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ORIGINAL PAPER

Country-wide assessment of biodiversity, naturalness and old-growth status using national forest inventory data

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Abstract

Assessing forest biodiversity, naturalness and old-growth status (B-N-OG) is crucial for supporting sustainable forest planning, yet comprehensive monitoring networks specifically designed for such purposes are lacking in many countries. National Forest Inventories (NFIs) are the official source of statistics on status and trends of forests. While initially designed for wood production assessment, NFI data may be pivotal for ecological forest monitoring, thanks to their robust sampling protocols—enabling statistical inference—and regular field campaigns that ensure continuous information updates. As a consequence, in this study we explore the potential of NFIs for estimating B-N-OG indexes, aiming to establish compatible, scientifically relevant, and cost-effective indicators using existing NFI data at a European level. Based on data from the 2005 Italian NFI collected from 6563 plots, 18 indicators were selected following previous experiences and then used to estimate B-N-OG aggregated indexes. Relationships between the 18 indicators and the three indexes were investigated, along with comparisons of their relationships relative to forest type categories, management types and protected versus non-protected areas. Results confirm that NFI data offer valuable insights into specific B-N-OG indexes, especially concerning forest structure and deadwood. Moreover, the indexes contribute to developing meaningful relationships across geographic regions, forest categories and types of management. However, limitations in NFI field protocols are evident, as they are not explicitly designed for certain indicators. The study suggests the potential for NFIs to evolve into accessible, harmonized European reference networks for B-N-OG assessment for better supporting sustainable forest management, planning and conservation decisions related to forest ecosystems.

Keywords Protected areas · Microhabitats · Deadwood · Saproxylic beetles · Ecological indicators · Italian forests

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Introduction

Forests and woodlands cover one-third of the global land surface (FAO and UNEP 2020), providing multiple benefits to society and contributing to sustaining human well-being (Kok et al. 2017; Haines-Young and Potschin 2018; Orsi et al. 2020). Despite the important benefits that forests grant, the provision of these services is threatened by climate change, over-harvesting and by the loss, degradation and fragmentation of forest landscapes and ecosystems (FAO 2015; Felipe-Lucia et al. 2020). In this context, sustainable forest management—management that concomitantly maintains forest biodiversity, productivity, regeneration capacity and vitality, as well as forests' potential to fulfill a wide range of functions and services (Ministerial Conference on the Protection of Forests in Europe 2007)—has been recognized as crucial to circumvent biodiversity loss. Indeed, forest biodiversity (CBD 2006) plays a crucial role in the variety of benefits forests can supply (Mori et al. 2017; Brockerhoff et al. 2017) thanks to the interconnection of its components, including structure (Gao et al. 2014; Bohn and Huth 2017; Ćosović et al. 2020; Toivonen et al. 2022), composition (Drever et al. 2006; Gao et al. 2015) and functions (Hilmers et al. 2018). Yet, the complex nature of ecosystems also poses challenges for biodiversity assessment (McElhinny et al. 2005; Schleicher-Tappeser 2018). In fact, an agreed definition of biodiversity still does not exist (Camia et al. 2023), but as is clear from Lyashevska & Farnsworth (2012), we can refer to forest biodiversity as a measure of the total complexity within a forest habitat considering the total variety of life forms (Wilson 1988).

In such a context, estimating biodiversity is challenging, and the scientific community has been actively engaged in trying to define the different components and dimensions of biodiversity for purposes of identifying variables that can be used for estimating and reporting spatial and temporal biodiversity trends (Pereira et al. 2013).

In this context, assessing forest biodiversity requires evaluating the extent to which forests are influenced by natural processes and free from human intervention (Reif and Walentowski 2008; Winter 2012; Côté et al. 2021), also known as naturalness. Assessing forest naturalness not only helps in accurately estimating and reporting the ecological condition of forests for biodiversity protection, but also plays a crucial role in establishing objective criteria for identifying natural, old-growth forests (Buchwald 2005). In fact, old-growth forests, which exhibit structural attributes and successional processes resulting from minimal human management and disturbances, play an essential role in biodiversity conservation (Paillet et al. 2010). Additionally, their complex structures support the abundance of microhabitats (Kozák et al. 2018; Parisi et al. 2021). Identifying the characteristics of old-growth forests–here referred to as old-growth status—is crucial for searching for potential gaps in the network of protected areas (European environment agency 2014; Côté et al. 2019), particularly in Europe where human impact has historically been substantial (Potapov et al. 2017). Therefore, gaps in monitoring can lead to the ineffective implementation of protection policies (Ette et al. 2023). This may explain why, despite international conventions such as the United Nations Strategic Plan for Forests 2030 (United Nations 2019) and the EU Biodiversity Strategy for 2030 (European Commission 2020), current rates of biodiversity loss remain large (Waldron et al. 2017; Ette and Geburek 2021). Indeed, to effectively achieve forest ecosystem conservation goals, it is crucial to have technically sound and economically viable methods that include well-defined criteria and indicators to support sustainable forest management and planning at multiple levels: local, regional and national (Heink and Kowarik 2010; Maes et al. 2018; FAO 2020; Lier et al. 2022).

In this context, NFIs may play a crucial role in evaluating and estimating indicators related to forest biodiversity, naturalness and old-growth status (B-N-OG) (Corona et al. 2011; Storch et al. 2018), given the extensive data routinely collected from numerous sample plots (Heym et al. 2021). The number of studies that have assessed the utility of NFI data for monitoring biodiversity, naturalness or old-growth status is relatively small, and none has compared estimates of B-N-OG simultaneously using data for an entire country-level NFI (Winter 2008; Corona et al. 2011; Pignatti et al. 2012; Chirici et al. 2012; Storch et al. 2018; Heym et al. 2021).

It is important to underline that in this study we inherited the definitions used in quantitative social sciences (e.g., Stockemer et al. 2018): The term "indicator" is used when its calculation is based only on one variable measured or estimated, while the term "index" is used when its calculation is based on multiple indicators. So, for example, the total volume of deadwood is an indicator that can be aggregated with others to estimate a biodiversity index. The objective of this study was to test a set of indicators satisfying three criteria : (i) they must be able to estimate aggregated indexes of B-N-OG, (ii) they should be supported by substantial scientific evidence, and (iii) they can be estimated using existing NFI datasets, thereby ensuring their compatibility with available data sources (Saint-André and Hervé 2015). After a comprehensive literature review, we selected 18 indicators that were then used to estimate B-N-OG indexes using raw data from 6563 plots visited in the field in the framework of the 2005 Italian NFI (Gasparini and Tabacchi 2011). To evaluate the potential usefulness of these indicators, we estimated pairwise correlations among them and the three aggregated B-N-OG indexes, their spatial distribution and relationships between the indicators and the indexes separately for protected areas and individual forest type categories. Finally, we used the results of our analysis to propose integration of new NFI variables to facilitate and optimize B-N-OG assessments.

Materials

Study area

Our study is conducted over the entirety of Italy which is divided into 20 Administrative Regions and 107 provinces. Forests in Italy cover nearly 11 million ha—more than one-third of the total Italian territory (INFC 2007a, b)—and are mainly found in mountainous, hilly and interior regions. Italian forests are composed mostly of deciduous species (68%), mainly oaks (*Quercus. cerris* L., *Q. pubescens* W., *Q. ilex* L., *Q. petraea* (M.) L., *Q. robur* L.), European beech (*Fagus sylvatica* L.) and chestnut (*Castanea sativa* M.). While dominant conifers are Norway spruce (*Picea abies* K.) and pines, the latter are mostly located in mountainous (e.g., *Pinus sylvestris* L. and *P. nigra* A.) and coastal areas (e.g., *P. pinea* L., *P. pinaster* A. and *P. halepensis* Mill.). Overall, due to its latitudinal and altitudinal variability, Italy is a very biodiverse country, hosting half of the European forest types (Barbati et al. 2014).

Italian national forest inventory

The Italian NFI was designed to satisfy the reporting requirements set by the United Nations Framework Convention on Climate Change. NFI estimates play a crucial role in various national and international reporting processes, including Italy's national forest report, Kyoto Protocol, national natural capital report, European report on sustainable forest management and the FAO's global Forest Resource Assessment. The 2005 Italian NFI has three phases and is based on an unaligned systematic sampling design (Fattorini et al. 2006) featuring a field plot randomly located in each cell of a 1 km × 1 km systematic grid (INFC 2007a, b). In the first phase, 301,000 sample points are photo-interpreted to identify their land use/land cover classes consistent with the first level of the CORINE Land Cover nomenclature system (Bossard et al. 2000) and with the FAO forest definition (Gasparini and Tabacchi 2011; FAO 2020). In the second phase, a subsample of approximately 30,000 forest and other wooded land sample points was selected from the first-phase set and visited in the field to assess forest categories and other qualitative information. Lastly, a third-phase sample of approximately 7,000 sample points was selected from among the 30,000 second-phase points. These points became the centers of 13-m radius NFI plots that were visited in the field to acquire quantitative data. The resulting database was used with statistically rigorous, unbiased design-based estimators to produce official estimates at both regional and national levels for approximately 50 qualitative and quantitative forest variables, mainly developed to estimate wood resources and the amount of carbon stocked and removed from the atmosphere.

In this study we used the data collected in the field during the third phase of the 2005 NFI cycle. After removing data for inaccessible plots and plots in temporarily unstocked areas, data for 6563 plots classified into 20 forest categories remained (Fig. 1). In Appendix, section A, Table 2 we report and explain the available raw 2005 Italian NFI data that we used.

Copernicus high-resolution layers: imperviousness degree

To assess forest naturalness, along with other single-variable indicators, we used an indicator of hemeroby that is based on the geographical distance of an NFI plot from the nearest impervious map unit as mapped by Sentinel-2 imagery in the Copernicus High-Resolution Layer, denoted as Imperviousness Degree (HRL IMD) for the year 2006 (Congedo et al. 2016; European Environment Agency 2018), (https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness, last accessed on September 13, 2022). The HRL IMD consists of a 20-m resolution pan-European raster layer produced using a semi-automated classification, based on calibrated NDVI (Kuc and Chormański 2019). The environmental indicator mapped by HRL IMD is defined as "human-produced surfaces that are essentially impenetrable by rainfall" (Moglen and Kim 2007; Strand 2022). The HRL IMD map was reclassified into a Boolean impervious/non-impervious mask, and the distance from the nearest impervious map unit was calculated for each NFI plot.

Italian network of protected areas

To study the potential relationship between the selected B-N-OG indexes and ecological and management conditions, we included the Italian protected areas in our analysis. We considered both the official dataset of protected areas from the Italian Ministry of Environment (EUAP—*Elenco Ufficiale delle Aree Protette*) and the Natura 2000 network.

The EUAP includes 24 National Parks, 144 State Natural Reserves, 134 Regional National Parks, 365 Regional Natural Reserves and 171 Other National Protected Areas (Fig. 2, *panel a*) for a total of 2,878,963 ha, in total approximately 11% of national territory (Boitani et al. 2003). The Natura 2000 consists of 2,314 sites (Fig. 2, *panel b*) established based on the "Habitats" and "Birds" European Directives (Council Directive 92/43/EEC and Directive 2009/147/EC, respectively), covering 5,844,915 ha, or approximately 19% of the national territory (Ministry of Environment and Energy Security 2022).

The two networks have substantial overlap. Almost 40% of the protected areas were included in both the EUAP and Natura 2000 areas. For this reason, we considered only the classification protected versus non-protected areas, independently of whether a plot was in EUAP or in Natura2000 area. Of the 6,563 NFI plots, 67% were outside protected areas, while the remaining 33% were included in EUAP or Natura 2000 areas.

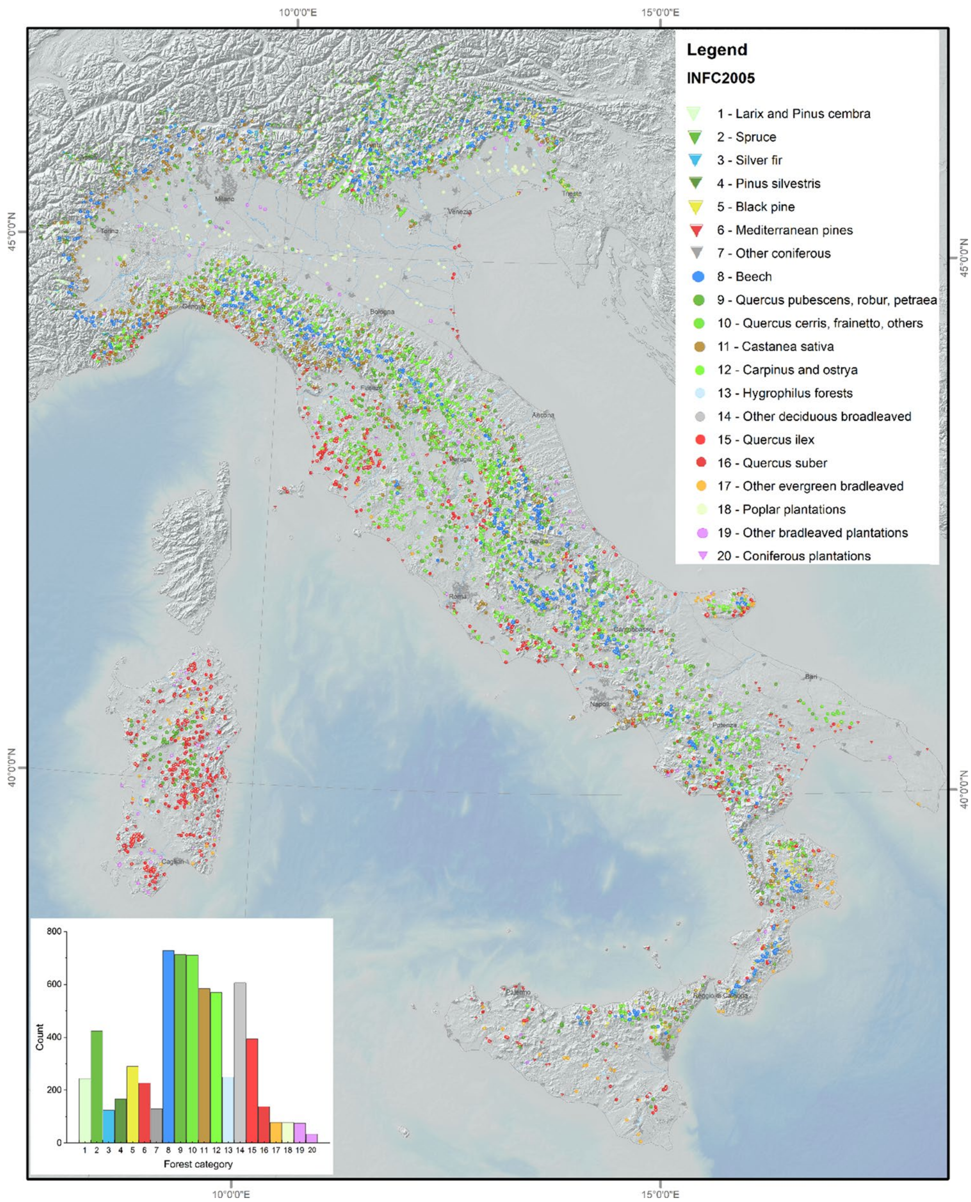


Fig. 1 Spatial distribution and relative frequency of Italian NFI (INFC 2007a, b) forest type categories

Methods

Based on a comprehensive literature search of scientific publications and reports, we defined 18 indicators (Sect. "Plot-level indicators used to assess B-N-OG"), each of which was further classified as relevant or not relevant for the three biodiversity indexes, B, N and OG. The indicators were then calculated for each of the 6,563 NFI plots (Sect. "Statistical analysis"). To facilitate aggregation for estimating the indexes, we normalized the indicators to the range 0–1 by applying a min–max normalization, the same approach used by Storch et al. (2018). The three B-N-OG aggregated indexes were then estimated for each plot as the average of the selected indicators.

