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Mapping forest condition in Europe: Methodological developments in support to forest biodiversity assessments

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ABSTRACT

Forest condition, biodiversity, and ecosystem services are strongly interlinked. The biodiversity levels depend to a large extent on the integrity, health, and vitality of forests at the same time as losses of forest biodiversity lead to decreased forest productivity and sustainability. Under this conceptual framework, this study presents a methodology for mapping forest condition at European scale supporting the attainment of the 2020 Aichi Biodiversity Target 5 "*the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced*" and the implementation of Sustainable Development Goals (SDG), as well as the EU forest strategy since the sustainable forest management is oriented to support the provision of forest services and to enhance the condition of biodiversity forests' host.

The work presents the developments of an operational indicator at European scale. This spatially explicit information on forest condition can be the baseline map with a 1 km resolution to monitor the state and changes of condition by exposition to pressures and threats. This condition indicator considers structural, functional, and compositional aspects of forest with relevance for health and vitality of species and habitats hosted by forest ecosystems.

The methodology implemented used harmonized, published and open datasets. It provided confident results for the assessment of the condition within hemiboreal, temperate and alpine forests, showing the Carpathian, Dinaric Alps and Alps, among others, as hotspots with pre-dominantly good condition. The results were validated with data derived from the reporting for the EU Habitat Directive and explicit dataset on known primary forests in Europe. However, this method underestimated the forest condition in the Mediterranean and Boreal forest types due to data gaps, regional specific characteristics, and design limitations.

This study illustrates an operational and transferable approach for addressing the assessment of ecosystem forest condition at European scale being considered as a support tool for European countries when mapping and assessing their national territory, as potential common approach to map forest ecosystems that allows for consistent aggregation and comparisons across scales.

1. Introduction

In recent years, the multiple functions and potential uses of forests have attracted interest. In addition to wood supply, forests also provide multiple ecosystem functions and services that are vital to society and human well-being. These include providing freshwater and clean air, regulating climate and nutrient cycling, and contributing to human health and recreation (Thompson et al., 2009). Although Sustainable Development Goal 15 (SDG 15) (life on land) includes several targets related to forests; the State of the World's Forests highlights the profound interlinkages that exist between forests and trees and multiple goals and targets of the 2030 Agenda for Sustainable Development

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(FAO, 2018) going well beyond SDG 15 to contribute to achieving multiple goals and targets across the 2030 Agenda.

In Europe, forest covers about 180 million hectares, this means more than 40% of land, making it as one of the most forest-rich regions in the world (EEA, 2016). However, this does not necessarily mean that Europe's forests are not subject to pressures and changes that may threaten their biodiversity and multi-functionality. This ecosystem is under increasing pressure as result of climate change which aggravates other key drivers of pressures such as pests, diseases, extreme weather events and forest fires. Additionally, other pressures come from air pollution, land abandonment and encroaching human development (infrastructure and tourism) (Moreira et al., 2020). While there has been an increase in the societal and political responses to biodiversity loss with ambitious targets, Europe continues to lose biodiversity at an alarming rate, and many agreed policy targets will not be achieved (EEA, 2019a). The mid-term evaluation of progress towards attaining the 2020 Aichi Biodiversity Targets set in the United Nations Convention on Biological Diversity (CBD) showed that, if the world stays on its current development path, the state of biodiversity will continue to decline.

Cardinale et al. (2012) revealed that the biodiversity levels depend largely on the integrity, health and vitality of forests. Losses of forest biodiversity led to decreased forest productivity and sustainability.

The condition of forest ecosystems depends on a multiplicity of factors whereas forest health and vitality are often considered the most significant factors to underpin its optimal function. Mapping forests with their bio-ecological values and functional status is an urgent task for its protection and sustainable development.

It is widely recognized that biodiversity is a major driving force in ecosystem function (Hooper et al., 2005; Schulze and Mooney, 2012). One of the main threats to forest biodiversity comprises the loss of 'naturalness' of forest ecosystems due to an inappropriate ecosystem management. Consequently, naturalness assessments are increasingly being required to determine and monitor both the ecological status and the development of forests (Chiarucci and Piovesan, 2020). However, naturalness is a complex term that could be defined from different perspectives (McRoberts et al., 2012). In the present study, naturalness is defined as 'the similarity of a current ecosystem state to its natural state' Winter (2012) and biodiversity is defined as 'the diversity of life in all its forms and all its levels of organization' (Hunter, 1990).

On the other hand, forest structure influences forest biodiversity directly, by complex interactions, through the formation of microhabitats as well as the determination of larger-scale habitat characteristics (McElhinny et al., 2005; Mac Nally et al., 2001). Forests with more complex structure are thought to be more resilient and potentially even more productive, delivering more forest functions. They provide valuable habitats for a greater diversity of plants and animals than do forests with less structural complexity. Forest degradation is usually associated with a reduction in vegetative cover, especially trees and modification of spatial patterns toward a fragmented forest. This means a decline in forest condition that leads to forest biodiversity loss by reducing the available habitat of forest-dependent species and indirectly through disruption of major ecological processes such as pollination, seed dispersal and gene flow.

This work aims to develop an operational indicator to assess the general forest condition in Europe. The methodology is based on the definition of the forest condition (health and vitality), on the combined presence of abiotic and biotic pressures and the way they affect tree growth and survival, the yield and quality of wood and non-wood products, wildlife habitat, recreation, and scenic and cultural values (FAO, 2017). Therefore, this approach includes the role of biodiversity, forest health and structures in the ecosystem condition and, consequently, the capacity to provide services. This indicator provides spatially explicit information on general forest condition in Europe using, as inputs, available, accessible, and reliable databases at European scale. The forest data availability across Europe is improving in the last decade, but further efforts are needed to integrate, harmonise and interpret this data (i.e. making data useable for non-experts) (Ruiz-Benito et al., 2020). The output contributes to a general forest monitoring, at EU or regional scale, and can support the evaluation of progress towards attaining forest-related SDGs.

2. Material and methods

According to the main objective above described, Fig. 1 outlines the conceptual approach followed in this work. The combination of the elements, datasets and tools, allows to integrate biodiversity, health and structures forest characteristics into a composite condition indicator.

The condition indicator is composed by three sub-indicators that comprise forest attributes based on diversity and abundance of forest species (FB_I), the structural ecosystem attributes by the horizontal structure measured as forest extension and compactness (FS_I), and the biomass value expected for the forest type (FF_I).

The study area was defined by the ecosystem types of Europe map that represents the terrestrial habitat classes of the European Nature Information System (EUNIS) at level 2 (Table 1; EEA, 2019b). We used the class "woodland, forest and other wooded land" to outline the forest areas from this ecosystem map. These areas are dominated by woody vegetation of various age or have a succession climax vegetation types on most areas, thus supporting many ecosystem services.

