Union. EUR26082EN Scientific and Technical Research series, Luxembourg. https://doi.org/10.2788/94128. ISSN 1831-9424.

Hiederer, R., Köchy, M., 2012. Global Soil Organic Carbon Estimates and the Harmonized World Soil Database. EUR 25225 EN – EUR Scientific and Technical Research series ISSN 1831-9424.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Japan Chapter 4: Forest Land.

Jackson, R.B., Jobbagy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2015. Trading water for carbon with biological carbon sequestration. Science 310 (5756), 1944–1947.

Jandl, R., Bauhus, J., Bolte, A., Schindlbacher, A., Schüler, S., 2015. Effect of climate-adapted forest management on carbon pools and greenhouse gas emissions. Curr. For. Rep. 1 (1), 1–7.

Jopke, C., Kreyling, J., Maes, J., Koellner, T., 2015. Interactions among ecosystem services across Europe: bagplots and cumulative correlation coefficients reveal synergies, trade-offs, and regional patterns. Ecol. Indic. 49, 46–52.

Kareksela, S., Haapalehto, T., Juutinen, R., Matilainen, R., Tahvanainen, T., Kotiaho, J.S., 2015. Fighting carbon loss of degraded peatlands by jump-starting ecosystem functioning with ecological restoration. Sci. Total Environ. 537, 268–276.

Kells, A.R., Goulson, D., 2003. Preferred nesting sites of bumblebee queens (Hymenoptera: apidae) in agroecosystems in the UK. Biol. Conserv. 109 (2), 165–174.

Kienast, F., Bolliger, J., Potschin, M., de Groot, R., Verburg, P.H., Heller, I., Wascher, D., Haines-Young, R., 2009. Assessing landscape functions with broad-scale environmental data: insights gained from a prototype development for Europe. Environ. Manage. 44, 1099–1120.

Lal, R., 2014. Soil conservation and ecosystem services. Int. Soil Water Conserv. Res. 2 (3), 36–47.

Langner, A., Irauschek, F., Perez, S., Pardos, M., Zlatanov, T., Öhman, K., Nordström, E.M., Lexer, M.J., 2017. Value-based ecosystem service trade-offs in multi-objective management in European mountain forests. Ecosyst. Serv. 26 (part A), 245–257.

Lee, H., Lautenbach, S., 2016. A quantitative review of relationships between ecosystem services. Ecol. Indic. 66, 340–351.

Lin, S., Wu, R., Yang, F., Wang, J., Wu, W., 2018. Spatial trade-offs and synergies among ecosystem services within a global biodiversity hotspot. Ecol. Indic. 84, 371–381.

Maes, J., Paracchini, M.L., Zulian, G., 2011. A European Assessment of the Provision of Ecosystem Services: Towards an Atlas of Ecosystem Services. Publications Office of the European Union, Luxembourg.

Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schägner, J.P., Grizzetti, B., Drakou, E.G., La Notte, A., Zulian, G., Bouraoui, F., Paracchini, M.L., Braat, L., Bidoglio, G., 2012. Mapping ecosystem services for policy support and decision making in the European Union. Ecosyst. Serv. 1 (1), 31–39.

Maes, J., Teller, A., Erhard, M., Liquete, C., Braat, L., Berry, P., Egoh, B., Puydarrieux, P., Fiorina, C., Santos, F., Paracchini, M.L., Keune, H., Wittmer, H., Hauck, J., Fiala, I., Verburg, P.H., Condé, S., Schägner, J.P., San Miguel, J., Estreguil, C., Ostermann, O., Barredo, J.I., Pereira, H.M., Stott, A., Laporte, V., Meiner, A., Olah, B., Royo Gelabert, E., Spyropoulou, R., Petersen, J.E., Maguire, C., Zal, N., Achilleos, E., Rubin, A., Ledoux, L., Brown, C., Raes, C., Jacobs, S., Vandewalle, M., Connor, D., Bidoglio, G., 2013. Mapping and Assessment of Ecosystems and Their Services. An Analytical Framework for Ecosystem Assessments Under Action 5 of the EU Biodiversity Strategy to 2020. Publications Office of the European Union, Luxembourg.