Finally, the resulting database was analyzed to investigate multiple relationships: i) pairwise correlations among the different indicators, ii) spatial distributions to highlight geographical trends, iii) distributions for individual forest type categories and management types to better understand different levels of forest biodiversity, naturalness and old-growth status in distinct ecosystems and iv) the effects of the network of protected areas.

Plot-level indicators used to assess B-N-OG

In the following sections we describe the indicators selected and their relevance for B-N-OG assessment. We classified the indicators into five categories: (i) composition, (ii)

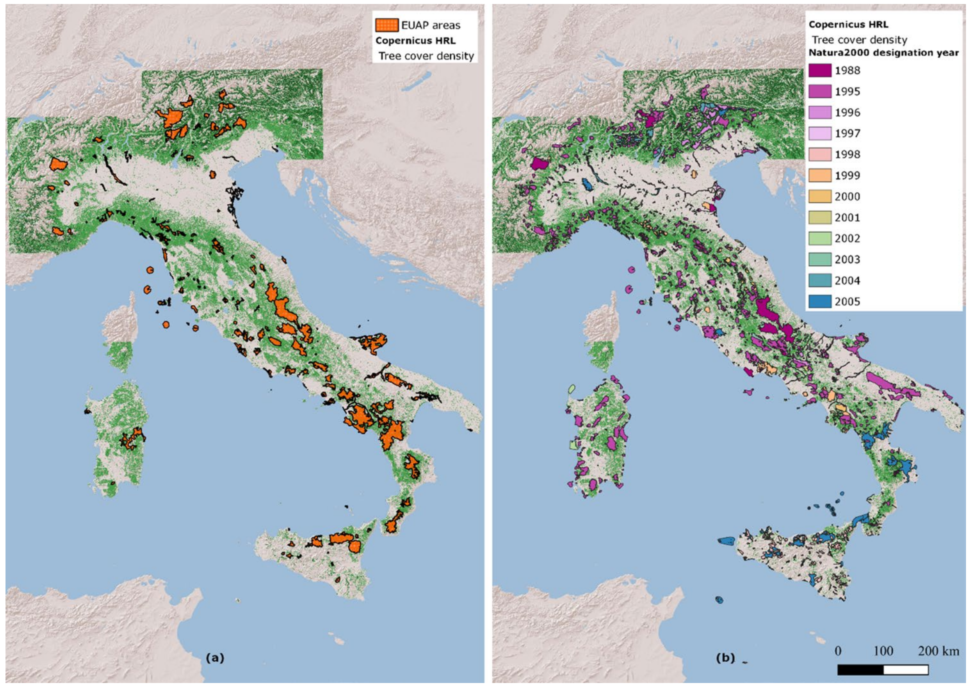


Fig. 2 Italian network of protected areas. Panel a (left) reports the Italian protected areas according to the EUAP; on panel b (right) different colors represent the Natura 2000 network in relation to the year of institution. On the background, the Copernicus High-Resolution Layer "Tree cover density" (ESA, 2018)

structure, (iii) regeneration, (iv) deadwood and (v) hemeroby (Table 1).

(i) Composition

First, we calculated the number of tree species, a very straightforward and frequently used indicator of biodiversity (Van Den Meersschaut and Vandekerkhove 2000; Sullivan et al. 2001; Crist et al. 2003).

The distribution of tree species was then characterized using the Shannon and the Evenness indexes; both calculated based on the basal area. The Shannon index, commonly used in ecological studies, served as a direct measure of compositional diversity (Varga et al. 2005; Lexerød and Eid 2006; Ozdemir et al. 2008; Arekhi et al. 2017). The Evenness index, which describes the strength of interactions within communities and functional trait diversity, was calculated as the ratio of the observed Evenness index to its maximum value with the same number of species (Pielou 1969).

(ii) Structure

For structural diversity we first considered growing stock volume (GSV) as reported by the NFI (Tabacchi et al., 2011). Then we considered the variability of tree height as estimated by the standard deviation of height as a measure of vertical forest layering (Zenner 2000). In addition, Stand Density Index (SDI) (Reineke 1933) was used to describe the density of living trees on each NFI plot. SDI is characterized in terms of quadratic mean diameter and number of trees per hectare by calculating the number of stems per hectare in these stands related to 25 cm mean diameter. SDI is independent of site conditions and tree age (Zeide 2005), the latter not commonly recorded during NFI field measurements.

The presence of large trees is often considered a relevant indicator for B-N-OG assessment (Basile et al. 2020; Asbeck et al. 2022; Marziliano et al. 2021; Larrieu et al. 2021, 2022; Santopuoli et al. 2022). Tree dimensions can be considered a proxy for the age of the trees, and the presence of old trees is a direct measure of OG. Large trees are also more frequently habitat trees, and the tree-related microhabitats they host are of primary concern for forest biodiversity because they can harbor many endangered specialized species of flora and fauna. To estimate tree size, we considered both maximum tree height and maximum DBH for all living trees. We also considered a frequency index at the plot level which determines the occurrence of living trees with DBH≥40 cm. While the threshold for identifying large trees could be differ by country (Gilhen-Baker et al. 2022), the Italian Environment Ministry proposed a 40-cm threshold for living trees in the Mediterranean area; we used this threshold for current study (Blasi et al. 2010).

Lastly, the Gini coefficient, widely used in forestry, was used to analyze diversity in the distribution of tree sizes (Valbuena et al. 2016; Meyer et al. 2021; Motta et al. 2022; Hirschmugl et al. 2023)

(iii) Forest regeneration

Forest regeneration has been recognized as an indicator of forest biodiversity within the guidelines of sustainable forestry issued through the Ministerial Conferences on the Protection of Forests in Europe and the Montréal Process (Ministerial Conference on the Protection of Forests in Europe 2007; Montréal Process 2009). For this study, regeneration was estimated using three indicators based on the methods and definitions used in the Italian NFI. The first indicator of

Table 1 Single-variable indicators and how they were combined to create biodiversity, naturalness and old-growth status (B-N-OG indexes), with main references

Indicator (abbreviation)	Component	B-N-OG relevance	Main references
Growing Stock Volume (GSV)	Structure	B-OG	Chirici et al. (2012) Liang et al. (2016)
Variability of tree height (v_H)		B	Zenner (2000) Heym et al. (2021)
Stand Density Index (SDI)		B	Reineke (1933)
Max DBH (max_DBH)		B-OG	Ziegler (2000) McElhinny et al. (2005)
Max height (max_H)		B-OG	Spies (1998) McElhinny et al. (2005)
Large living trees (L_trees)		B-OG	Blasi et al. (2010) Ćosović et al. (2020)
Gini coefficient (GINI)		B	Cordonnier and Kunstler (2015) Valbuena et al. (2016)
Number of species (n_SP)	Composition	B	Crist et al. (2003) Zhang et al. (2012)
Shannon index (S)		B	Shannon (1948)
Evenness (E)		B	Hill (1973) Stirling and Wilsey (2001)
Deadwood volume (DWD)	Deadwood	B-N-OG	Chirici et al. (2012)
Dead-to-living volume ratio (DLR)		B-N-OG	Hahn and Christensen (2005) Wirth et al. (2009a, b)
Stump decay class ratio (DWD_stump_ratio)		B-OG	Bertini et al. (2010), Badalamenti and Cairone (2017) Parisi et al. (2020a, b)
Standing dead trees decay class ratio (DWD_stand_ratio)		B-OG	Vuidot et al. (2011) Parisi et al. (2016, 2019)
Regeneration class I (REG_1)	Regeneration	B	Chirici et al. (2012)
Regeneration class II (REG_2)		B	
Regeneration class III (REG_3)		B	
Distance from anthropogenic disturbance (HEM)	Hemeroby	N	Jalas (1955) Winter et al. (2010) McRoberts et al. (2012)

regeneration refers to the number of small trees with heights between 50 and 130 cm; the second indicator is for small trees taller than 130 cm but with maximum DBH of 2.4 cm, and finally the third indicator was similar to the second but with a maximum DBH of 4.4 cm.

(iv) Deadwood

The amount of deadwood volume plays a crucial role for assessing B-N-OG because it influences the presence of bryophytes, lichens and saproxylic beetles and is also used for assessing N and OG (DeWalt et al. 2003; Lassauce et al. 2011; Parisi et al. 2016, 2019, 2020a; Czerepko et al. 2021). In this study we also considered the ratio of dead-to-living biomass because it contributes to understanding ecosystem dynamics (Olson 1963; Harmon et al. 2001; Hahn and Christensen 2005; Wirth et al. 2009a, b). The assessment of deadwood volume includes use of a classification into five classes (Maser et al. 1979) that offer valuable information for assessing the development stage of forest stands (Bertini et al. 2010; Parisi et al. 2019, 2020a). In addition, it is associated with the presence of diverse organisms that utilize trees at different decay stages (Franklin 1981; Gibbons and Lindenmayer 2002; DeWalt et al. 2003; Vuidot et al. 2011), because it is useful for assessing the impact of deadwood on soil carbon storage (Błońska et al. 2023). For these reasons, we included two indicators, one for stumps and one for standing dead trees, each calculated as a ratio between the volume in more decayed classes divided by the volume in the less decayed classes.

(v) Hemeroby

Hemeroby can be considered as the opposite of naturalness and is used to measure the impact of humans on the ecosystems (Chirici et al. 2012). As an indicator of hemeroby for this study, we calculated the distance of each NFI plot from the nearest impervious map unit (urban areas, artificial surfaces) as mapped by the European Earth Observation Copernicus program. Firstly, we constructed a Boolean impervious/non-impervious map reclassifying the Copernicus High-Resolution Layer—Imperviousness Density map (European Environment Agency 2018) for the year 2006 at 20 m resolution. Then, we constructed a map of the distance from the artificial surface class of the Boolean map using a maximum distance of 10 km and extracted a distance for each NFI plot. The values of the indicator were standardized on the basis of a threshold of 10 km.

Statistical analysis

The values of the 18 standardized indicators were estimated for each of the 6,535 NFI plots and then averaged at national, provincial and regional levels, as well as for protected areas and for each of the 20 forest type categories outlined in the Italian NFI. The distribution of the 18 selected indicators is reported in Fig. 3.

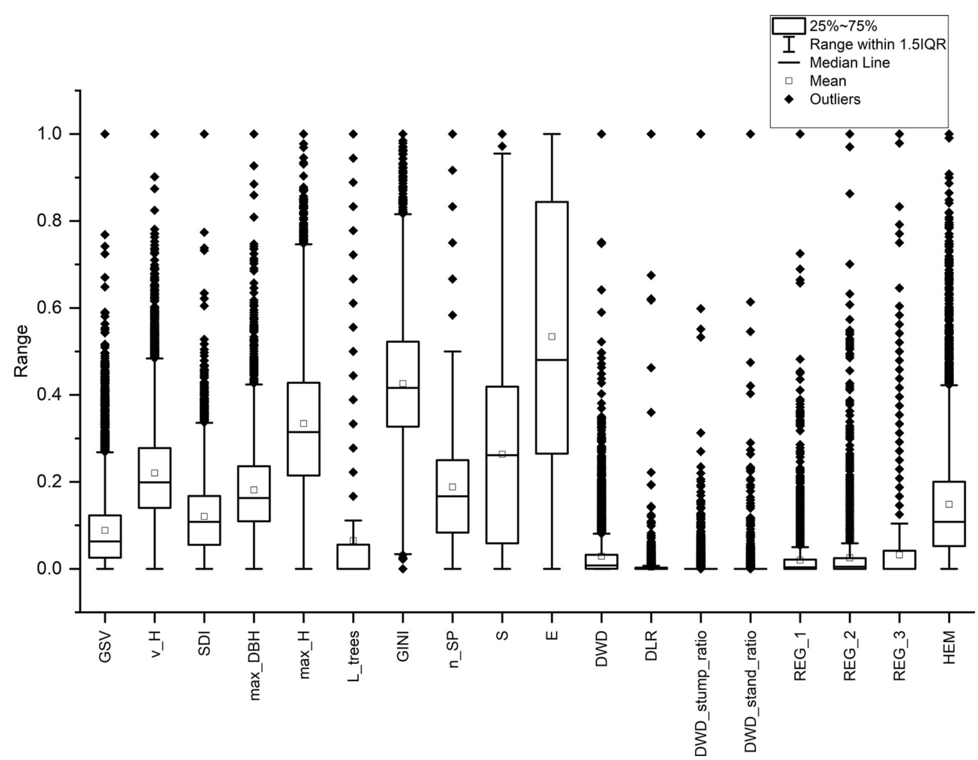
The indicators were averaged for the five categories (composition, structure, regeneration, deadwood, hemeroby) and on the basis of the three B-N-OG indexes.

Multiple statistical analyses were conducted using the database. First, we estimated correlations for all pairs of the 18 indicators from Table 1 (Wei et al. 2017). Second, we conducted a principal component analysis (PCA), a multivariate technique that reduces the data's dimensionality while preserving their covariances. When applied to our data (18 indicators for 6535 observations), PCA finds the eigenvalues and eigenvectors of the covariance matrix of each indicator. The purpose of the PCA was to better understand the relationships among the indicators.

Combining the correlation analysis and the PCA, we estimated the pairwise correlations between the indicators to assess their interrelationships (highlighting overlaps and gaps) and to ensure a rigorous quantitative approach for analyzing their redundancy when the indicators are aggregated to estimate the B-N-OG indexes. The pairwise correlations (r) among B-N-OG indexes were then analyzed using the Pearson correlation method. Analyzing the correlation between B-N-OG indexes serves the purpose of understanding underlying ecological processes and dynamics within forest ecosystems. For instance, positive correlations between B-N-OG may suggest shared ecological traits or processes that led the indexes to increase, while negative correlations may indicate trade-offs between indexes. The same approach was also used to analyze the relationships between the five different categories (composition, structure, regeneration, deadwood and hemeroby).