The main datasets used to assess the forest ecosystem condition are summarised in Table 1. Most of the datasets are not truly empirical data but products derived from original empirical data by different modelling approaches properly described and validated in their respective metadata (see table 1).

The spatial resolution of the condition indicator is 1 km^2. The coverage is the 27 EU Member States and the United Kingdom together with the other EEA member countries Iceland, Liechtenstein, Norway, Switzerland, and cooperating countries: Albania, Bosnia Herzegovina, Kosovo under the UN SCR 1244/99, North Macedonia, Montenegro, and Serbia. The Macaronesia region (Azores, Madeira and the Canary Islands) and Turkey were excluded of the assessment due to lack of information in some of the data input.

The target area of the study is the European forest, above mentioned, but the assessment was designed and implement by disaggregating the EU forest extent in forest typologies. The European Forest Types - EFTs-classification stratifies the forest area into homogeneous ecologically units in a meaningful way. This facilitates the analysis, interpretation, and reporting of forest data, especially concerning biodiversity-related information (Barbati et al., 2011). The EFTs classification was transferred to spatially explicit information through the European habitat suitability map which relation is one-to-one (Casalegno et al., 2011).

The following sections outline the composite indicator on Forest Condition indicator (FC_I) that drives the overall condition of forest ecosystems.

2.1. Forest biodiversity sub-indicator

The forest biodiversity sub-indicator (FBI) is a composition of the natural assemblage tree species (FNI) and the tree species distribution (TDI) variables here considered as a proxy of the biodiversity (Chirici et al., 2012; Garo et al., 2014). The TDI shows, in percentage, the number of tree species present within each pixel in respect to the maximum number of tree species present in the respective forest type (Eq. (1)). The data source was the relative probability of the presence of tree species (RPP) maps available in the database of the European Atlas of Forest Tree Species (de Rigo et al., 2016; San-Miguel-Ayanz et al., 2016). A tree species was counted in a pixel if the RPP > 1%.

$$TD_I = \left(\frac{\sum_{k=1}^{K} TS_i}{Max_{TS}}\right) \cdot 100 \quad (1)$$

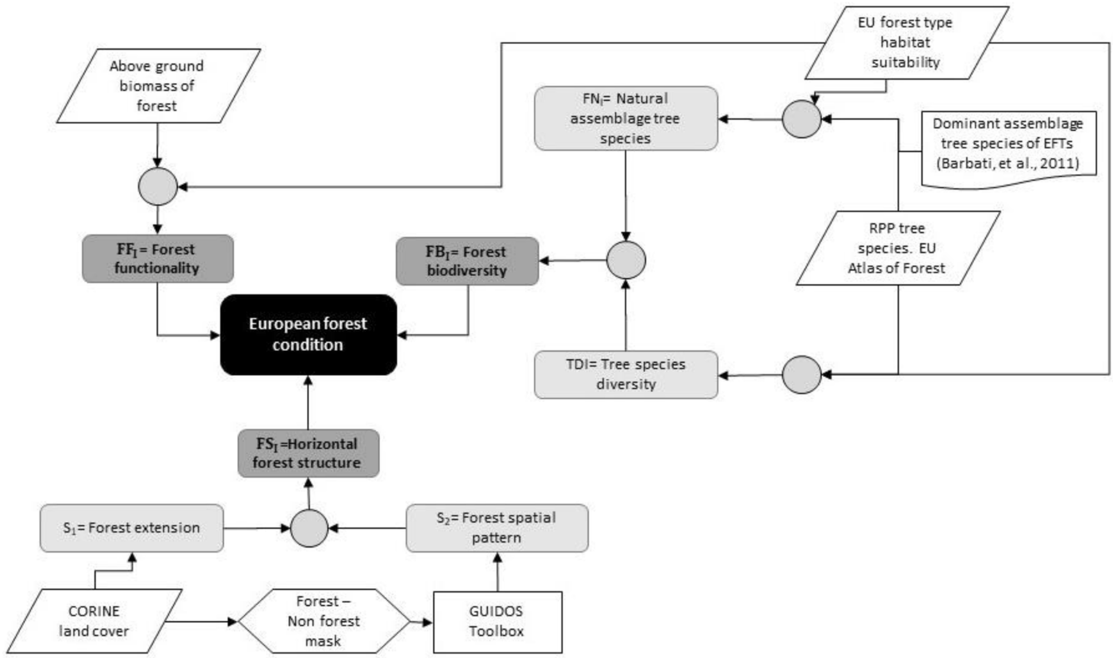

Fig. 1. Methodological approach used for the development of the condition indicator of European woodland and forest ecosystems.

Table 1
Sources and reference year of the main datasets included in the development of the forest condition indicator.

Name of the data set	Attribute supported	Year	Data owner
European Ecosystem map v.2.1[(1)]	General. Ecosystem coverage	2012	EEA
Forest type habitat suitability[(2)]	General. Forest type distribution	2011	JRC
Corine Land Cover (CLC)[(3)]	Structural attributes	2012	EEA
EUNIS woodland, forest and other wooded land habitats, predicted potential distribution of habitat suitability[(4)]	Biodiversity attributes	1940–2011	EEA
Relative probability of presence of forest tree species (RPP) of European Atlas of Forest Tree Species[(5)]	Biodiversity attributes	2006	JRC
Above ground biomass of forest[(6)]	Functional attributes	2012	JRC

EEA: European Environment Agency.
JRC: Joint Research Centre of the European Commission.
(1) https://www.eea.europa.eu/data-and-maps/data/ecosystem-types-of-europe.
(2) https://forest.jrc.ec.europa.eu/en/past-activities/tree-species-and-forest-habitat-suitability/.
(3) https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012.
(4) https://sdi.eea.europa.eu/catalogue/srv9008075/api/records/af43952c-393b-426f-8660-01fccdf758eb.
(5) https://forest.jrc.ec.europa.eu/en/european-atlas/atlas-data-and-metadata/.
(6) https://data.jrc.ec.europa.eu/dataset/71a38170-4a68-443c-9425-cd713c85291d.

TS_i = tree species present in i pixel

Max_{TS} = maximum number of tree species by EU Forest Type

The TD_I ranges between 0 and 100 where low values show forest areas hosting species assemblages having low tree species richness, as proxy of biodiversity, and high values identify forests hosting tree species with high biodiversity in respect of their forest type.

The second variable evolved in FBI is related to the assessment of the natural assemblage tree species (FN_I). This measures is a proxy for measuring the spatial congruency between the suitable habitat distribution of tree species (based on predicted potential distribution of EUNIS habitat suitability (EEA, 2015a)) and current tree species distribution based on RPP of tree species maps (de Rigo et al., 2016; San-Miguel-Ayanz et al., 2016). Those tree species did the relationship between these two datasets that the EUNIS system classifies as dominant in each habitat (EEA 2015b). The approach follows the methodology proposed for calculating forest naturalness in Bastrup-Birk et al. (2014) by the Eq. (2).