Maes, J., Fabrega Domenech, N., Zulian, G., Lopes Barbosa, A., Vizcaino Martinez, M., Polce, C., Vandecasteele, I., Mari Rivero, I., Bastos de Morais Guerra, C., Perpiña Castillo, C., Vallecillo Rodriguez, S., Baranzelli, C., Ribeiro Barranco, R., Batista E Silva, F., Jacobs, C., Trombetti, M., Lavalle, C., 2015. Mapping and Assessment of Ecosystems and Their Services: Trends in Ecosystems and Ecosystem Services in the European Union Between 2000 and 2010. EUR 27143. Publications Office of the European Union, JRC94889, Luxembourg.

Maes, J., Teller, A., Erhard, M., Grizzetti, B., Barredo, J.I., Paracchini, M.L., Condé, S., Somma, F., Orgiazzi, A., Jones, A., Zulian, A., Petersen, J.E., Marquardt, D., Kovacevic, V., Abdul Malak, D., Marin, A.I., Czúcz, B., Mauri, A., Loffler, P., Bastrup-Birk, A., Biala, K., Christiansen, T., Werner, B., 2018. Mapping and Assessment of Ecosystems and Their Services: An Analytical Framework for Ecosystem Condition. Publications office of the European Union, Luxembourg.

MEA, 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopcic, M., Pardos, M., Cailleret, M., 2017. Future ecosystem services from European mountain forests under climate change. J. Appl. Ecol. 54 (2), 389–401.

Mokondoko, P., Manson, R.H., Ricketts, T.H., Geissert, D., 2018. Spatial analysis of ecosystem service relationships to improve targeting of payments for hydrological services. PLoS One 13 (2), e0192560.

Mouchet, M.A., Paracchini, M.L., Schulp, C.J.E., Stürck, J., Verkerk, P.J., Verburg, P.H., Lavorel, S., 2017a. Bundles of ecosystem (dis)services and multifunctionality across European landscapes. Ecol. Indic. 73, 23–28.

Mouchet, M.A., Rega, C., Lasseur, R., Georges, D., Paracchini, M.L., Renaud, J., Stürck, J., Schulp, C.J.E., Verburg, P.H., Verkerk, P.J., Lavorel, S., 2017b. Ecosystem service supply by European landscapes under alternative land-use and environmental policies. Int. J. Biodivers. Sci. Ecosyst. Serv. Manage. 13 (1), 342–354.

Nistor, M.M., Cheval, S., Gualtieri, A.F., Dumitrescu, A., Botan, V.E., Berni, A., Hognogi, G., Irimus, I.A., Porumb-Ghiurco, C.G., 2017. Crop evapotranspiration assessment under climate change in the Pannonian basin during 1991–2050. Meteorol. Appl. 24, 84–91.

O'Farrell, P.J., Reyers, B., Le Maitre, D.C., Milton, S.J., Egoh, B., Maherry, A., Colvin, C., Atkinson, D., de Lange, W., Blignaut, J.N., Cowling, R.M., 2010. Multi-functional landscapes in semi arid environments: implications for biodiversity and ecosystem services. Landsc. Ecol. 25 (8), 1231–1246.

Orsi, F., Church, R.L., Geneletti, D., 2011. Restoring landscapes for biodiversity conservation and rural livelihoods: a spatial optimisation model. Environ. Model. Softw. 26 (12), 1622–1638.

Paavola, J., Primmer, E., 2019. Governing the provision of insurance value from ecosystems. Ecol. Econ. 164, 106346.

Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: response to European policy support and public data requirements. Land Use Policy 29 (2), 329–338.

Paracchini, M.L., Zulian, G., Kopperoinen, L., Maes, J., Schägner, P., Termansen, M., Zandersen, M., Perez-Soba, M., Scholefield, P.A., Bidoglio, G., 2014. Mapping cultural ecosystem services: a framework to assess the potential for outdoor recreation across the EU. Ecol. Indic. 45, 371–385.

Plieninger, T., Dijks, S., Oteros-Rozas, E., Bieling, C., 2013. Assessing, mapping, and quantifying cultural ecosystem services at community level. Land Use Policy 33, 118–129.

Primmer, E., Furman, E., 2012. Operationalising ecosystem service approaches for governance: do measuring, mapping and valuing integrate sector-specific knowledge systems? Ecosyst. Serv. 1 (1), 85–92.

Pulla, P., Schuck, A., Verkerk, P.J., Lasserre, B., Marchetti, M., Green, T., 2013. Mapping the Distribution of Forest Ownership in Europe. EFI Technical Report 88. European Forest Institute.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. 107, 5242–5247.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). US Dept Agriculture, Agr. Research Service. Agr. Handbook No. 703.