Finally, a one-way analysis of variance (ANOVA) was conducted to analyze the relationship between B-N-OG

Fig. 3 Distribution of the 18 selected indicators



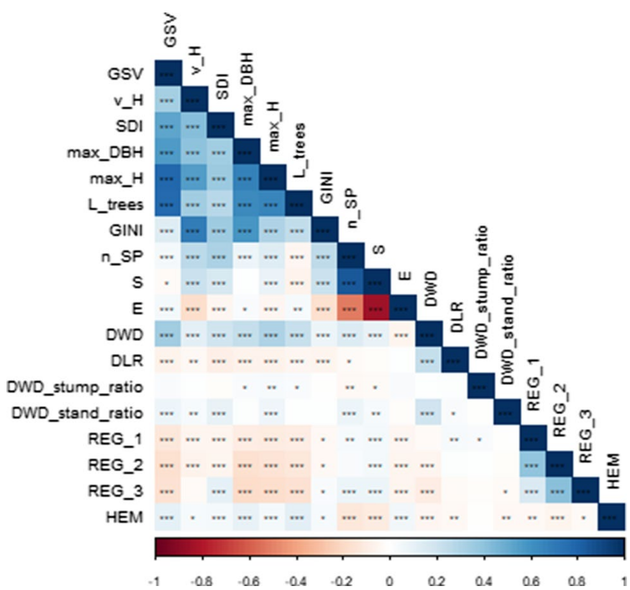


Fig. 4 Correlation matrix among Italian NFI's derived indicators. Statistically insignificant correlations ($p < 0.01$) are left blank

indexes and the classes of specific variables available in external datasets. Specifically, the one-way ANOVA was used to assess statistically significant differences among the means of B-N-OG indexes (i) between areas inside and outside the boundaries of protected areas (considering both EUAP and Natura 2000 networks) and (ii) between different forest type categories. To better understand the relationships between the three aggregated B-N-OG indexes and the forest type categories we performed a ranking analysis. All the analyses were performed using R software (Chambers 2008; Wei et al. 2017).

Results

Analysis of single-variable indicators

The pairwise correlations between the 18 indicators are presented in Fig. 4, while the results of the PCA are shown in Fig. 5. Further details are available in Appendix, section A, Table 3 and 4.

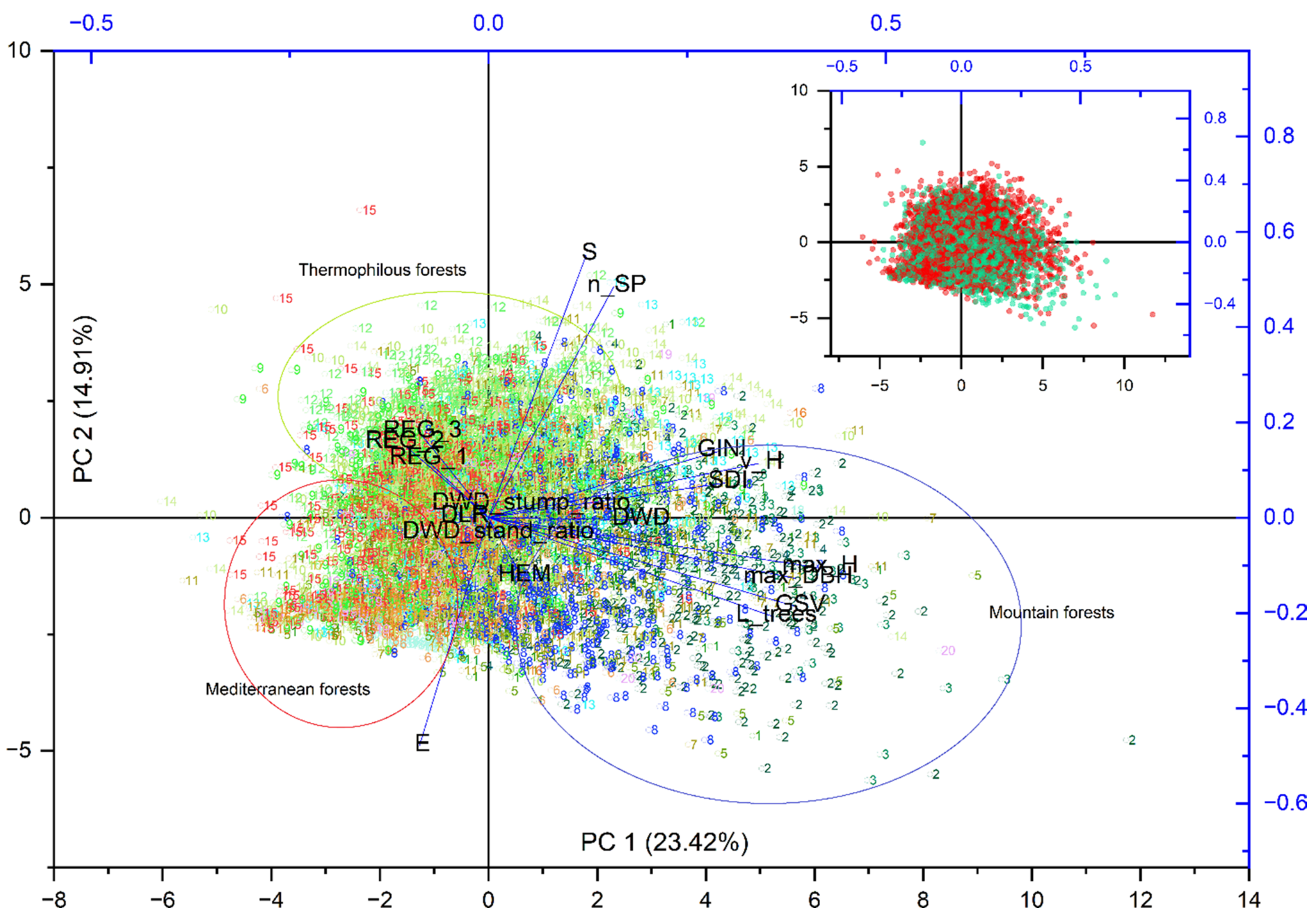


Fig. 5 Results of the PCA showing the first two components. The plots in the main graph are colored based on the 20 forest categories (same colors and codes of the map in Fig. 1). In the smaller graph the same plot is instead colored on the basis of the belonging to a protected area (green) or not (red). (Color figure online)

For a large proportion of the cases, the relationships between the indicators were statistically meaningful even though the correlations were quite variable. Considered in terms of absolute values, the max_H, GSV and the L_trees had the largest average correlations, $r=0.27$ and $r=0.23$, respectively. The PCA confirmed the same results with GSV, v_H, SDI, max_DBH and max_H having the largest eigenvalues with the first two principal components together explaining only the 38% of the total variability.

On the opposite side, HEM (as the distance from artificial surfaces) was less correlated with the other indicators (average $r=0.06$), with greatest (positive) correlation with the GSV. Small correlations were also found for the three regeneration indicators with average r ranging between 0.08 and 0.1. Once again, PCA confirmed these results with HEM, REG_1, REG_2 and REG_3 having the smallest eigenvalues.

The largest correlation was between GSV and max_H ($r=0.79$) and max_DBH ($r=0.77$).

In general, the average agreement between the seven indicators belonging to the “structure” category is large ($r=0.48$) and always positive. The relationship between the three indicators belonging to the “composition” category is even greater in absolute values (0.74) because the relationships between E and the other two indicators, n_SP and S, were $r=-0.52$ and $r=-0.85$, respectively. A different behavior is shown by the deadwood category indicators with only small agreement among them with average absolute value of only $r=0.08$. The main indicator of this category (DWD) is positively related to GSV ($r=0.35$), and consequently also with the max_H ($r=0.31$) and max_DBH ($r=0.24$), as well as with L_trees (r = 0.22) and SDI ($r=0.19$). The average correlation for the three regeneration category indicators is always positive ($r=0.32$), although correlations with indicators external to this category were small. Correlations between GSV and the B-N-OG indexes were small, ranging from $r=0.12$ to $r=0.16$. Finally, HEM had only small correlations with all the other indicators with the greatest values for GSV ($r=0.10$) and n_SP ($r=-0.125$). The correlations and the statistical significances among indexes for the five categories is reported in Fig. 6. More details are available in Appendix, section A, Table 5 and 6.

The results confirm a positive and consistent agreement of structure with deadwood and composition ($r=0.2$ and $r=0.14$, respectively), while the relationship between composition and deadwood is weaker ($r=0.1$). Regeneration has weak negative relationships with structure and deadwood and no meaningful relationship with composition. Finally, hemeroby shows a weak positive relationship with structure, and negative relationship with the other categories of indicators.

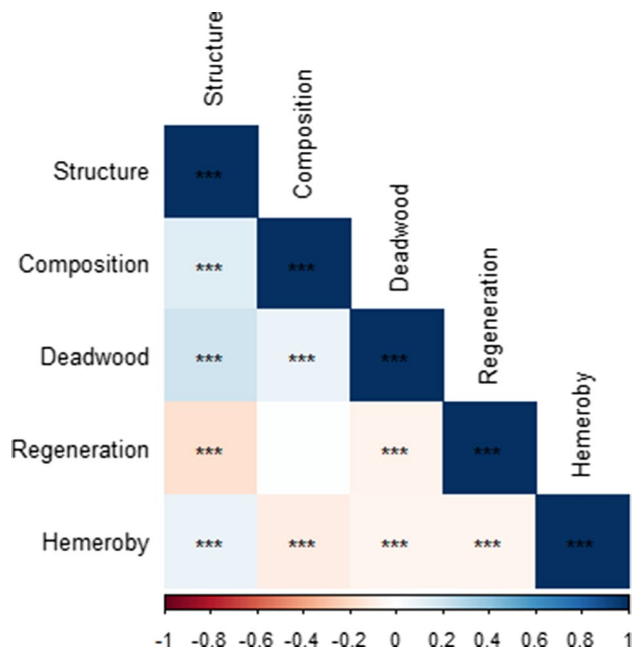


Fig. 6 Correlations and statistical significances among B-N-OG indexes components. Statistically insignificant correlations ($p<0.01$) are left blank

Analysis of aggregated B-N-OG indexes

Following are the results of aggregating the indicators to estimate the indexes. Plot-level B estimates ranged between 0.031 and 0.357 with mean of 0.149 and standard deviation (sd) of 0.042; N estimates ranged between 0 and 0.435 with mean of 0.060 and sd of 0.048, while OG estimates ranged between 0 and 0.441 with mean of 0.088 and sd of 0.054) (Fig. 7). More details on B-N-OG estimates at plot-level are available in Appendix, section B.

The correlations between the three aggregated B-N-OG indicators are also reported in Fig. 7. The data demonstrated a stronger relationship between plot-level B and OG ($r=0.81$), than between B and N ($r=0.15$) or between N and OG ($r=0.25$).

Mean estimates of the three aggregated B-N-OG indexes demonstrated relevant diversity across Italy. Greatest B and OG means were in the northern regions, i.e., Trentino Alto Adige, Veneto and Friuli Venezia Giulia (B 0.178, 0.169, 0.166 and OG 0.140, 0.110, 0.109, respectively) (Fig. 8). On the other hand, the southern regions, such as Calabria, Puglia and Sicilia, had the greatest N mean estimates (i.e., 0.089, 0.084 and 0.082, respectively).

Further detail of B-N-OG at national and regional levels is available in Appendix, section B.

Figure 9 shows the relationships between regional forest area—as reported in official NFI statistics for 2005 (INFC 2007a, b)—and the relative mean B-N-OG estimates.

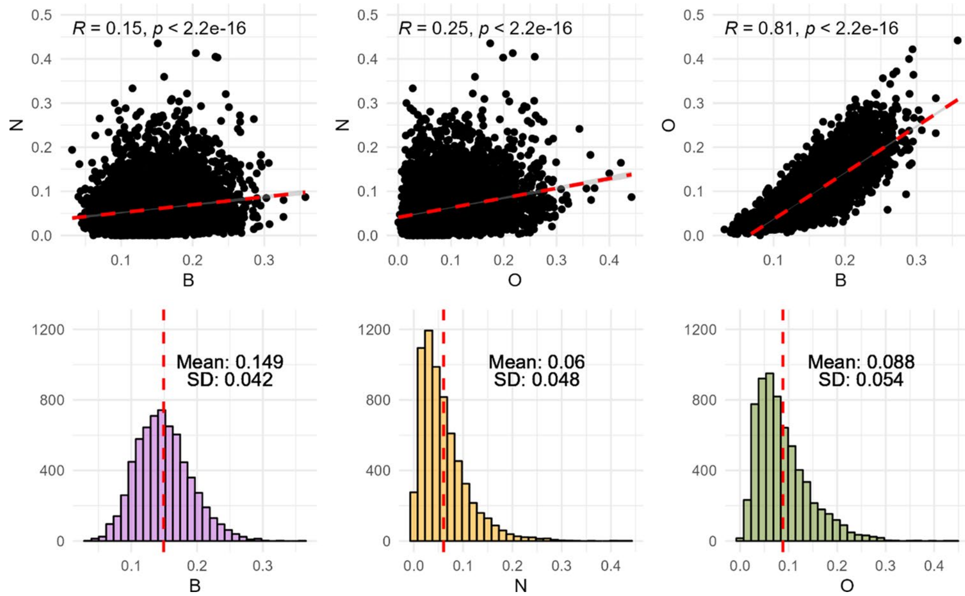


Fig. 7 Histogram distributions and correlations between the biodiversity, naturalness and old-growth status (B-N-OG) indexes

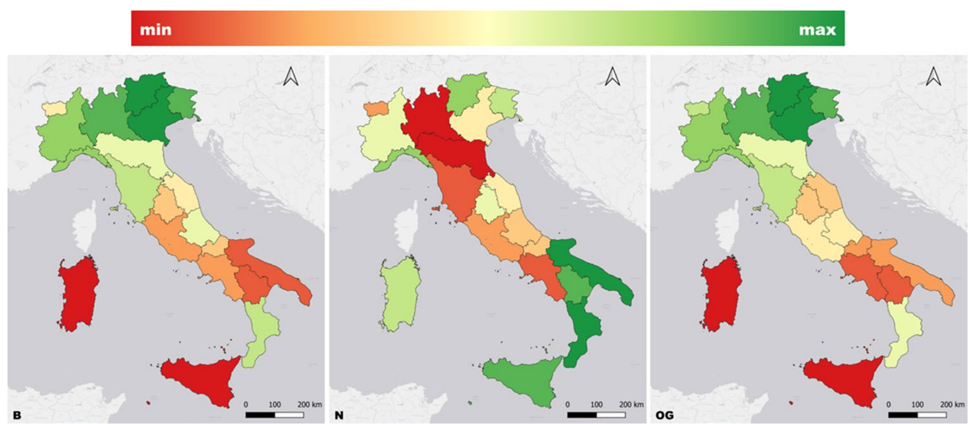


Fig. 8 Regional, NFI plot-level means for biodiversity, naturalness and old-growth status (B-N-OG) indexes