EUNIS habitat maps represent the suitability distribution by habitat type. These datasets, modelized based on sample plot data and the Maxent software package, indicate where conditions are favourable for the habitat type. The grid values in these maps represent the probability (ranging from 0 to 1) that the cell is suitable for each habitat.

For the FN_I calculation, the EUNIS habitat maps were converted to Boolean layers (suitable / non suitable) setting the break value as the percentile 25 of the statistical distribution of the sample points used for the EUNIS habitats suitability modelling (EEA, 2015b).

Then, naturalness is related to the presence and the coverage of those potentially dominant species within the habitat suitable area according to the RPP maps and greater than 1% criterium.

The result of Eq. (2) expresses the percentage of natural tree species composition in the fuzzy values between 0 and 100. The values close to 100 mean a high percentage of native tree species (natural) whereas values close to 0 approximate a low level of naturalness.

$$FN_I = \sum_{i=1}^{n} (C \cdot P)_i \tag{2}$$

i = EUNIS habitats

C = fractional area covered by tree species

P = suitable habitat for tree species. 0 (absence/ non-suitable) or 1 (presence/suitable).

The forest biodiversity indicator (FB_I) was calculated based on the average natural assemblage species and tree species distribution sub-indicators, as shown in the Eq. (3). The indicator values range from 0 to 100 where higher values indicate high value from biodiversity perspective including high natural tree species composition and high tree biodiversity. In contrast, low values of FB_I define forest with low naturalness and low tree species diversity.

$$FB_I = 0.5 \cdot TD_I + 0.5 \cdot FN_I \quad (3)$$

2.2. Horizontal forest structure sub-indicator

Horizontal forest structure was assessed by two morphological features: extent (S_1) and spatial pattern (S_2) of forest. S1 identifies the extent of forests as percentage of forest cover per 1 km^2 grid cell. S_2 evaluates the extent and compactness of forest patch as percentage of core forest. The core forest is defined as the interior of forest patches, excluding the perimeters. Essentially these areas refer to the interior part of the forest. From a purely geometric concept, the core pixels are defined as those forest pixels whose distance to the non-forest is greater than the given size-parameter (100 m in this study) (Soille and Vogt, 2009).

From a forest functionally perspective, within the same forest communities, core forests ensure a higher and more specific biodiversity than in forest boundaries. Forest core function ensures the best condition for area-sensitive edge-intolerant species (Burkey, 1995; Ferraz et al., 2003). Both indicators were computed based on Corine Land Cover (CLC) 2012 at a pixel resolution of 100 m. A forest pattern map was derived by applying the GUIDOS Toolbox (Vogt and Riitters, 2017) on this dataset. Eq. (4) shows the forest structure sub-indicator (FS_I) as a composition of the two aforementioned variables. The FS_I ranges from 0 to 100 with high values indicating high interior forest habitat, whereas low values define forest with lower interior habitat quality.

$$FS_I = \left(\frac{S2}{S1}\right)*100 \quad (4)$$

S1 = % forest coverage per 1 km^2
S_2 = % core forest per 1 km^2

2.3. Forest function sub-indicator

The forest function sub-indicator **(FF_I)** was derived from the forest biomass map for Europe (Barredo et al., 2012). Forest biomass is an important measure of ecosystem productivity. It is used in quantifying the role of forests in the carbon cycle, the potential for energy production, and the carbon stock estimation for climate change modelling.

Eq. (5) describes the forest biomass value per grid cell normalized among the EFTs. FF_I ranges between 0 and 100 that can be interpreted as a range between less favourable forest quality (low values indicate low biomass value compared to the mean biomass values of its respective forest type) to 100 (where higher values indicate higher biomass value compared to the respective mean).

$$FF_I = \left(\frac{B_i}{B_-}\right)*100/max(\frac{B_i}{B_-} \quad (5)$$

B_i = Forest biomass value in pixel i.
B_- = mean of forest biomass value within EU forest type.

Max.is the maximum value of the function $\left(\frac{B_i}{B_-}\right)$.

2.4. Forest condition indicator

The Forest Condition indicator (FC_I) was computed as the three above-mentioned indicators by the Eq. (6). In fuzzy values ranging from 0 and 100, the result expresses the forest condition as a composite indicator of the percentage of native species, the biodiversity, the coverage and connectivity of forest, and the aboveground biomass. The values close to 100 mean good condition whereas values close to 0 indicate poor forest condition.

$$FC_I = \frac{FF_I + FS_I + FB_I}{3} \quad (6)$$

2.5. Validation and reliability assessment

The developed composite forest condition indicator was tested by regression analysis against other spatial explicit information about forest condition available in Europe (Fig. 2). The analyses aimed to demonstrate any congruencies and differences between the different sources of information, validate the produced map, and gauge the potential use of forest condition map in the context of ecosystem service assessments.

Primary forests are considered hot spots for forest biodiversity and as such represent a high overall forest condition regarding compositional, structural and functional aspects. The forest condition map was tested against field observations from primary forest patches inventoried by Sabatini et al. (2018) being the most comprehensive spatially explicit dataset on known primary forests in Europe currently available. Furthermore, a sub-set of 56 Natura 2000 sites were randomly selected across Europe. The conditions of the forest habitats protected by Natura 2000 sites were derived from the information reported by the countries in compliance with the Habitats Directive (Council Directive 92/43/EEC). We used specifically the conservation status of habitats and on compensation measures taken for projects having a negative impact on Natura 2000 sites. The proxy value was computed as the area-weighted average of the habitats forest present in the Natura 2000 site, considering A: excellent value as 3; B: good value as 2; and C: significant value as 1.

3. Results

The three sub-indicators that composed the European forest condition index are shown in Fig. 3. Fig. 3A shows the map of the forest function sub-indicator (FF_I) where higher values of forest condition according to their functionality are in the mountainous areas, in the southern part of Fennoscandia, and in some Baltic and Balkan countries. Fig. 3B shows the results of the forest structure indicator (FS_I). Central and Eastern Europe or mountainous regions present the higher values than the relatively moderate to lower values in inner Boreal forests and lowlands, particularly the Atlantic zones and some patches in the Mediterranean region.

The higher values of the biodiversity indicator (FB_I) are located in mountainous areas (Alps, Dinaric Alps, Carpathian Mountains and Pyrenees), with other small patches in the Ligurian region and southern part of the Iberian Peninsula (Fig. 3C). Low values are found for forest plantations with exotic tree species as Eucalyptus and in the Mediterranean region.