Roces-Diaz, J.V., Vayreda, J., Banqué-Casanovas, M., Cuso, M., Anton, M., Bonet, J.A., Brotons, L., DE Cacaceres, M., Herrando, S., Martinez de Aragon, J., de-Miguel, S., Martinez-Vilalta, J., 2018. Assessing the distribution of forest ecosystem services in a highly populated Mediterranean region. Ecol. Indic. 93, 986–997.

Saarikoski, H., Jax, K., Harrison, P.A., Primmer, E., Barton, D.N., Mononen, L., Vihervaara, P., Furman, E., 2015. Exploring operational ecosystem service definitions: the case of boreal forests. Ecosyst. Serv. 14, 144–157.

Sabogal, C., Guariguata, M.R., Broadhead, J., Lescuyer, G., Savilaakso, S., Essoungou, N., Sist, P., 2013. Multiple-use Forest Management in the Humid Tropics: Opportunities and Challenges for Sustainable Forest Management. FAO Forestry Paper No. 173. Rome, Food and Agriculture Organization of the United Nations, and Bogor, Indonesia, Center for International Forestry Research.

Santoro, M., Cartus, O., Mermoz, S., Bouvet, A., Le Toan, T., Carvalhais, N., Rozendaal, D., Herold, M., Avitabile, V., Quegan, S., Carreiras, J., Rauste, Y., Balzter, H., Schmullius, C., Seifert, F.M., 2018. GlobBiomass Global Above-Ground Biomass and Growing Stock Volume Datasets. available on-line at. http://globbiomass.org/products/global-mapping.

Santos-Martín, F., Geneletti, D., Burkhard, B., 2019. Mapping and assessing ecosystem services: methods and practical applications. One Ecosyst. 4, e35904. https://doi.org/10.3897/oneeco.4.e35904.

Schenk, H.J., Jackson, R.B., 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. J. Ecol. 90 (3), 480–494.

Schirpke, U., Candiago, S., Vigl, L.E., Jäger, H., Labadini, A., Marsoner, T., Meisch, C., Tasser, E., Tappeiner, U., 2019. Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services. Sci. Total Environ. 651 (Part 1), 928–941.

Schröter, M., Remme, R.P., 2016. Spatial prioritisation for conserving ecosystem services: comparing hotspots with heuristic optimization. Landsc. Ecol. 31, 431–450.

Schulp, C.J.E., Thuiller, W., Verburg, P.H., 2014a. Wild food in Europe: a synthesis of knowledge and data of terrestrial wild food as an ecosystem service. Ecol. Econ. 105, 292–305.

Schulp, C.J., Burkhard, B., Maes, J., Van Vliet, J., Verburg, P.H., 2014b. Uncertainties in ecosystem service maps: a comparison on the European scale. PLoS One 9 (10), e109643.

Schulp, C.J.E., Levers, C., Kuemmerle, T., Tieskens, K.F., Verburg, P.H., 2019. Mapping and modelling past and future land use change in Europe's cultural landscapes. Land Use Policy 80, 332–344.

Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J. Appl. Ecol. 48, 630–636.

Stürck, J., Poortinga, A., Verburg, P.H., 2014. Mapping ecosystem services: the supply and demand of flood regulation services in Europe. Ecol. Indic. 38, 198–211.

Swallow, B.M., Sang, J.K., Nyabenge, M., Bundotich, D.K., Duraiappah, A.K., Yatich, T.B., 2009. Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa. Environ. Sci. Policy 12 (4), 504–519.

Tattoni, C., Ianni, E., Geneletti, D., Zatelli, P., Ciolli, M., 2017. Landscape changes, traditional ecological knowledge and future scenarios in the Alps: a holistic ecological approach. Sci. Total Environ. 579, 27–36.

Tieskens, K.F., Schulp, C.J.E., Levers, C., Lieskovsky, J., Kuemmerle, T., PLieninger, T., Verburg, P.H., 2017. Characterizing European cultural landscapes: accounting for structure, management intensity and value of agricultural and forest landscapes. Land Use Policy 62, 29–39.

Trabucco, A., Zomer, R., 2019. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. available at. Figshare. Fileset. https://cgiarcsi.community/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v2/.