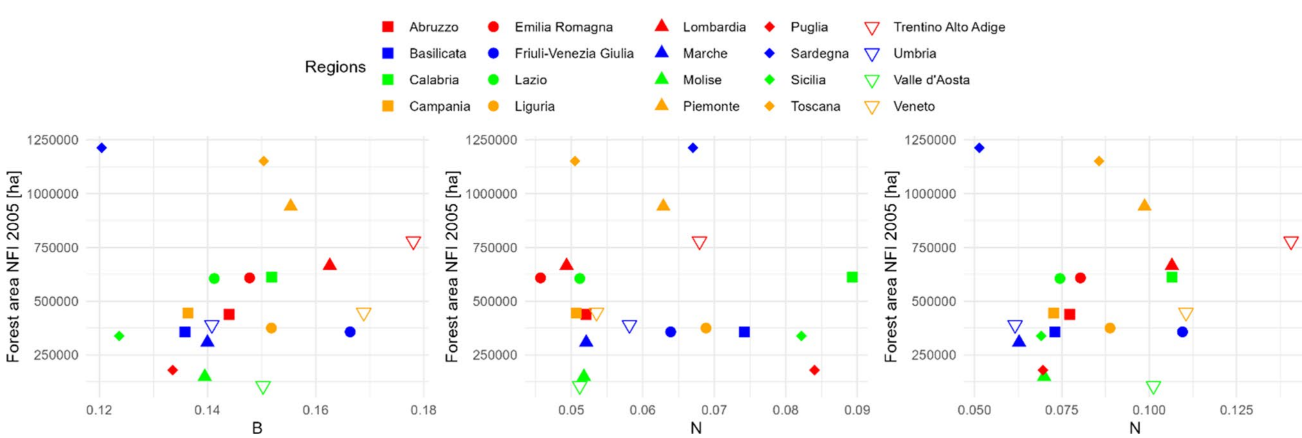


Fig. 9 B-N-OG mean estimates in Italian regions and forest area (INFC 2007a)

As reported in Fig. 10, the greatest estimates of the mean for the three indexes were for the mountainous coniferous forest type categories (dominated by fir, spruce, stone pine and larch), while the smallest mean estimates were for broadleaved artificial plantations including poplar plantations, especially regarding N.

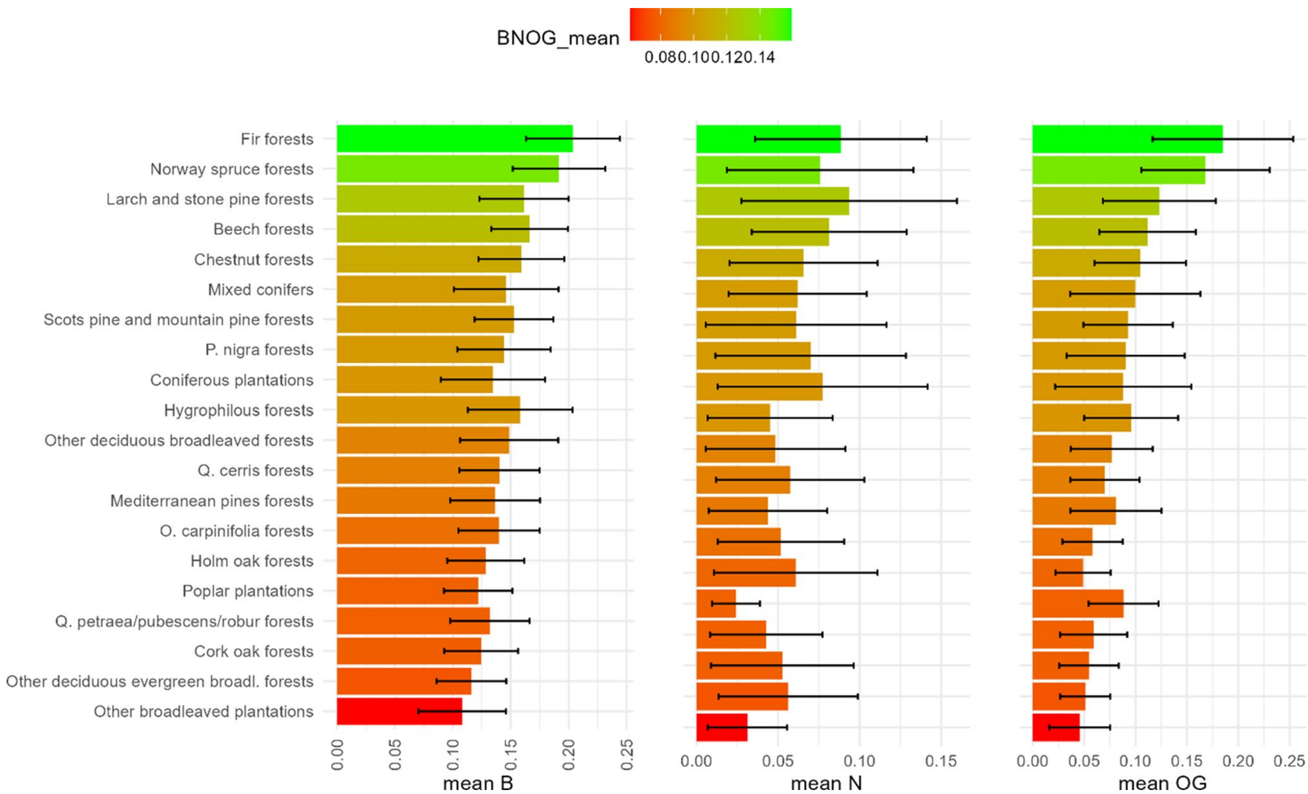


Fig. 10 Biodiversity, naturalness and old-growth status (B-N-OG) mean estimates (with standard deviation bars) over plots in the Italian NFI plots among the 20 Italian NFI forest categories. The Italian NFI forest categories are sorted by the overall B-N-OG mean, in descending order

The ANOVA suggested that the main effect of species groups, conifers or broadleaves, on B-N-OG means was statistically significant ($p < 0.001$). Further information on ANOVA results is reported in Appendix, section D.

After ranking the forest type categories on the basis of the mean estimates of the three indexes, we found a strong relationship not just between B and OG ($r = 0.929$) but also between N and B ($r = 0.693$) and N and OG ($r = 0.665$). The greatest rank order was always obtained for beech, fir, spruce and larch forests (Fig. 11).

Relationship with protected areas

More than one-third of the plots are located inside protected areas (2154 plots, 32.8% of the total). Specifically, the Natura 2000 network comprises 1924 plots, while EUAP comprises 1062 plots with 832 plots located in both

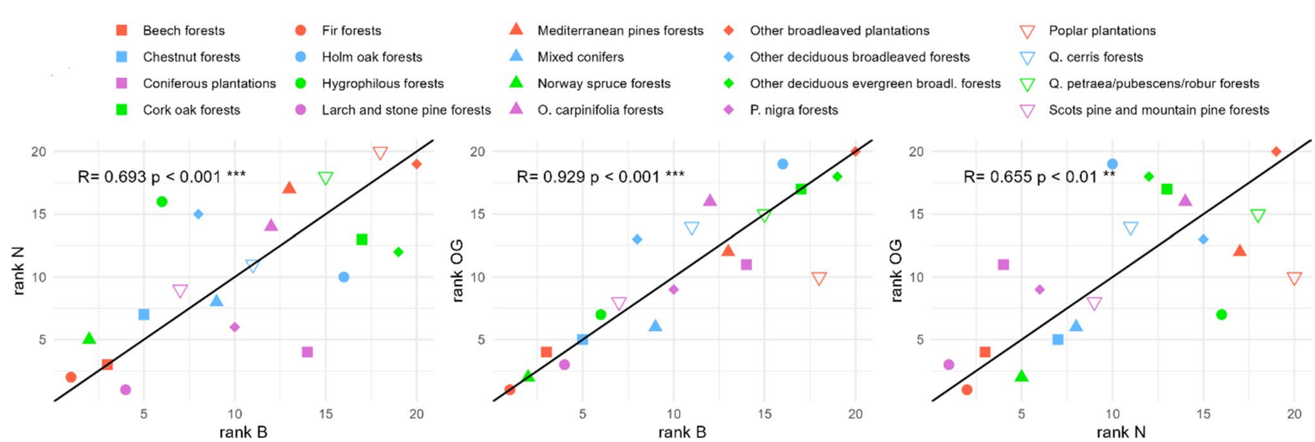


Fig. 11 B-N-OG pairwise ranking in forest categories

EUAP and Natura 2000 protected areas. Considering that each Natura 2000 site could host more than one habitat, most NFI plots were located in habitats “Quercus ilex and Quercus rotundifolia forests” (9340) and "Apennine beech forests with Taxus and Ilex" (type 9210) with 925 and 830 plots, respectively (Biondi et al. 2010; Commissione Europea 2013). Further information and habitat descriptions are available in Appendix, section C.

Mean B estimates for inside and outside protected areas were not statistically significantly different ($p=0.483$). On the other hand, the differences between mean N and OG inside and outside EUAP protected areas were statistically significant ($p<0.001$ and $p=0.005$, respectively). Hence, mean N and OG over plots inside protected areas were larger than outside protected areas (N 0.077 vs. 0.052, OG 0.091 vs. 0.087).

Figure 12 shows the distribution of B, N and OG inside (blue) and outside (red) protected areas.

Among Natura 2000 habitat macroclasses (Biondi et al. 2010), temperate mountains coniferous forests registered the greatest B-N-OG estimates (0.170, 0.101, and 0.132, respectively), while deciduous Mediterranean forests and sclerophyllous Mediterranean forests registered the smallest estimates for all the three indexes (Fig. 13). Moreover, mean B estimates for inside and outside protected areas were not statistically different ($p=0.280$). Conversely, the differences between mean N estimates and between mean OG estimates inside and outside protected areas were statistically significant ($p<0.001$ and $p=0.006$, respectively).

Discussion

Threats to forest habitats are likely to increase, mostly due to human-related activities such as climate change, urbanization and habitat loss and degradation (Seto et al. 2012; Aronson et al. 2014; Curtis et al. 2018; Kondratyeva et al. 2020). In this scenario, multiple international processes (Montréal Process 2009; Maes et al. 2018; Convention on Biological Diversity 2019; Forest Europe 2020; FISE 2021) require consistent tools to assess and report on B-N-OG.

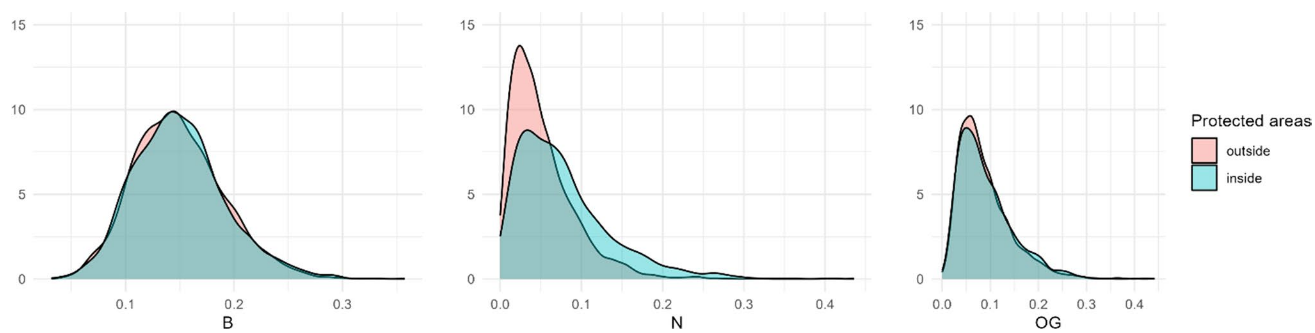


Fig.12 Biodiversity, naturalness and old-growth status (B-N-OG) distribution inside and outside protected area

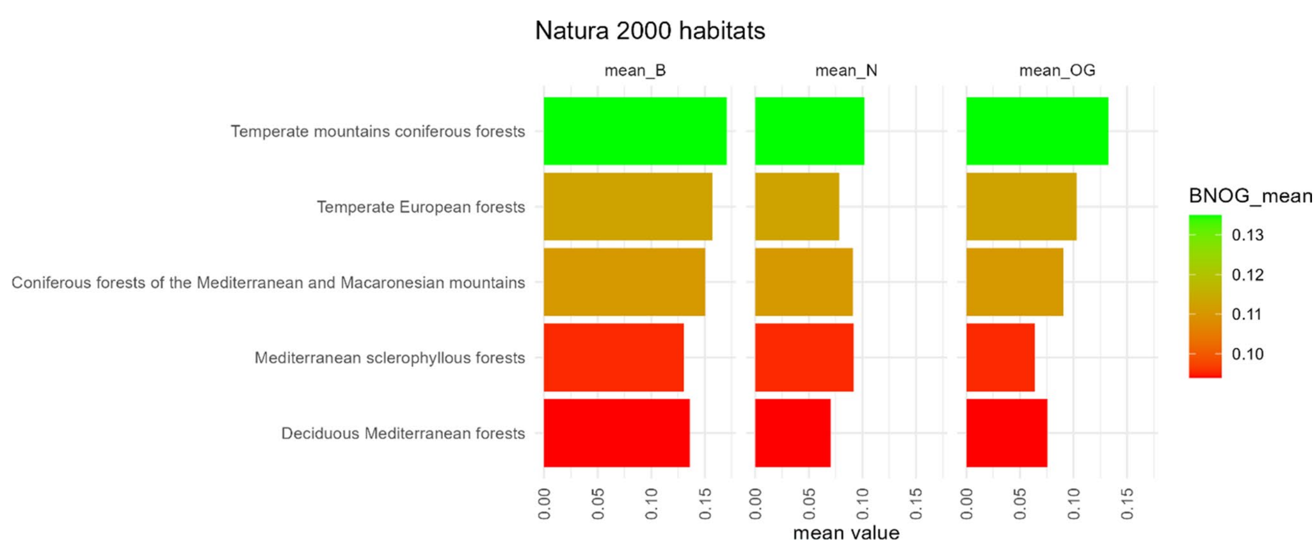


Fig. 13 Biodiversity, naturalness and old-growth status (B-N-OG) mean estimates over plots, per ‘Natura 2000 habitats’ macroclasses. The classes are sorted by the overall B-N-OG mean per habitat, in descending order

These requirements could be fulfilled by implementation of a sound, multipurpose, forest monitoring system based on data acquired from multiple sources (Chirici et al. 2011, 2012; Rondeux et al. 2012; Reise et al. 2019). In such a context, a relevant question is whether data routinely acquired by NFIs can contribute to such monitoring systems. For this study, we tested a set of indicators for assessing forest B-N-OG indexes using data acquired by the Italian 2005 NFI.