The overlap of the three maps abovementioned by Eq. (6) resulted in the forest condition map shows in Fig. 4A. This map indicates that the areas with the highest forest condition values are located along the Lithuania-Belarus and Poland-Belarus borders, in mountainous areas, especially the Carpathians, the eastern Alps, the Dinaric Mountains and, to a lesser extent, the highest parts of the Pyrenees. These are the areas where forests show high species and habitat diversity as well as the core forest provides a strong forest structure. On the other hand, the indicator predicted low values of forest condition in the Atlantic regions, Britannic Archipelago, Boreal and most of the Mediterranean biogeographical regions (Fig. 4 and Fig. 5).

4. Validation

The forest condition indicator developed in this study was validated based on a multi-criteria evaluation and compared to other independent European spatial data sets (see section 3). Concerning the statistical

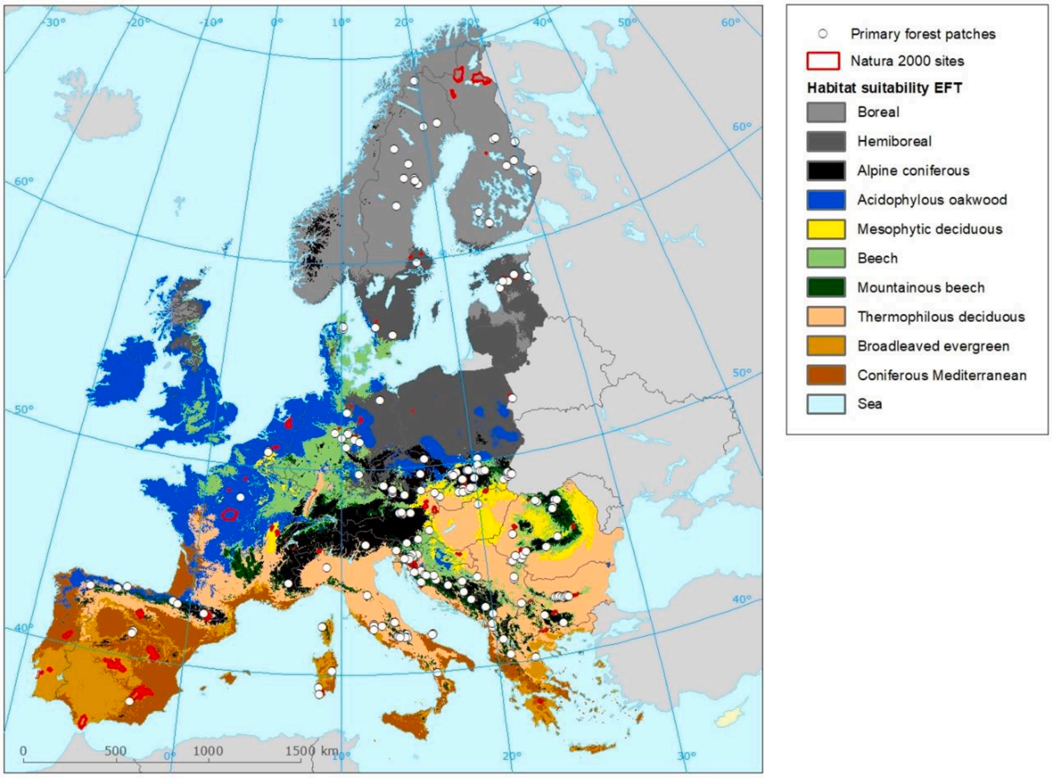

Fig. 2. Distribution of primary forest patches (Sabatini et al., 2018) and Natura 2000 sites used as validation sites. The map of habitat suitability of forest types in the background (Casalegno et al., 2011).

analysis done against the primary forest patches (Fig. 5), the model predicted coherently the condition values for most of the primary forest identified as Hemiboreal forests, Alpine coniferous, Mesophytic deciduous and acidophilus forest, beech forest, mountainous beech forest and thermophilus deciduous forest. In the case of acidophylous oakwood, broadleaved evergreen and coniferous Mediterranean, the number of plots was insufficient to determine the significance of results. We cannot extract conclusions of the comparison with primary forest of those forest types.

However, Figs. 5 and 6 showed an underestimation of the forest condition for the Mediterranean (coniferous and broadleaved) and Boreal forest types. This bias result is linked to the gaps in the data sources but also to structural specificities of the primary forest within these biogeographical regions.

To determine the relationship of ecosystem condition and the protection regimes, a test in/out was implemented to compare condition values of forest within Natura 2000 areas to the rest of forest extent in Europe (EU 27 and the UK). Fig. 7 shows the distribution of forest condition values, categorized in five classes and separated between Natura 2000 areas. The mean value of the condition indicator is labelled as number that ranges from 0 to 100. The assessment indicates that, at EU scale, there are not significant difference between the mean values of the forest indicator within (35.89) and outside (40.22) Natura 2000 sites (t-value −0.72 and p-value 0.47 of Student's T Test). The highest mean values were in the Alpine coniferous and mesophytic deciduous forest types, the lowest values were in the broadleaves evergreen and coniferous Mediterranean forest types.

The Natura 2000 sites host most of the areas with the highest values of forest condition (almost 70% of the area in the upper interval is under Natura 2000 protection). The percentage of forest area with an estimated forest condition value lower than 20 points is almost equally distributed in the protected and non-protected areas across Europe. This indicates that the protection policy under Natura 2000 sites seems to have a limited impact. Although forests with the best condition are mostly found within these areas, areas with low values of forest condition are very similar to unprotected areas.

5. Discussion

The forest condition map presented in this work can be considered as baseline to assess the European forest condition under the evaluation of progress towards the attainment of sustainable and biodiversity goals. We developed a method for constructing an operational indicator forest ecosystem condition from open and public data sources at 1 km^2 spatial resolution showing a general overview of the ecosystem at EU 27 and UK scale. The basic requirements for computing the condition of forest ecosystems include indicators for the horizontal structure, biodiversity, and functionality. Other forest characteristics could be added to enrich the condition assessment such as pressure indicators, dead wood, occupancy/dominance of invasive/introduced species, presence of pioneer species/indicator species; soil properties, species composition; etc. Many of these indicators are difficult to measure or quantify at the European scale due to a lack of consistent and harmonised data. Complex methodologies for data acquisition or index calculation derived in challenging results with the risk to be un-operational.

The aim of this work is to provide an approach which is simple and spatially explicit, as strength for its implementation and usability, for producing a European map from harmonized and publicly available datasets to measure progress/trends towards the achievement of the CBDs and SDGs target. The data sources used in this study, after the screening process, are derived data generated from original data after harmonization processes and protocols led by renowned institutions, e.g., Intergovernmental Panel on Climate Change (IPCC) and JRC for Biomass dataset or EEA for CLC dataset.