Triviño, M., Juutinen, A., Mazziotta, A., Miettinen, K., Podkopaev, D., Reunanen, P., Mönkkönen, M., 2015. Managing a boreal forest landscape for providing timber, storing and sequestering carbon. Ecosyst. Serv. 14, 179–189.

Tudoran, G.M., Zotta, M., 2020. Adapting the planning and management of Norway spruce forests in mountain areas of Romania to environmental conditions including climate change. Sci. Total Environ. 698, 133761.

Turner, K.G., Odgaard, M.V., Bøcher, P.K., Dalgaard, T., Svenning, J.C., 2014. Bundling ecosystem services in Denmark: trade-offs and synergies in a cultural landscape. Landsc. Urban Plan. 125, 89–104.

UN, 1992. Report of the United Nations Conference on Environment and development, Rio de Janeiro, 3-14 June 1992. Annex III: Non-Legally Binding Authoritative Statement of Principles for a Global Consensus on the Management, Conservation and Sustainable Development of All Types of Forests, A/CONF.151/26 Vol. III United Nations.

Vallecillo, S., Maes, J., Polce, C., Lavalle, C., 2016. A habitat quality indicator for common birds in Europe based on species distribution models. Ecol. Indic. 69, 488–499.

Van der Plas, F., et al., 2018. Continental mapping of forest ecosystem functions reveals a high but unrealized potential for forest multifunctionality. Ecol. Lett. 21 (1), 31–42.

Van Zanten, B.T., Verburg, P.H., Espinosa, M., Gomez-y-Paloma, S., Galimberti, G., Kantelhardt, J., Kapfer, M., Lefebvre, M., Manrique, R., Piorr, A., Raggi, M., Schaller, L., Targetti, S., Zasada, I., 2014. European agricultural landscapes, common agricultural policy and ecosystem services: a review. Agron. Sustain. Dev. 34 (2), 309–325.

Vandecasteele, Ii, Rivero, I.M., Baranzelli, C., Becker, W., Dreoni, I., Lavalle, C., Batelaan, O., 2017. The Water Retention Index: using land use planning to manage water resources in Europe. Sustain. Dev. 26, 122–131.

Verkerk, P.J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G.J., Potočnik, J., Palahí, M., 2020. Climate-Smart Forestry: the missing link. For. Policy Econ. 115, 102164.

Werners, S.E., Szalai, S., Zingstra, H., Kopataki, E., Beckmann, A., Bos, E., Civic, K., Hlasny, T., Hulea, O., Jurek, M., Koch, H., Csaba Kindor, A., Kovbasko, A., Lakatos, M., 2016. Climate change adaptation in the Carpathian mountain region. In: Salzmann, N., Huggel, C., Nussbaumer, S., Ziervogel, G. (Eds.), Climate Change Adaptation Strategies – An Upstream-Downstream Perspective. Springer.

Winkel, G., Sotirov, M., 2016. Whose integration is this? European forest policy between the gospel of coordination, institutional competition, and a new spirit of integration. Environ. Plann. C Gov. Policy 34 (3), 496–514.

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses – A Guide to Conservation Planning. Agriculture Handbook, No. 537. USDA, Washington DC.

Wolf, S.A., Primmer, E., 2006. Between incentives and action: a pilot study of biodiversity conservation competencies for multifunctional forest management in Finland. Soc. Nat. Resour. 19 (9), 845–861.

Xu, J., Morris, P.J., Liu, J., Holden, J., 2018. PEATMAP: refining estimates of global peatland distribution based on a meta-analysis. Catena 160, 134–140.

Yousefpour, R., Temperli, C., Jacobsen, J.B., Thorsen, B.J., Meilby, H., Lexer, M.J., Lindner, M., Bugmann, H., Borges, J.G., Palma, J.H.N., Ray, D., Zimmermann, N.E., Delzon, S., Kremer, A., Kramer, K., Reyer, C.P.O., Lasch-Born, P., Garcia-Gonzalo, J., Hanewinkel, M., 2017. A framework for modeling adaptive forest management and decision-making under climate change. Ecol. Soc. 22 (4), 40.

Zhang, L., Potter, N., Hickel, K., Zhang, Y., Shao, Q., 2008. Water balance modeling over variable time scales based on the Budyko framework – model development and testing. J. Hydrol. 360 (1), 117–131.

Zulian, G., Maes, J., Paracchini, M.L., 2013. Linking land cover data and crop yields for mapping and assessment of pollination services in Europe. Land 2, 472–492.