Single-variable indicators

When analyzed in terms of single-variable indicators, on the basis of both PCA and correlation analysis, our results confirm the relevance of the GSV variable but at a greater level than previous studies such as Storch et al. (2018). GSV is, in fact, strongly correlated with both the B index ($r=0.68$) and the OG index ($r=0.88$). This is easily explicable from an ecological perspective view, at least in forest conditions typical of Italy where the accumulation of GSV is typical of less disturbed forest ecosystems that can accumulate a greater level of biodiversity and can evolve to conditions that have greater OG. This is confirmed by the finding that forest type categories with greater estimates of the aggregated B-N-OG indexes (beech, spruce, silver fir, larch and stone pine forests) are those dominating mountain areas in Italy. These areas are less disturbed by forest logging and by fires, while deciduous broadleaved forests dominated by oaks (mainly *Q. cerris* and *Q. pubescens*) together with Mediterranean forests are more disturbed by forest loggings of the coppice system and by fires.

Further, deadwood volume showed a strong, positive correlation with the presence of large trees, GSV and structural indicators in general. While data on deadwood are extremely relevant for assessing B-N-OG indexes from an ecological perspective, the Italian dataset was strongly characterized by the dominance of forests with very small deadwood values (Fig. 3). For this reason, more advanced indicators based on the analysis of just one component of deadwood volume were only weakly related to the overall aggregated indexes. Because we cannot generalize these results, these indicators should be reconsidered when analyzing regions characterized by greater values of deadwood volume.

Results for regeneration are similar to the results for deadwood, because only very limited regeneration was found for the plots (Fig. 3). Nevertheless, these indicators showed a general negative correlation with structure indicators—especially GSV, max DBH and height, and the presence of large trees—suggesting that greater forest structures could hinder certain stages of regeneration (class III, above all).

As expected, forest structure (i.e., variability of tree height and Gini coefficient) and composition indicators (i.e., Evenness) showed an overall negative pattern of correlation, apart from the number of species which was positively correlated with SDI and variability of tree height.

As underlined in several other studies (Chirici et al. 2011; Galluzzi et al. 2019), the composition indicators estimated using NFI data consider only tree species, a very small component of the overall α-biodiversity. Therefore, the results of this study should be interpreted with caution.

Additionally, the hemeroby indicator (i.e., calculated on the basis of the distance from anthropic disturbance) displayed small correlations with other indicators. Nevertheless, the correlations are still meaningful; for example, GSV is greater when the distance from urban areas increases because such areas are probably more difficult to access and thus less easily exploitable for forest operations.

Importantly, when we analyzed the PCA results (Fig. 5), we found an interesting possibility for clustering into subpopulations among plots on the basis of their forest type categories. A comprehensive quantitative cluster analysis is beyond the scopes of this study, but we tried to characterize the subpopulations using three ellipses in Fig. 5 that we labeled on the basis of the European forest type categories from Barbati et al. (2014). Mountain forests are thus dominated by Alpine and Appennine forests with beech, spruce, silver fir and larch, Mediterranean forests are those with holm and cork oaks together with Mediterranean pines, and finally thermophilus forests are instead dominated by deciduous broadleaved (mainly downy and Turkey oaks).

Aggregated B-N-OG indexes

When compared in an aggregated way, the B and OG indexes demonstrated strong correlation, while naturalness was mostly uncorrelated with either of them. This is, of course, easily explained because of the selection of the input indicators. However, when geographical regions and forest type categories are ranked based on the three indexes, interesting differences emerged between B and OG, too. The indexes have consistent estimates when compared across the different types of management types. High forests have the greatest estimates followed by uneven-aged systems then by even-aged forests and finally by coppice forests. An example for the B index is reported in Fig. 14.

From a geographical perspective, our results showed that the northern part of Italy, particularly Trentino Alto Adige, Veneto and Friuli Venezia Giulia, exhibited the greatest B-OG estimates, most probably for three reasons: (i) mountainous topography, (ii) dominant forest type categories with greater B-OG estimates and (iii) large amounts of deadwood and GSV (Giannetti et al. 2022; Vangi et al. 2021). Smaller levels of anthropogenic disturbance (Riitano et al. 2016), compared to northern regions, are related to the largest mean N estimates obtained in southern regions such as Calabria, Puglia and Sicilia. Forest fragments with large N estimates were mainly found in protected areas or remote mountainous regions which experienced fewer human disturbances

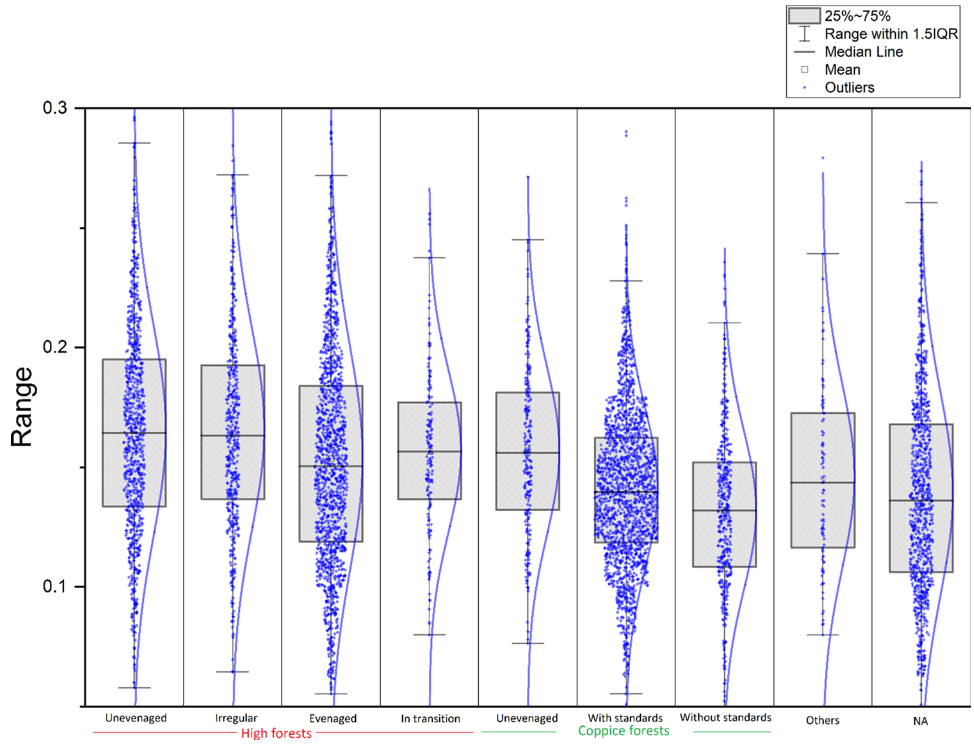


Fig. 14 Example of distribution of the biodiversity index in the different sylviculture systems

compared to forests nearby to population centers (e.g., Lombardi et al. 2012; Motta et al. 2006). Moreover, previous studies confirmed that habitat quality increases where human population become sparser (Newbold et al. 2015), such as from lowland to mountainous areas. The combined presence of protected areas in mountainous areas (Sallustio et al. 2015, 2017) and different forest management approaches used in the different forest type categories can indeed explain this trend in Italy.

It is interesting to note that despite artificial broadleaved plantations (including poplar) exhibiting the smallest B-N-OG estimates among forest type categories, artificial coniferous plantations displayed a different trend (Fig. 10). Indeed, several studies in Italy (De Meo et al. 2017b, a, 2022) demonstrated that artificial coniferous plantations could host large amounts of deadwood, compared to the average deadwood volume per hectare highlighted in the Italian NFI (Pignatti et al. 2009). Similarly, coniferous forests—particularly fir forests—exhibited some of the greatest mean estimates of B and OG. This finding aligns with previous research indicating that Alpine coniferous forests, including fir forests, have large volumes of deadwood compared to other European forest types (Barbati et al. 2014; Puletti et al. 2019). Here, the effects of windthrow events caused by climatic factors are compounded by limited harvesting in high-altitude forests or less accessible areas (Pignatti et al. 2009). Moreover, multiple studies conducted in Italy (Ciancio and Nocentini 2004; Travaglini et al. 2012; Parisi et al. 2016) highlighted the complexity of fir forests, emphasizing their potential to reach old-growth conditions, even when mixed with broadleaved species. Additionally, larch and stone pine forests recorded the largest N mean estimates over plots, closely followed by fir forests, perhaps given their capacity to reach the upper altitudinal limit of the forest (Didier 2001; Blasi C. and Biondi E. 2017). Notably, forests dominated by broadleaf species are predominantly managed using the coppice system (Fabbio 2016; Gasparini and Tabacchi 2011), such as deciduous oaks (*Quercus* spp., 33%), European hophornbeam (*Ostrya carpinifolia* Scop., 17%), beech (*Fagus sylvatica* L., 13%), sweet chestnut (*Castanea sativa Miller*, 16%), which are usually grown as pure stands, and the evergreen holly oak (*Quercus ilex* L., 10%) forests. This approach holds great significance in Italy, because coppices account for 35% of the overall forest area and are the main source of wood production (INFC 2007a). Thus, our results indicated that these forest type categories tend to have smaller B-N-OG estimates, most probably because of the strong negative impact of the coppice system and the easy accessibility.

These results can support future forest management strategies for coppice forests, used in Italy for fuel-wood and biomass production. Due to its consistent impact on B-N-OG, future application of the coppice system should be reconsidered. If these results are confirmed, the conversion of coppice to high forests should be preferred.

Consistently with other studies (Winter et al. 2014), no large differences in the index estimates can be found between forests within or outside protected areas. This can be explained by considering that forest management and conservation rules can be applied in very different ways within the protected areas. Once again, it is important to underline that protected areas, and more specifically large National Parks, are predominantly located in highland or mountainous regions and have a historical association with depopulation (Romano 1995; Romano et al. 2021). NFI plots within these forests, adjacent to protected areas, may exhibit specific structural traits that are directly influenced by the N and OG status of the protected areas (Barredo et al. 2021). Furthermore, the significant differences found for mean N and OG over plots in protected forest areas—compared to plots located outside protected areas—could be also related to the large amount of deadwood (Parisi et al. 2022). Moreover, creation of protected areas is relatively new in ecological timescales and thus consolidated results of their protection could not be visible yet. Finally previous studies have already underlined the strong variability of environmental conditions in national parks due to their phytogeographic, ecological and physiognomic heterogeneity (Capotorti et al. 2012).

Conclusions

The results of our test case demonstrate a useful assessment of forest biodiversity, naturalness and old-growth-status (B-N-OG) based on NFI data at multiple scales, from national to local levels. Moreover, the proposed set of indicators incorporated additional variables that are not related to traditional inventory purposes (Corona 2016), thus aiming toward multipurpose resource surveys. The set of the indicators we used demonstrated that PCA can identify groups of the main dominant types of forest ecosystems in Italy. We found this to be an encouraging result for future applications in larger pan-European monitoring framework.

The use of B-N-OG indexes presented here could enhance design-based assessment at the national level, enlarging the added value of NFI for supporting conservation strategies and sustainable forest management planning with trend analysis over time (Ćosović et al. 2020).

Our results also highlighted several considerations regarding the potential of NFI data in B-N-OG assessment at the European level. Firstly, NFIs should consider the future possibility of including field assessment of specific variables more directly related to biodiversity indicators: (i) the presence/absence census of all vegetation components, thus including herbs and lichens in order to be able to report a more complete assessment of α-diversity and (ii) tree-related microhabitats that can more accurately complement deadwood assessment for biodiversity monitoring purposes. Secondly, more resources for the harmonization/standardization of NFIs in Europe should be invested by the European Union and by the member countries; otherwise, differences in definitions and methods will hinder implementation of a complete pan-European forest monitoring system. Thirdly, because some basic historical forest variables such as the GSV that are traditionally designed for assessing the wood production of forests, were also important for monitoring B-N-OG, a more relevant role of remote sensing for such purposes can be hypothesized, because GSV can be quite easily mapped with remotely sensed data (Camia et al. 2023). In fact modern methods in combination with large datasets of multisource remotely sensed data can be used for accurately monitoring indicators (such as GSV) and forest disturbances trends in time.

Future recommendations can be envisaged for additional progress in the studies on forest biodiversity, naturalness and old-growth status, facilitating a more robust monitoring and comparison of results in Europe.

- More investments in NFIs to improve the consistency and comparability of B-N-OG indicators across different countries.
- More objective approaches for selecting the indicators. The aggregation of the indicators to create B-N-OG indexes is still very subjective. The method used in these cases is based on the opinion of experts and the review of previous studies, but the scientific background and the ideas of scientists related to such complex and debated disciplines may strongly and adversely affect the final decision on which indicators should be considered. For this study, we introduced the use of the well-known principal component analysis that can be used to support a more objective selection and aggregation of the indicators, eventually also on a weighted basis.
- More time-trend analysis. As correctly demonstrated in Reise et al. (2019), future studies should concentrate more on the analysis of temporal trends in the indexes using the NFI data acquired at multiple dates. Unfortunately, at the date when this study was initiated, data for NFI2015 in Italy were not yet available (Burrascano et al., 2023).
- More use of stratification. We think that all the indexes proposed should be applied with caution if not stratified based on potential conditions. In fact, areas affected by strong environmental limiting conditions (a typical example is for the island of Sardinia with extreme heat and drought) may result in small B-N-OG estimates. This can be easily implemented through stratification.

Appendix A: 2005 Italian NFI raw data

See Tables 2, 3, 4, 5 and 6.