The European forest condition map presented in Fig. 4 shows that the areas with better conditions are located along the Lithuania-Belarus and Poland-Belarus borders, in mountainous ranges, especially the Carpathians, the eastern Alps, the Dinaric Mountains and, to a lesser extent,

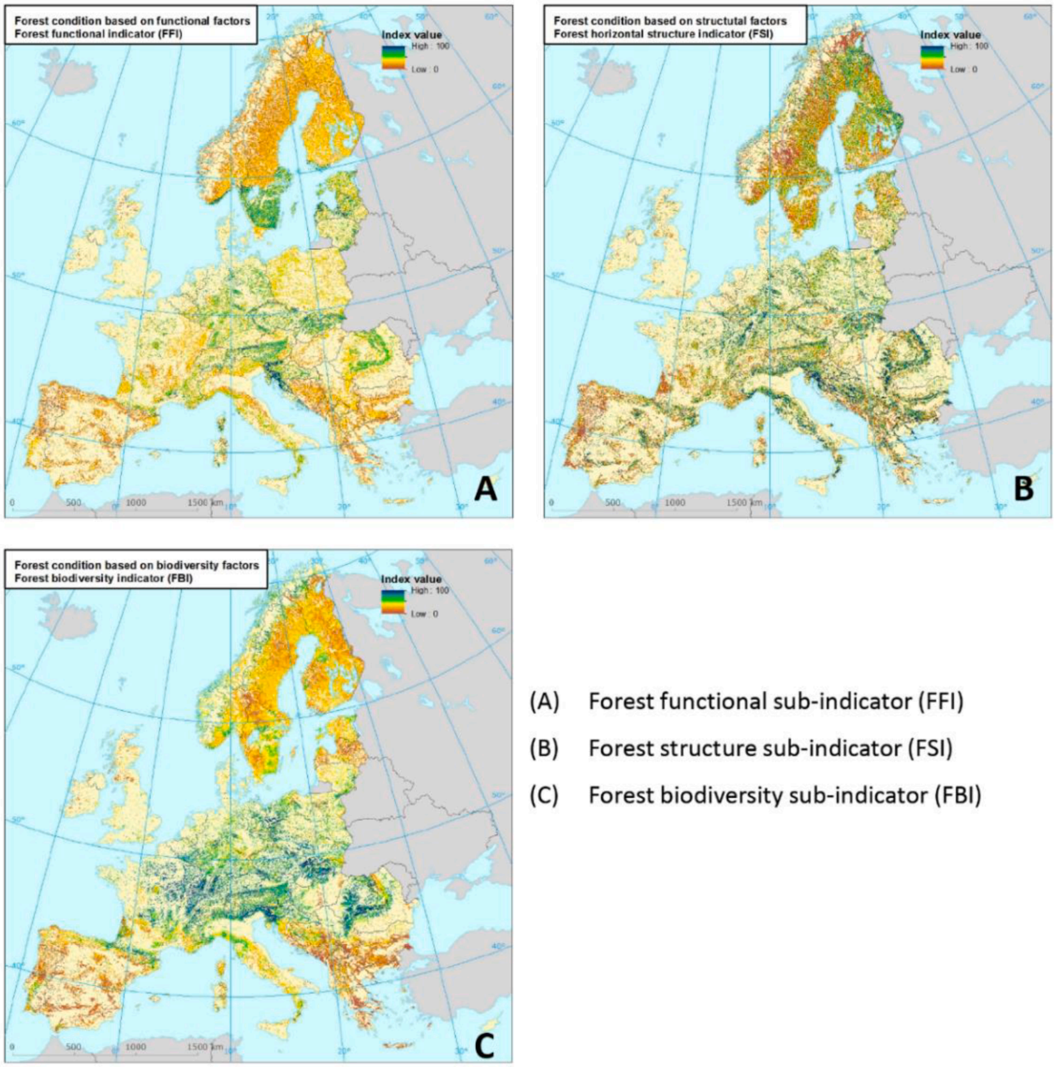

Fig. 3. Maps for EU forest sub-indicators used for assessing the European forest condition.

the highest parts of the Pyrenees. This finding is also consistent with previous results (Forest Europe, 2015; Kuuluvainen and Aakala, 2011; Sabatini et al., 2018). Mainly remote and rural areas host most of the forests in good condition since accessibility and the distance from markets or other centres of demand is one of the main drivers of land-use allocation. Indeed, mountainous regions are key for European biological richness and its conservation (EEA, 2010).

The high values respect the functional forest elements in the sub mountainous areas like the southern part of Fennoscandia, and some Baltic and Balkan countries and are consistent with the results of Avitabile and Camia (2018).

In contrast, the low values of forest condition were identified in the Atlantic regions, Britannic Archipelago, Boreal, north-west of Iberian Peninsula and most of the Mediterranean biogeographical regions (Figs. 4 and 5). The low values of forest condition forest in Western Europe were expected considering the accessibility and historically high population density and high pressures from urban and transport infrastructure expansion (EEA, 2018). Accessibility and population density have been identifying as important spatial determinants for explaining the patterns of wood production and harvesting intensity in Europe (Levers et al., 2014; Verkerk et al., 2015). Also, the north-western forest of the Iberian Peninsula is highly pressured by the Eucalyptus plantations for paper pulp production (Cerasoli et al., 2016).

However, the final condition index presents a degree biased results for some EU regions, e.g., the Mediterranean and Boreal regions.

The bias in the Boreal area is linked with the specific dynamics of this forest type in natural and pristine conditions. Natural disturbances acting over a range of spatial and temporal scales (large intense fires, low-intensity ground fires and insect outbreaks) are shaping the forest stand age structure at the landscape level (Kuuluvainen and Gauthier, 2018).

The relationship and rate of young post-disturbance stages, along with mature forest stages with old-growth characteristics is key to maintain an adequate share and the ecological qualities of these ecosystems. Fig. 6 shows a negative correlation between the forest condition value predicted in this study and the global condition reported in the assessment of the value of the Natura 2000 sites in boreal forests. This means that the forest characteristic included in this assessment are not positively correlated with the “good” condition of the boreal forest as reported, which was the basic assumption in this multi-criteria approach. Values of the structure and function indicators close to the maximum value (1 0 0) were not associated with “good” condition since the heterogeneous stand age distributions and landscape mosaics resulted in intermediate values.

However, in the Mediterranean case, two aspects coexist in the weakness index: gap of data information related to the tree species distribution and the structural specificities of the Mediterranean forest.