Table 2 A2005 Italian NFI raw data per plot and single-tree levels

Plot-level							
Quantitative data on living trees and deadwood							
NFI-plot number	x	Dry weight of small branches of living trees, per hectare		Volume of stumps, per hectare	x	Dry weight of regeneration individuals class 3 ($h>130$ cm $d=2.5$–4.4 cm), per hectare	
Latitude of the S–W node of the NFI grid, WGS84 datum		Dry weight of stumps of living trees, per hectare		Dry weight of stumps, per hectare		Organic carbon stock of regeneration individuals class 3 ($h>130$ cm $d=2.5$–4.4 cm), per hectare	
Longitude of the S–W node of NFI grid, WGS84 datum		Dry weight of total above-ground biomass of living trees, per hectare		Organic carbon stock of stumps, per hectare		Dry weight of shrubs—class 1 ($h=50$–130 cm), per hectare	
North coordinate of the S–W node of NFI grid, Gauss-Boaga projection		Organic carbon stock of total above-ground biomass of living trees, per hectare		Volume of coarse woody debris on the ground, per hectare	x	Organic carbon stock of shrubs—class 1 ($h=50$–130 cm), per hectare	
East coordinate of the S–W node of NFI grid, Gauss-Boaga projection		Number of standing dead trees, per hectare	x	Dry weight of coarse woody debris on the ground, per hectare		Dry weight of shrubs—class 2 (h > 130 cm $d=0$–2.4 cm), per hectare	
zone (Est = East, Ovest = West), Gauss-Boaga projection		Basal area of standing dead trees, per hectare	x	Organic carbon stock of the coarse woody debris on the ground, per hectare		Organic carbon stock of shrubs—class 2 ($h>130$ cm $d=0$–2.4 cm), per hectare	
Administrative region, Italian National Statistics code		Volume of standing dead trees (total above-ground), per hectare	x	Number of regeneration individuals class 1 ($h=50$–130 cm), per hectare	x	Dry weight of shrubs—class 3 ($h>130$ cm $d=2.5$–4.4 cm), per hectare	
Administrative region, name		Dry weight of the above-ground biomass of standing dead trees, per hectare		Dry weight of regeneration individuals class 1 ($h=50$–130 cm), per hectare		Organic carbon stock of shrubs—class 3 ($h>130$ cm $d=2.5$–4.4 cm), per hectare	
Forest category, code	x	Organic carbon stock of the total above-ground biomass of standing dead trees, per hectare		Organic carbon stock of regeneration individuals class 1 ($h=50$–130 cm), per hectare		Volume of wood (stem + large branches) exploited in the 12 months preceding the NFI survey, per hectare	
Number of living trees, per hectare	x	Current annual volume increment of living trees, per hectare	x	Number of regeneration individuals class 2 ($h>130$ cm d = 0–2.4 cm), per hectare	x	Dry weight of wood (stem + large branches) exploited in the 12 months preceding the NFI survey, per hectare	
Basal area of living trees, per hectare	x	Dry weight correspondent to the current annual volume increment of living trees, per hectare		Dry weight of regeneration individuals class 2 ($h>130$ cm $d=0$–2.4 cm), per hectare		Organic carbon stock of wood (total above-ground biomass) exploited in the 12 months preceding the NFI survey, per hectare	
Volume of living trees (stem + large branches), per hectare	x	Organic carbon stock correspondent to the current annual volume increment of living trees, per hectare		Organic carbon stock of regeneration individuals class 2 ($h>130$ cm $d=0$–2.4 cm), per hectare			
Dry weight of stem + large branches of living trees, per hectare		Number of stumps, per hectare	x	Number of regeneration individuals class 3 ($h>130$ cm $d=2.5$–4.4 cm), per hectare	x		
Quantitative data on litter, fine wood debris and soil							
NFI-plot number	x	East coordinate of the S–W node of NFI grid, Gauss-Boaga projection		Forest category, code	x	Organic carbon stock of organic soil layer, per hectare	
Latitude of the S–W node of the NFI grid, WGS84 datum		Zone (Est = East, Ovest = West), Gauss-Boaga projection		Dry weight of fine woody debris, per hectare		Organic carbon stock of upper (0–10 cm) mineral soil layer, per hectare	

Table 2 (continued)

Plot-level							
Longitude of the S–W node of NFI grid, WGS84 datum		Administrative region, Italian National Statistics code		Organic carbon stock of fine woody debris, per hectare		Organic carbon stock of deep (10–30 cm) mineral soil layer, per hectare	
North coordinate of the S–W node of NFI grid, Gauss-Boaga projection		Administrative region, name		Organic carbon stock of litter, per hectare			
Single-tree level							
Living trees							
NFI-plot number	x	Basal area of the living tree	x	Diameter at breast height of the living tree	x	Dry weight of total above-ground biomass of the living tree	
Living tree identification number		Volume of the living tree (stem + large branches)		Total height of the living tree	x	Current annual volume increment of the living tree	
Species code	x	Dry weight of stem + large branches of the living tree		Dry weight of small branches of the living tree			
Vitality/integrity code	x	Expansion factor to hectare		Dry weight of the stump of the living tree			
Standing dead trees							
NFI-plot number	x	Vitality/integrity code	x	DBH of the dead tree	x	Volume of the dead tree (stem + large branches)	x
Dead tree identification number		Decay class	x	Total height of the dead tree	x	Dry weight of the above-ground biomass of the dead tree	
Species code	x	Expansion factor to hectare	x	Basal area of the dead tree	x		
Stumps							
NFI-plot number	x	Time of the cut		Stump volume	x	Stump height	
Stump identification number		Decay class	x	Dry weight of the stump			
Species code	x	Expansion factor to hectare		Cut section diameter of the stump			

Ticks “x” indicates whether the data were used for the elaboration of indicators in “Methods” section , Table 1

Table 3 Pearson's correlation (r) between single-variables indicators

	Growing stock volume	Variability of tree height	SDI	Max DBH	Max height	Large living trees	Gini coeff	n° species	Shannon index
Growing stock volume	1	0.34	0.528	0.565	0.789	0.774	0.133	0.043	−0.029
Variability of tree height	0.34	1	0.423	0.41	0.554	0.345	0.69	0.265	0.22
SBI	0.528	0.423	1	0.344	0.369	0.276	0.353	0.313	0.167
Max DBH	0.565	0.41	0.344	1	0.672	0.638	0.583	0.076	0.002
Max height	0.789	0.554	0.369	0.672	1	0.654	0.309	0.137	0.086
Large living trees	0.774	0.345	0.276	0.638	0.654	1	0.244	−0.044	−0.066
Gini coeff	0.133	0.69	0.353	0.583	0.309	0.244	1	0.253	0.213
n° species	0.043	0.265	0.313	0.076	0.137	−0.044	0.253	1	0.84
Shannon index	−0.029	0.22	0.167	0.002	0.086	−0.066	0.213	0.84	1
Evenness	0.044	−0.177	−0.045	0.026	−0.043	0.033	−0.165	−0.518	−0.847
Dead wood volume	0.347	0.111	0.195	0.238	0.31	0.222	0.07	0.142	0.096
Dead-to-living ratio	−0.068	−0.036	−0.086	−0.062	−0.062	−0.043	−0.053	−0.027	−0.015
Stump decay class ratio	0.021	−0.036	−0.015	0.027	0.038	0.024	−0.004	−0.032	−0.026
Standing dead tree decay ratio	0.075	0.033	0.098	0.016	0.061	0.009	0.003	0.071	0.039
Regeneration I	−0.12	−0.058	−0.053	−0.097	−0.101	−0.094	−0.031	0.033	0.043
Regeneration II	−0.165	−0.066	−0.057	−0.162	−0.149	−0.13	−0.031	0.023	0.041
Regeneration III	−0.151	−0.021	0.107	−0.188	−0.179	−0.151	0.026	0.07	0.072
Distance from anthropic dist	0.101	0.031	0.049	0.092	0.044	0.117	0.032	−0.125	−0.1

	Evenness	Deadwood volume	Dead-to-living ratio	Stump decay class ratio	Standing dead tree decay ratio	Regeneration I	Regeneration II	Regeneration III	Distance from anthropic dist
Growing stock volume	0.044	0.347	−0.068	0.021	0.075	−0.12	−0.165	−0.151	0.101
Variability of tree height	−0.177	0.111	−0.036	0.003	0.033	−0.058	−0.066	−0.021	0.031
SBI	−0.045	0.195	−0.086	−0.015	0.098	−0.053	−0.057	0.107	0.049
Max DBH	0.026	0.238	−0.062	0.027	0.016	−0.097	−0.162	−0.188	0.092
Max height	−0.043	0.31	−0.062	0.038	0.061	−0.101	−0.149	−0.179	0.044
Large living trees	0.033	0.222	−0.043	0.024	0.009	−0.094	−0.13	−0.151	0.117
Gini coeff	−0.165	0.07	−0.053	−0.004	0.003	−0.031	−0.031	0.026	0.032
n° species	−0.518	0.142	−0.027	−0.032	0.071	0.033	0.023	0.07	−0.125
Shannon index	−0.847	0.096	−0.015	−0.026	0.039	0.043	0.041	0.072	−0.1

Table 3 (continued)

	Evenness	Deadwood volume	Dead-to-living ratio	Stump decay class ratio	Standing dead tree decay ratio	Regeneration I	Regeneration II	Regeneration III	Distance from anthropic dist
Evenness	1	−0.053	0.005	0.02	−0.016	−0.045	−0.05	−0.058	0.055
Dead wood volume	−0.053	1	0.237	0.003	0.191	−0.024	−0.058	−0.097	−0.047
Dead-to-living ratio	0.005	0.237	1	0.019	0.029	0.035	0.016	−0.021	−0.033
Stump decay class ratio	0.02	0.003	0.019	1	−0.006	0.029	0.007	−0.019	−0.003
Standing dead tree decay ratio	−0.016	0.191	0.029	−0.006	1	−0.008	−0.016	−0.028	−0.039
Regeneration I	−0.045	−0.024	0.035	0.029	−0.008	1	0.394	0.159	−0.038
Regeneration II	−0.05	−0.058	0.016	0.007	−0.016	0.394	1	0.413	−0.051
Regeneration III	−0.058	−0.097	−0.021	−0.019	−0.028	0159	0.413	1	−0.026
Distance from anthropic dist	0.055	−0.047	−0.033	−0.003	−0.039	−0.038	−0.051	−0.026	1

Table 4 *p*-value between single-variables indicators

	Growing stock volume	Variability of tree height	SDI	Max DBH	Max height	Large living trees	Gini coeff	n° species	Shannon index
Growing stock volume	0	0	0	0	0	0	0	0	0.02
Variability of tree height	0	0	0	0	0	0	0	0	0
SBI	0	0	0	0	0	0	0	0	0
Max DBH	0	0	0	0	0	0	0	0	0.869
Max height	0	0	0	0	0	0	0	0	0
Large living trees	0	0	0	0	0	0	0	0	0
Gini coeff	0	0	0	0	0	0	0	0	0
n° species	0	0	0	0	0	0	0	0	0
Shannon index	0.02	0	0	0.869	0	0	0	0	0
Evenness	0	0	0	0.033	0.001	0.008	0	0	0
Dead wood volume	0	0	0	0	0	0	0	0	0
Dead-to-living ratio	0	0.003	0	0	0	0.001	0	0.031	0.239
Stump decay class ratio	0.092	0.827	0.217	0.026	0.002	0.049	0.766	0.01	0.033

Table 4 (continued)

	Growing stock volume	Variability of tree height	SDI	Max DBH	Max height	Large living trees	Gini coeff	n° species	Shannon index
Standing dead tree decay ratio	0	0.008	0	0.191	0	0.485	0.828	0	0.001
Regeneration I	0	0	0	0	0	0	0.012	0.008	0
Regeneration II	0	0	0	0	0	0	0.012	0.06	0.001
Regeneration III	0	0.096	0	0	0	0	0.035	0	0
Distance from anthropic dist	0	0.012	0	0	0	0	0.01	0	0

	Evenness	Deadwood volume	Dead-to-living ratio	Stump decay class ratio	Standing dead tree decay ratio	Regeneration I	Regeneration II	Regeneration III	Distance from anthropic dist
Growing stock volume	0	0	0	0.092	0	0	0	0	0
Variability of tree height	0	0	0.003	0.827	0.008	0	0	0.096	0.012
SBI	0	0	0	0.217	0	0	0	0	0
Max DBH	0.033	0	0	0.026	0.191	0	0	0	0
Max height	0.001	0	0	0.002	0	0	0	0	0
Large living trees	0.008	0	0.001	0.049	0.485	0	0	0	0
Gini coeff	0	0	0	0.766	0.828	0.012	0.012	0.035	0.01
n° species	0	0	0.031	0.01	0	0.008	0.06	0	0
Shannon index	0	0	0.239	0.033	0.001	0	0.001	0	0
Evenness	0	0	0.672	0.103	0.201	0	0	0	0
Dead wood volume	0	0	0	0.837	0	0.053	0	0	0
Dead-to-living ratio	0.672	0	0	0.133	0.019	0.005	0.184	0.083	0.007
Stump decay class ratio	0.103	0.837	0.133	0	0.619	0.019	0.562	0.119	0.816
Standing dead tree decay ratio	0.201	0	0.019	0.619	0	0.511	0.2	0.025	0.001
Regeneration I	0	0.053	0.005	0.019	0.511	0	0	0	0.002
Regeneration II	0	0	0.184	0.562	0.2	0	0	0	0
Regeneration III	0	0	0.083	0.119	0.025	0	0	0	0.033
Distance from anthropic dist	0	0	0.007	0.816	0.001	0.002	0	0.033	0

Table 5 Pearson's correlation (r) between B-N-OG components

	Structure	Composition	Deadwood	Regeneration	Hemeroby
Structure	1	0.137	0.203	−0.161	0.0S5
Composition	0.137	1	0.082	0.01	−0.094
Deadwood	0.203	0.082	1	−0.067	−0.057
Regeneration	−0.161	0.01	−0.067	1	−0.051
Hemeroby	0.085	−0.094	−0.057	−0.051	1

Table 6 *p*-value between B-N-OG components

	Structure	Composition	Deadwood	Regeneration	Hemeroby
Structure	0	0	0	0	0
Composition	0	0	0	0.433	0
Deadwood	0	0	0	0	0
Regeneration	0	0.433	0	0	0
Hemeroby	0	0	0	0	0

Appendix B: B-N-OG at national, regional, provincial and plot levels

See Tables 7 and 8.

Table 7 B-N-OG results at the regional level in Italy

Region	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
Abruzzo	295	0.144	0.289	0.052	0.194	0.077	0.236
Basilicata	218	0.136	0.259	0.074	0.227	0.073	0.267
Calabria	311	0.152	0.271	0.089	0.293	0.107	0.310
Campania	261	0.136	0.241	0.051	0.220	0.073	0.254
Emilia Romagna	436	0.148	0.296	0.046	0.183	0.080	0.365
Friuli-Venezia Giulia	278	0.166	0.307	0.064	0.360	0.110	0.319
Lazio	377	0.141	0.327	0.051	0.265	0.074	0.268
Liguria	285	0.152	0.296	0.069	0.403	0.089	0.266
Lombardia	376	0.163	0.285	0.049	0.413	0.106	0.274
Marche	222	0.140	0.264	0.052	0.169	0.063	0.222
Molise	141	0.139	0.254	0.052	0.180	0.070	0.204
Piemonte	584	0.155	0.267	0.063	0.405	0.099	0.274
Puglia	152	0.134	0.285	0.084	0.283	0.070	0.267
Sardegna	416	0.120	0.223	0.067	0.273	0.051	0.176
Sicilia	235	0.124	0.230	0.082	0.300	0.069	0.234
Toscana	681	0.150	0.327	0.051	0.320	0.086	0.422
Trentino Alto Adige	539	0.178	0.357	0.068	0.435	0.141	0.442
Umbria	330	0.141	0.261	0.058	0.249	0.062	0.170
Valle d'Aosta	107	0.150	0.272	0.051	0.218	0.101	0.260
Veneto	319	0.169	0.288	0.054	0.264	0.111	0.356

Table 8 B-N-OG results at the regional level in Italy

Province	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
Agrigento	16	0.095	0.168	0.074	0.138	0.046	0.089
Alessandria	104	0.139	0.259	0.053	0.192	0.070	0.186
Ancona	23	0.141	0.261	0.034	0.086	0.064	0.145
Arezzo	128	0.140	0.272	0.053	0.196	0.080	0.372
Ascoli Piceno	54	0.149	0.264	0.049	0.169	0.075	0.188
Asti	25	0.146	0.218	0.032	0.136	0.074	0.167
Avellino	51	0.132	0.203	0.048	0.164	0.067	0.205
Bari	19	0.108	0.169	0.048	0.153	0.049	0.151
Belluno	136	0.181	0.266	0.062	0.264	0.133	0.356
Benevento	27	0.135	0.220	0.041	0.101	0.062	0.135
Bergamo	58	0.165	0.264	0.033	0.103	0.103	0.257
Biella	25	0.151	0.253	0.060	0.270	0.094	0.197
Bologna	61	0.146	0.240	0.038	0.147	0.082	0.184
Bolzano/Bozen	253	0.175	0.303	0.060	0.435	0.145	0.308
Brescia	92	0.157	0.246	0.057	0.182	0.100	0.274
Brindisi	2	0.114	0.131	0.015	0.017	0.077	0.112
Cagliari	84	0.113	0.170	0.083	0.273	0.042	0.133
Caltanissetta	7	0.118	0.148	0.089	0.157	0.060	0.099
Campobasso	68	0.131	0.242	0.055	0.134	0.064	0.204
Caserta	40	0.140	0.235	0.039	0.122	0.084	0.186
Catania	43	0.124	0.211	0.112	0.300	0.068	0.234
Catanzaro	40	0.152	0.212	0.083	0.293	0.114	0.249
Chieti	56	0.145	0.284	0.040	0.141	0.077	0.210
Como	34	0.163	0.254	0.042	0.112	0.104	0.246
Cosenza	170	0.149	0.266	0.096	0.272	0.099	0.285
Cremona	5	0.093	0.116	0.020	0.040	0.041	0.089
Crotone	25	0.134	0.198	0.077	0.195	0.078	0.154
Cuneo	164	0.157	0.258	0.077	0.282	0.103	0.274
Enna	17	0.121	0.181	0.049	0.145	0.065	0.137
Ferrara	6	0.142	0.193	0.047	0.120	0.092	0.103
Firenze	117	0.159	0.327	0.054	0.320	0.099	0.321
Foggia	112	0.142	0.285	0.103	0.283	0.078	0.267
Forlì-Cesena	71	0.137	0.296	0.059	0.183	0.073	0.365
Frosinone	84	0.139	0.252	0.042	0.151	0.074	0.212
Genova	84	0.160	0.290	0.063	0.193	0.099	0.237
Gorizia	11	0.146	0.206	0.029	0.078	0.084	0.204
Grosseto	102	0.146	0.290	0.049	0.135	0.073	0.220
Imperia	63	0.151	0.296	0.105	0.403	0.091	0.266
Isernia	74	0.148	0.254	0.049	0.180	0.076	0.199
L'Aquila	167	0.143	0.289	0.059	0.194	0.076	0.236
La Spezia	48	0.150	0.227	0.053	0.133	0.091	0.198
Latina	36	0.138	0.217	0.042	0.167	0.076	0.144
Lecce	3	0.122	0.139	0.012	0.031	0.045	0.060
Lecco	15	0.158	0.219	0.041	0.099	0.086	0.182
Livorno	26	0.151	0.212	0.046	0.152	0.070	0.188
Lodi	1	0.099	0.099	0.020	0.020	0.031	0.031
Lucca	64	0.163	0.233	0.055	0.141	0.112	0.237
Macerata	72	0.132	0.219	0.058	0.149	0.053	0.180
Mantova	5	0.114	0.125	0.031	0.058	0.089	0.112
Massa-Carrara	30	0.147	0.225	0.054	0.140	0.092	0.183
Matera	42	0.123	0.200	0.075	0.184	0.061	0.167
Messina	77	0.139	0.230	0.096	0.280	0.087	0.184

Table 8 (continued)

Province	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
Milano	6	0.182	0.270	0.060	0.117	0.132	0.207
Modena	59	0.152	0.272	0.041	0.108	0.090	0.293
Napoli	12	0.140	0.181	0.034	0.064	0.079	0.157
Novara	25	0.164	0.255	0.041	0.106	0.111	0.190
Nuoro	171	0.126	0.218	0.064	0.214	0.058	0.176
Oristano	37	0.122	0.193	0.063	0.141	0.054	0.138
Padova	8	0.149	0.220	0.030	0.073	0.077	0.132
Palermo	48	0.115	0.169	0.075	0.210	0.058	0.126
Parma	96	0.156	0.217	0.048	0.155	0.087	0.229
Pavia	47	0.155	0.285	0.037	0.133	0.087	0.192
Perugia	258	0.141	0.261	0.059	0.249	0.061	0.170
Pesaro e Urbino	73	0.141	0.252	0.055	0.131	0.062	0.222
Pescara	24	0.139	0.197	0.043	0.104	0.076	0.139
Piacenza	56	0.149	0.227	0.044	0.119	0.072	0.200
Pisa	54	0.152	0.236	0.041	0.171	0.073	0.194
Pistoia	32	0.167	0.294	0.061	0.242	0.125	0.422
Pordenone	63	0.154	0.254	0.074	0.360	0.095	0.249
Potenza	176	0.139	0.259	0.074	0.227	0.076	0.267
Prato	13	0.167	0.239	0.058	0.092	0.109	0.164
Ragusa	7	0.124	0.182	0.018	0.029	0.068	0.107
Ravenna	21	0.135	0.191	0.050	0.125	0.069	0.137
Reggio di Calabria	51	0.165	0.271	0.093	0.253	0.130	0.310
Reggio nell'Emilia	62	0.149	0.241	0.039	0.153	0.078	0.146
Rieti	122	0.140	0.290	0.057	0.170	0.066	0.239
Rimini	4	0.158	0.183	0.027	0.061	0.082	0.115
Roma	84	0.154	0.327	0.053	0.183	0.088	0.245
Rovigo	3	0.116	0.135	0.019	0.031	0.086	0.119
Salerno	130	0.137	0.241	0.059	0.220	0.073	0.254
Sassari	124	0.117	0.223	0.062	0.226	0.048	0.119
Savona	90	0.146	0.214	0.058	0.265	0.077	0.189
Siena	115	0.143	0.247	0.044	0.142	0.070	0.181
Siracusa	14	0.109	0.156	0.035	0.072	0.052	0.146
Sondrio	73	0.177	0.258	0.072	0.413	0.135	0.268
Taranto	16	0.109	0.184	0.015	0.062	0.041	0.097
Teramo	48	0.149	0.225	0.048	0.177	0.084	0.192
Terni	72	0.141	0.215	0.056	0.171	0.064	0.149
Torino	157	0.159	0.264	0.061	0.405	0.101	0.259
Trapani	6	0.123	0.158	0.039	0.066	0.066	0.146
Trento	286	0.181	0.357	0.075	0.333	0.136	0.442
Treviso	41	0.155	0.288	0.054	0.185	0.096	0.282
Trieste	16	0.147	0.214	0.030	0.063	0.074	0.190
Udine	188	0.174	0.307	0.065	0.291	0.119	0.319
Valle d'Aosta/Vallée d'Aoste	107	0.150	0.272	0.051	0.218	0.101	0.260
Varese	40	0.170	0.254	0.042	0.156	0.116	0.216
Venezia	7	0.144	0.184	0.030	0.063	0.086	0.183
Verbano-Cusio-Ossola	61	0.170	0.267	0.066	0.200	0.133	0.252
Vercelli	23	0.162	0.258	0.068	0.227	0.106	0.201
Verona	42	0.159	0.244	0.031	0.105	0.079	0.212
Vibo Valentia	25	0.161	0.271	0.059	0.119	0.126	0.243
Vicenza	82	0.167	0.270	0.056	0.240	0.103	0.287
Viterbo	51	0.129	0.210	0.055	0.265	0.070	0.268

Appendix C: Italian protected areas: EUAP and Natura 2000 networks

See Tables 9, 10 and 11.

Table 9 B-N-OG mean estimates in EUAP areas

EUAP code	Site name	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
EUAP0001	Parco nazionale dell'Abruzzo, Lazio e Molise	21	0.183	0.258	0.096	0.194	0.126	0.236
EUAP0002	Parco nazionale dei Monti Sibillini	39	0.144	0.219	0.058	0.146	0.064	0.151
EUAP0003	Parco nazionale del Cilento e Vallo di Diano	56	0.140	0.241	0.063	0.185	0.081	0.210
EUAP0004	Parco nazionale del Circeo	4	0.171	0.217	0.035	0.082	0.114	0.144
EUAP0005	Parco nazionale del Gargano	67	0.150	0.285	0.135	0.283	0.088	0.267
EUAP0006	Parco nazionale del Gran Paradiso	8	0.161	0.253	0.062	0.124	0.125	0.195
EUAP0007	Parco nazionale del Gran Sasso e Monti della Laga	58	0.148	0.264	0.061	0.177	0.087	0.192
EUAP0008	Parco nazionale del Pollino	47	0.142	0.238	0.099	0.249	0.087	0.230
EUAP0009	Parco nazionale del Vesuvio	5	0.139	0.168	0.038	0.064	0.093	0.157
EUAP0010	Parco nazionale dell' Arcipelago Toscano	2	0.139	0.154	0.018	0.019	0.061	0.089
EUAP0011	Parco nazionale dell'Aspromonte	22	0.166	0.211	0.126	0.253	0.139	0.235
EUAP0013	Parco nazionale della Maiella	32	0.139	0.209	0.069	0.141	0.074	0.162
EUAP0014	Parco nazionale della Val Grande	1	0.169	0.169	0.129	0.129	0.120	0.120
EUAP0015	Parco Nazionale delle Dolomiti Bellunesi	6	0.149	0.211	0.063	0.161	0.097	0.192
EUAP0016	Parco nazionale delle Foreste Casentinesi, Monte Falterona e Campigna	26	0.170	0.296	0.071	0.183	0.139	0.372
EUAP0017	Parco nazionale dello Stelvio	25	0.163	0.271	0.093	0.235	0.133	0.295
EUAP0021	Riserva naturale Fara San Martino Palombaro	1	0.066	0.066	0.104	0.104	0.034	0.034
EUAP0022	Riserva naturale Feudo Intramonti	1	0.134	0.134	0.074	0.074	0.081	0.081
EUAP0023	Riserva naturale Feudo Ugni	1	0.168	0.168	0.141	0.141	0.122	0.122
EUAP0025	Riserva naturale Monte Rotondo	1	0.065	0.065	0.049	0.049	0.015	0.015
EUAP0026	Riserva naturale Monte Velino	2	0.163	0.222	0.140	0.191	0.094	0.155
EUAP0030	Riserva naturale Quarto Santa Chiara	1	0.131	0.131	0.019	0.019	0.045	0.045
EUAP0039	Riserva naturale Rubbio	1	0.153	0.153	0.180	0.180	0.127	0.127
EUAP0040	Riserva naturale Coturelle Piccione	1	0.182	0.182	0.177	0.177	0.176	0.176
EUAP0043	Riserva naturale Gariglione—Pisarello	2	0.172	0.198	0.206	0.217	0.120	0.144
EUAP0049	Riserva naturale Marchesale	2	0.128	0.154	0.078	0.105	0.110	0.173
EUAP0058	Riserva naturale Tirone Alto Vesuvio	3	0.131	0.153	0.052	0.064	0.070	0.109
EUAP0060	Riserva naturale Bassa dei Frassini—Balanzetta	1	0.144	0.144	0.120	0.120	0.088	0.088
EUAP0061	Riserva naturale Bosco della Mesola	1	0.161	0.161	0.027	0.027	0.101	0.101
EUAP0062	Riserva naturale Campigna	3	0.224	0.267	0.083	0.121	0.262	0.365
EUAP0069	Riserva naturale Pineta di Ravenna	1	0.127	0.127	0.029	0.029	0.074	0.074
EUAP0075	Riserva naturale Sasso Fratino	1	0.209	0.209	0.082	0.082	0.133	0.133
EUAP0076	Riserva naturale Badia Prataglia	2	0.259	0.296	0.152	0.183	0.301	0.364
EUAP0079	Riserva naturale Foresta demaniale del Circeo	3	0.184	0.217	0.044	0.082	0.135	0.144
EUAP0086	Riserva naturale Litorale romano	3	0.145	0.162	0.041	0.082	0.088	0.116
EUAP0093	Riserva naturale Montedimezzo	1	0.254	0.254	0.038	0.038	0.147	0.147
EUAP0094	Riserva naturale Pesche	1	0.096	0.096	0.073	0.073	0.061	0.061
EUAP0098	Riserva naturale Foresta Umbra	1	0.153	0.153	0.270	0.270	0.089	0.089
EUAP0113	Riserva naturale Abetone	2	0.230	0.294	0.114	0.165	0.266	0.422
EUAP0115	Riserva naturale Belagaio	1	0.234	0.234	0.039	0.039	0.195	0.195
EUAP0118	Riserva naturale Camaldoli	1	0.223	0.223	0.060	0.060	0.271	0.271
EUAP0121	Riserva naturale Cornocchia	1	0.232	0.232	0.063	0.063	0.148	0.148

Table 9 (continued)