Most central and northern European forests are dominated by around

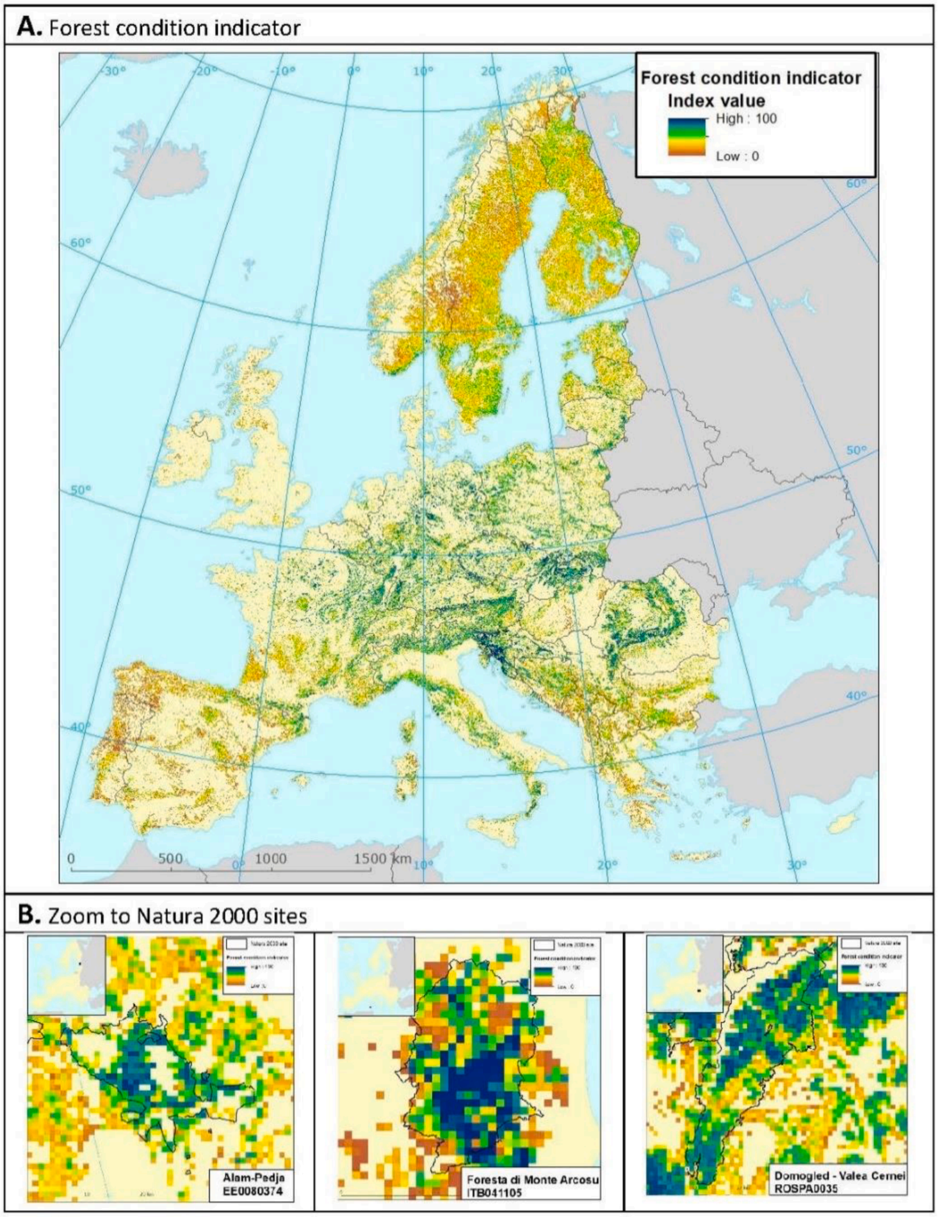

Fig. 4. A) European forest condition indicator. B) Zoom to Natura 2000 sites. Indicator shows as colour ramp where areas in dark blue mean high forest condition values, whereas areas in red are poor forest condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a dozen of tree species only. The Mediterranean forests are much more diverse, as more than 100 different tree species can be found in this biogeographical region (EC, 2009). Those forests are exceptionally rich in endemic species: 201 out of the 290 woody species and subspecies (shrubs and trees) are exclusively or preferentially found under Mediterranean bioclimates (Quézel & Médail, 2003). So, the biodiversity values calculated in this assessment underestimate the biodiversity for this zone. However, the biodiversity indicator can be considered adequately defined and formulated, although it could be further enhanced by adding other factors such as endemism or genetic variability of individual species. The errors found for Mediterranean forests are linked to data limitations at the European level. The main data source for the biodiversity sub-indicator, European Atlas of Forest Tree Species, provides limited datasets for the dominant tree species of Mediterranean forest type (e.g., *Juniperus spp, Platanus orientalis, Quercus coccifera, Quercus faginea,* among others) (San-Miguel-Ayanz et al., 2016).

Additionally, Mediterranean forests show fundamentally different structural characteristics from temperate mesic forests, due to the high-drought stress Mediterranean forests experience during the summer and due to fire disturbance (Karavani et al., 2018). These conditions may hinder the development of structural features typically associated with old-growth stages, as dense forest, unfragmented as was assumed in this work (Burrascano et al., 2013; Kulakowski et al., 2017). This is a limitation found in other studies for modelling Mediterranean forest characteristics on large scale (Sabatini et al., 2018).

The method presented requires readjustments in the sub-indicators of functional and horizontal structure to integrate the aspects associated with the natural disturbances to which these forests are exposed and which form part of their condition, in a natural or non-managed regime.

Additionally, it is to note that in areas dominated by forest plantations with indigenous tree species, this index could show, due to a weakness of the algorithm, medium to high values as e.g., in Les Landes

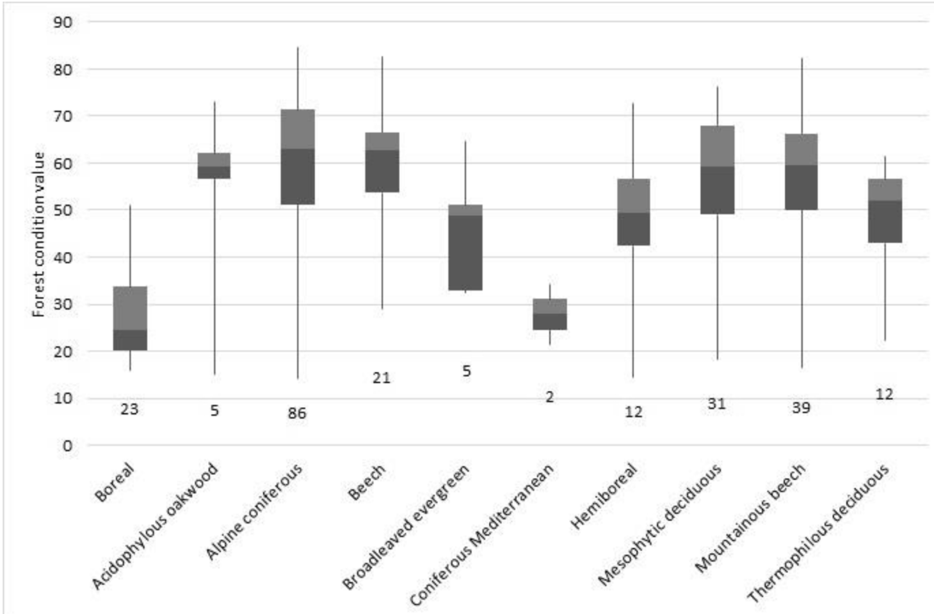

Fig. 5. Box plot graph of the distribution of forest condition values predicted within primary forest patches from Sabatini et al. (2018). See locations in Fig. 2. Forest categorized by EFT (number of plots by EFT in labels).

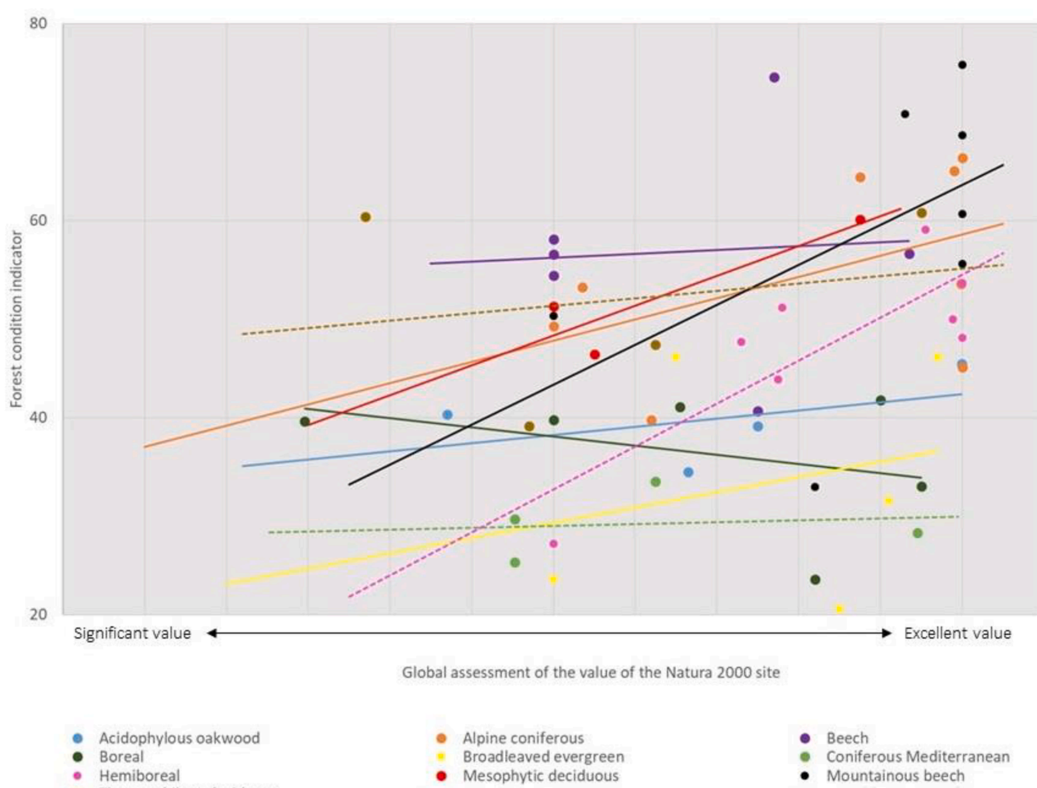

Fig. 6. Forest condition relationships for sub-set of 56 Natura 2000 sites (see locations in Fig. 2) characterized according to the major habitat suitability of forest map of Casalegno, et al. (2011). X-axis represents the global assessment of the site's value for conservation of the natural habitat type concerned reported by the country as part of the information provided in Natura 2000 standard data form (only the forest habitats were included in the assessment, http://natura2000.eea.europa.eu/). Y-axis shows the forest condition indicator predicted in this study, extracted and averaged for the pixels corresponding to the Natura 2000 areas.

de Gascogne (southwestern of France) an indigenous species plantation of about 1 million hectares of *Pinus pinaster* (Vallauri et al., 2012). This limitation could be minimized by including additional information related to the forest plantation and forest harvesting intensity. Eurostat, the Timber Committee of the United Nations Economic Commission for Europe (UNECE), among others, collect and collate statistics on the production and trade of wood through their Joint Forest Sector Questionnaire (JFSQ). However, this information is mainly tabular, i.e., it is

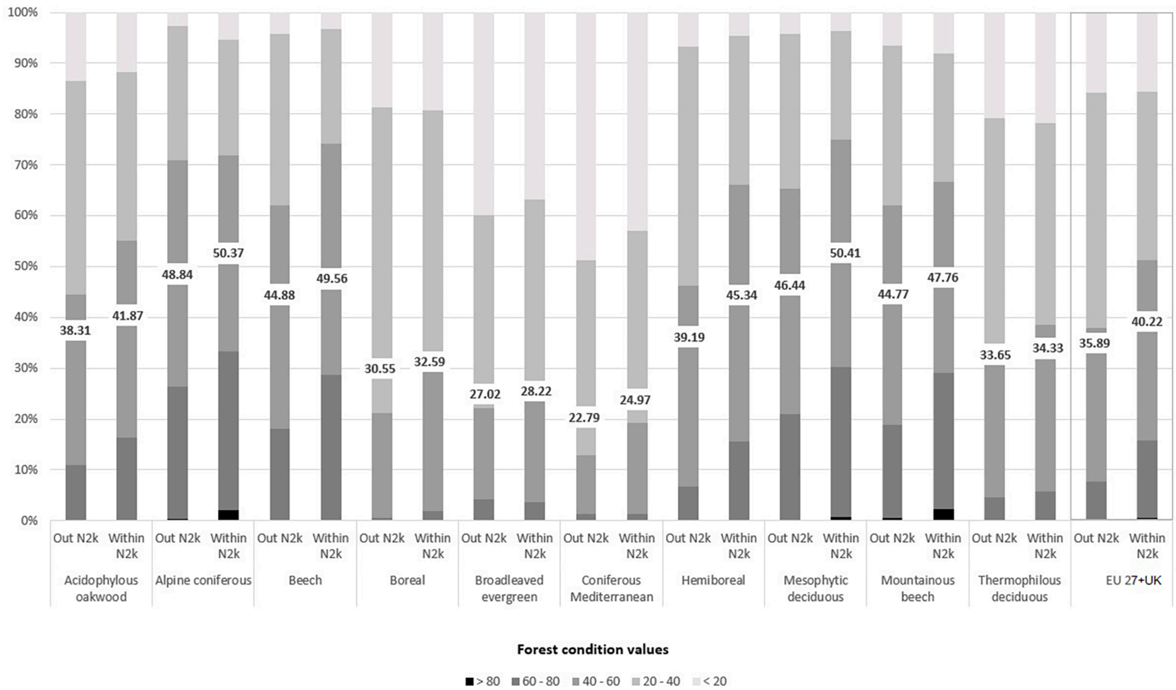

Fig. 7. Relative distribution of the forest condition values within and outside of the Natura 2000 sites per European forest type (in % the forests in each region). In label the mean value of the forest condition indicator.

not spatially explicit data, being a gap for forest monitoring and analysis as presented in this work. Recently, there are important advances by monitoring the harvest and management pressure by Earth observation techniques (Ceccherini et al., 2020). This can be an additional variable to include in a future enhanced version of this forest condition index, one the methodology is solid and consistent at EU scale.

Natura 2000 sites are the focus of EU's nature and biodiversity policies. The aim of the Natura 2000 network is to secure the long-term survival of Europe's most valuable and threatened species and habitats. As part of this study, the role of the protection practices within the Natura 2000 sites was assessed by comparing the forest condition within and outside Natura 2000 areas. The assessment did not show statistically significant difference between the average values within Natura 2000 sites but almost 70% of areas with higher values of condition are found within Natura 2000 sites. However, the percentage of forest area with low predicted values of forest condition is almost equal in and outside protected areas, indicating that the protection policy that is carried out under the Natura 2000 umbrella has limited impact on the indicator. Indeed, the latest EEA State of nature in the EU about the conservation status of species and habitats protected under the Habitat and Bird Directives indicated that the conservation status of forests habitats is not good in general (EEA, 2015c).

The map shows consistency, with good reliability, for a large area of European forest ecosystems. The performed validation and reliability assessment showed coherent pattern distributions with the relative likelihood of primary forest occurrence map published by Sabatini, et al. (2018). The predicted condition values are consistent with the primary forests identified as Hemiboreal forest, Alpine coniferous, Mesophytic deciduous and Acidophilus forest, Beech forest, Mountainous beech forest and Thermophilus deciduous forest. For these forest types, the indicator shows positive relationship with the conservation status reported by the countries as part of the information provided in Natura 2000 standard data form.

However, the study here presented shows limitations regarding the regular update and replicability of the datasets used as input for having accurate and effective operational monitoring as aiming in this study. This limitation affects to the index but not the methodological approach that, in our opinion, being based on relative indices can be transferred and replicated using other available datasets and providing rooms for updating ingesting emerging data sources. Currently, the combination of high-resolution satellite records and cloud-computing infrastructures that can handle 'big data' provides a complementary asset for monitoring forest. In this way, the structural indicator that here was implemented using as input CORINE land cover (updated every 6 year) could be calculated by Pan-European High Resolution Forest Layers (HRL) from Copernicus Program (updated every 3 year). Biomass estimations (data set 6) are based in a very simple approach (Barredo et al., 2012), being selected due to the limitation of available datasets for a consistent assessment year. However, there are being relevant scientific progresses in terms of monitoring biomass at EU scale based on Earth observation (Ceccherini, et al., 2020) that would allow a sophisticated and regular updating of the Forest function sub-indicator. However, one of the key elements in forest condition monitoring is the biodiversity-related characteristic. The data sources here used (tree species distribution, habitat suitability, table 1) are created based on forest national inventories and other sources by modelling. In both cases, regular updating is not planned but they are not static variables. They are based on probabilistic models and would be updated since the environmental conditions, that act as predictors, and the current species distribution (compiled by NFI) could change in the next future under the current climate change framework.

The study demonstrates the strong demand for access to biodiversity status and trend data at multiple spatial scales to effectively inform policy and decision-making processes. Our results propose a way to produce baseline to assess progress in the state and condition of forest biodiversity. It highlights the challenges in the updating of biodiversity indicators, e.g., when the needed data are not available as part of regular monitoring or inventory schemes (Biala et al., 2012; Han et al., 2014). Technical barriers such as access to data and information and large differences in the scientific standards for monitoring and data analysis may prevent insights on efforts towards improved and maintained biodiversity protection (Kühl et al., 2020; Aubin et al., 2020).

6. Conclusions

The forest condition index (FCI) is the first European wide indicator developed so far to assess the condition of forest ecosystems at this scale considering a variety of factors including the structure and function of this ecosystem and the biodiversity that depends on it. Good condition will most likely result in an increased capacity to supply ecosystem services.

We estimated the relative condition of forest, from 0 to 100, into grid cell at 100 m spatial resolution. Although we recognize that the relatively coarse assumption of the main characteristics that drive the forest condition may weaken the performance of our indicator, we focused our assessment on the operability of the indicator as well as the data availability at large scale.

The results were validated against data derived from the EU Habitat Directive reporting obligations and a dataset on known primary forests in Europe. The map provided confident results for the assessment of the condition within Hemiboreal, Temperate and Alpine forests, showing the Carpathian, Dinaric Alps and Alps, among others, as good condition hotspots. However, the assessment showed weak results in the of Mediterranean forest due to data limitations for these areas. The work presented requires additional inputs for Macaronesian, Mediterranean and Boreal forest types representing singularities linked to species composition, coverages, spatial pattern and ecosystem dynamics.

The results reported in this paper contribute to increase the knowledge and the implementation of biodiversity and environmental policies. The approach and maps presented here, illustrate the integration of multiple data sources, target-oriented, for constructing environmental information at European scale. This work provides underpinning information for the mid-term evaluation of progress towards the attainment of the Aichi Biodiversity Targets supporting the monitoring of trends and potential improvements of the forest diversity by restoration of degraded forest ecosystems. Additionally, it highlights the challenges in the updating of biodiversity indicators, e.g., when the needed data are not available as part of regular monitoring or inventory schemes.

The maps presented in this paper are to be considered a first-tier approach to map forest condition that need to be defined using additional characteristics and factors, not only by the concept per se but also incorporating regional differences in the European forests.

In summary, the presented forest condition map contributes to the assessment of current and coming changes that affect European forest ecosystems and supports the monitoring of post-2020 CBD targets as well as the SDGs. This information on forest condition, biodiversity and the extent of forest degradation is essential for prioritizing human and financial resources to prevent further degradation and restore and rehabilitate degraded forest ecosystems.

CRediT authorship contribution statement

Ana Isabel Marín: Conceptualization, Investigation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Dania Abdul Malak:** Conceptualization, Project administration, Supervision, Writing - review & editing. **Annemarie Bastrup-Birk:** Conceptualization, Project administration, Supervision, Writing - review & editing. **Gherardo Chirici:** Conceptualization. **Anna Barbati:** Conceptualization, Supervision. **Stefan Kleeschulte:** Conceptualization.

Declaration of Competing Interest

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

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