EUAP code	Site name	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
EUAP0128	Riserva naturale Lamarossa	1	0.157	0.157	0.028	0.028	0.091	0.091
EUAP0141	Riserva naturale Scodella	1	0.272	0.272	0.107	0.107	0.372	0.372
EUAP0144	Riserva naturale Tombolo di Cecina	1	0.159	0.159	0.018	0.018	0.188	0.188
EUAP0145	Riserva naturale Vallombrosa	5	0.242	0.327	0.098	0.209	0.234	0.321
EUAP0148	Riserva naturale integrale Bosco Nordio	2	0.152	0.156	0.042	0.063	0.075	0.082
EUAP0151	Riserva naturale integrale Gardesana Orientale	1	0.156	0.156	0.009	0.009	0.023	0.023
EUAP0152	Riserva naturale integrale Lastoni Selva Pezzi	1	0.236	0.236	0.097	0.097	0.212	0.212
EUAP0154	Riserva naturale Monti del Sole	1	0.108	0.108	0.068	0.068	0.049	0.049
EUAP0173	Parco regionale naturale del Sirente—Velino	21	0.136	0.217	0.059	0.124	0.067	0.155
EUAP0174	Parco regionale Monti Picentini	24	0.153	0.218	0.094	0.220	0.102	0.254
EUAP0176	Parco fluviale regionale dello Stirone	1	0.191	0.191	0.026	0.026	0.119	0.119
EUAP0180	Parco regionale del Corno alle Scale	3	0.162	0.188	0.053	0.072	0.108	0.153
EUAP0181	Parco regionale Delta del Po (ER)	3	0.129	0.140	0.018	0.047	0.093	0.096
EUAP0182	Parco regionale dell' Alto Appennino Modenese	9	0.168	0.272	0.086	0.108	0.116	0.293
EUAP0186	Parco naturale regionale Monti Simbruini	16	0.145	0.192	0.056	0.128	0.087	0.180
EUAP0187	Parco regionale dei Castelli Romani	5	0.146	0.152	0.035	0.061	0.091	0.121
EUAP0190	Parco regionale naturale dei Monti Lucretili	5	0.141	0.178	0.074	0.122	0.060	0.097
EUAP0193	Parco naturale dell'Alto Garda Bresciano	7	0.141	0.179	0.074	0.124	0.048	0.075
EUAP0195	Parco naturale lombardo della Valle del Ticino	9	0.174	0.270	0.067	0.119	0.117	0.207
EUAP0196	Parco naturale del Campo dei Fiori	3	0.173	0.194	0.100	0.156	0.129	0.216
EUAP0199	Parco regionale dell'Adamello	2	0.149	0.162	0.083	0.086	0.082	0.099
EUAP0201	Parco naturale di Montevecchia e della Valle di Curone	1	0.176	0.176	0.004	0.004	0.090	0.090
EUAP0203	Parco regionale del Conero	1	0.098	0.098	0.000	0.000	0.017	0.017
EUAP0209	Parco naturale del Monte Fenera	1	0.220	0.220	0.025	0.025	0.131	0.131
EUAP0214	Parco naturale della Alta Valle Pesio e Tanaro	3	0.187	0.255	0.123	0.178	0.145	0.274
EUAP0218	Parco naturale della Valle del Ticino	2	0.204	0.222	0.095	0.098	0.132	0.167
EUAP0219	Parco naturale delle Capanne di Marcarolo	8	0.137	0.170	0.126	0.192	0.069	0.095
EUAP0220	Parco naturale delle Lame del Sesia	1	0.246	0.246	0.022	0.022	0.170	0.170
EUAP0223	Parco naturale Orsiera—Rocciavre'	2	0.168	0.191	0.151	0.151	0.110	0.143
EUAP0224	Parco regionale La Mandria	1	0.239	0.239	0.021	0.021	0.157	0.157
EUAP0226	Parco dei Nebrodi	42	0.136	0.193	0.137	0.280	0.078	0.155
EUAP0227	Parco dell' Etna	28	0.132	0.211	0.124	0.300	0.079	0.234
EUAP0228	Parco delle Madonie	10	0.133	0.169	0.104	0.210	0.067	0.097
EUAP0229	Parco naturale regionale delle Alpi Apuane	3	0.151	0.170	0.057	0.071	0.098	0.146
EUAP0230	Parco naturale della Maremma	1	0.173	0.173	0.061	0.061	0.096	0.096
EUAP0231	Parco naturale di Migliarino, San Rossore e Massaciuccoli	3	0.162	0.173	0.004	0.006	0.156	0.194
EUAP0232	Parco naturale Paneveggio—Pale di San Martino	7	0.217	0.244	0.127	0.180	0.242	0.322
EUAP0235	Parco del Monte Cucco	7	0.145	0.231	0.041	0.094	0.078	0.165
EUAP0236	Parco del Monte Subasio	6	0.157	0.181	0.062	0.094	0.062	0.088
EUAP0237	Parco fluviale del Nera	1	0.196	0.196	0.025	0.025	0.049	0.049
EUAP0238	Parco fluviale del Tevere	2	0.136	0.141	0.023	0.043	0.045	0.053
EUAP0240	Parco naturale regionale del Fiume Sile	1	0.110	0.110	0.035	0.035	0.067	0.067
EUAP0241	Parco naturale regionale della Lessinia	7	0.177	0.244	0.070	0.105	0.110	0.168
EUAP0243	Parco regionale dei Colli Euganei	6	0.144	0.180	0.035	0.073	0.067	0.088
EUAP0247	Riserva naturale controllata Lago di Serranella	1	0.080	0.080	0.020	0.020	0.036	0.036
EUAP0253	Riserva regionale Lago Piccolo di Monticchio	1	0.173	0.173	0.077	0.077	0.118	0.118
EUAP0267	Riserva naturale delle Montagne della Duchessa	1	0.137	0.137	0.025	0.025	0.050	0.050
EUAP0271	Riserva naturale Lago di Vico	1	0.189	0.189	0.038	0.038	0.196	0.196
EUAP0272	Riserva naturale Monte Navegna e Monte Cervia	1	0.245	0.245	0.076	0.076	0.239	0.239

Table 9 (continued)

EUAP code	Site name	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
EUAP0273	Riserva naturale Monte Rufeno	3	0.128	0.137	0.093	0.139	0.043	0.052
EUAP0276	Riserva naturale parziale Selva del Lamone	2	0.150	0.169	0.082	0.085	0.068	0.073
EUAP0318	Riserva naturale Monte Alpe	1	0.179	0.179	0.031	0.031	0.085	0.085
EUAP0370	Riserva naturale speciale delle Sorgenti del Belbo	1	0.171	0.171	0.065	0.065	0.128	0.128
EUAP0378	Riserva naturale Le Montagne delle Felci e dei Porri	1	0.220	0.220	0.061	0.061	0.171	0.171
EUAP0384	Riserva naturale Alto Merse	4	0.184	0.219	0.049	0.092	0.068	0.105
EUAP0390	Riserva naturale Farma	2	0.200	0.232	0.054	0.067	0.147	0.155
EUAP0403	Riserva naturale guidata della Scanuppia	1	0.213	0.213	0.091	0.091	0.172	0.172
EUAP0452	Parco naturale regionale del Beigua	4	0.145	0.172	0.081	0.093	0.061	0.085
EUAP0454	Oasi di Bosco Casale (Casacalenda)	1	0.165	0.165	0.049	0.049	0.066	0.066
EUAP0458	Sistema delle aree protette della fascia fluviale del Po	1	0.107	0.107	0.080	0.080	0.089	0.089
EUAP0469	Riserva di Monte Arcosu	1	0.031	0.031	0.194	0.194	0.014	0.014
EUAP0477	Biotopo La Rocchetta	1	0.139	0.139	0.002	0.002	0.078	0.078
EUAP0527	Parco regionale dei Monti Lattari	8	0.132	0.181	0.042	0.072	0.070	0.149
EUAP0541	Zona di salvaguardia dei Boschi e delle Rocche del Roero	2	0.124	0.145	0.074	0.121	0.081	0.115
EUAP0547	Riserva naturale orientata Bosco Pantano di Policoro	2	0.132	0.160	0.058	0.100	0.073	0.093
EUAP0550	Parco nazionale della Sila	35	0.176	0.266	0.152	0.293	0.146	0.285
EUAP0660	Parco naturale regionale Serre	20	0.174	0.271	0.065	0.121	0.129	0.213
EUAP0727	Acquaviva—Cima del Monte—Quercia del Monaco	1	0.109	0.109	0.047	0.047	0.057	0.057
EUAP0734	Parco regionale della Valle del Lambro	2	0.214	0.237	0.063	0.109	0.160	0.179
EUAP0838	Monumento naturale Promontorio Villa Tiberio e Costa Torre Capovento-Punta Cetarola	1	0.151	0.151	0.003	0.003	0.111	0.111
EUAP0839	Riserva naturale orientata Monte Pellegrino	2	0.100	0.140	0.020	0.031	0.090	0.126
EUAP0851	Parco nazionale dell'Appennino Lucano—Val d'Agri—Lagonegrese	37	0.144	0.246	0.086	0.202	0.078	0.190
EUAP0852	Parco nazionale dell'Alta Murgia	6	0.079	0.109	0.063	0.104	0.042	0.075
EUAP0882	Riserva naturale speciale del Sacro Monte di Oropa	1	0.161	0.161	0.111	0.111	0.118	0.118
EUAP0886	Parco naturale del Monte San Giorgio	1	0.147	0.147	0.018	0.018	0.085	0.085
EUAP0887	Parco naturale del Monte Tre Denti—Freidour	1	0.125	0.125	0.081	0.081	0.044	0.044
EUAP0894	Parco naturale regionale Terra delle Gravine	6	0.096	0.184	0.012	0.027	0.033	0.097
EUAP0922	Riserva naturale Il Bogatto	1	0.192	0.192	0.091	0.091	0.052	0.052
EUAP0930	Parco naturale provinciale dell' Adamello Brenta	11	0.156	0.266	0.124	0.288	0.103	0.275
EUAP0937	Parco naturale Dolomiti di Sesto	1	0.157	0.157	0.004	0.004	0.112	0.112
EUAP0938	Parco naturale Vedrette di Ries—Aurina	3	0.140	0.155	0.083	0.125	0.091	0.120
EUAP0940	Parco naturale Monte Corno	5	0.173	0.237	0.051	0.090	0.113	0.191
EUAP0941	Parco naturale dello Sciliar—Catinaccio	2	0.182	0.215	0.043	0.061	0.155	0.210
EUAP0942	Parco naturale Fanes—Sennes e Braies	2	0.207	0.241	0.071	0.087	0.204	0.272
EUAP0943	Parco naturale Gruppo di Tessa	4	0.206	0.254	0.078	0.133	0.203	0.263
EUAP0944	Parco nazionale del Golfo di Orosei e del Gennargentu	23	0.124	0.209	0.083	0.214	0.061	0.150
EUAP0954	Parco regionale del Partenio	5	0.135	0.153	0.075	0.106	0.069	0.093
EUAP0955	Parco regionale del Matese	13	0.164	0.235	0.069	0.122	0.109	0.186
EUAP0956	Parco regionale di Roccamonfina—Foce Garigliano	4	0.152	0.173	0.031	0.043	0.128	0.172
EUAP0957	Parco regionale del Taburno—Camposauro	2	0.100	0.124	0.022	0.031	0.032	0.033
EUAP0961	Parco regionale dei Laghi Suviana e Brasimone	2	0.164	0.194	0.062	0.080	0.100	0.118
EUAP0962	Parco naturale delle Dolomiti Friulane	6	0.158	0.195	0.181	0.360	0.104	0.164
EUAP0965	Parco naturale regionale dell'Antola	2	0.149	0.150	0.035	0.038	0.085	0.095
EUAP0966	Parco naturale regionale dell'Aveto	3	0.185	0.211	0.089	0.112	0.141	0.211
EUAP0968	Parco naturale regionale di Montemarcello—Magra	2	0.139	0.140	0.019	0.025	0.055	0.059
EUAP0971	Riserva naturale Foce Sele—Tanagro	1	0.219	0.219	0.026	0.026	0.168	0.168
EUAP0972	Riserva naturale Foce Volturno—Costa di Licola	1	0.131	0.131	0.012	0.012	0.107	0.107

Table 9 (continued)

EUAP code	Site name	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
EUAP0973	Riserva naturale Monti Eremita—Marzano	2	0.196	0.223	0.119	0.131	0.177	0.245
EUAP0981	Riserva naturale della Foce dell' Isonzo	1	0.205	0.205	0.047	0.047	0.204	0.204
EUAP0983	Riserva naturale dei Laghi di Doberdo' e Pietrarossa	2	0.109	0.115	0.031	0.048	0.040	0.052
EUAP0987	Riserva naturale di Monterufoli—Caselli	4	0.171	0.205	0.110	0.171	0.078	0.113
EUAP0988	Riserva naturale Foresta di Berignone	2	0.163	0.179	0.037	0.060	0.047	0.070
EUAP0995	Oasi naturale di Guardiaregia—Campochiaro	1	0.199	0.199	0.017	0.017	0.158	0.158
EUAP1010	Parco interprovinciale di Montioni	2	0.139	0.156	0.084	0.091	0.056	0.074
EUAP1020	Riserva naturale del Monti Rognosi	1	0.144	0.144	0.056	0.056	0.077	0.077
EUAP1023	Riserva naturale dell' Alpe della Luna	2	0.142	0.150	0.142	0.156	0.105	0.129
EUAP1027	Riserva naturale Acquerino Cantagallo	1	0.140	0.140	0.092	0.092	0.068	0.068
EUAP1034	Parco naturale di Veio	2	0.162	0.171	0.025	0.045	0.086	0.093
EUAP1035	Parco naturale dei Monti Aurunci	7	0.116	0.162	0.069	0.120	0.060	0.097
EUAP1038	Riserva naturale di Monte Catillo	1	0.098	0.098	0.025	0.025	0.037	0.037
EUAP1039	Riserva naturale di Nomentum	1	0.122	0.122	0.017	0.017	0.070	0.070
EUAP1046	Riserva naturale della Marcigliana	1	0.121	0.121	0.025	0.025	0.053	0.053
EUAP1052	Parco naturale regionale di Porto Conte	1	0.116	0.116	0.069	0.069	0.036	0.036
EUAP1053	Parco naturale di Gallipoli Cognato—Piccole Dolomiti Lucane	12	0.146	0.178	0.120	0.227	0.093	0.167
EUAP1054	Parco naturale regionale della Gola della Rossa e di Frasassi	4	0.131	0.173	0.046	0.086	0.070	0.103
EUAP1057	Parco naturale delle Alpi Marittime	2	0.136	0.136	0.084	0.085	0.071	0.078
EUAP1062	Parco regionale del Delta del Po (VE)	1	0.120	0.120	0.031	0.031	0.099	0.099
EUAP1067	Parco nazionale delle Cinque Terre	3	0.135	0.178	0.064	0.133	0.089	0.153
EUAP1069	Riserva naturale guidata Abetina di Rosello	1	0.284	0.284	0.042	0.042	0.210	0.210
EUAP1079	Parco naturale regionale del complesso lacuale Bracciano—Martignano	3	0.145	0.220	0.060	0.090	0.103	0.163
EUAP1089	Riserva naturale guidata Monte Genzana e Alto Gizio	2	0.144	0.148	0.099	0.118	0.072	0.074
EUAP1091	Riserva naturale guidata Gole di S. Venanzio	1	0.126	0.126	0.021	0.021	0.024	0.024
EUAP1103	Riserva naturale orientata Bosco della Ficuzza, Rocca Busambra, Bosco del Cappelliere e Gorgo d	4	0.102	0.150	0.083	0.095	0.058	0.094
EUAP1116	Riserva naturale orientata Fiumedinisi e Monte Scuderi	1	0.114	0.114	0.134	0.134	0.044	0.044
EUAP1121	Riserva naturale orientata Bosco di Favara e Bosco Granza	3	0.134	0.160	0.077	0.102	0.069	0.080
EUAP1123	Riserva naturale orientata Monte Cammarata	1	0.121	0.121	0.116	0.116	0.074	0.074
EUAP1126	Riserva naturale orientata Bosco di Malabotta	2	0.142	0.158	0.152	0.178	0.107	0.111
EUAP1130	Riserva naturale orientata Monte Altesina	1	0.095	0.095	0.020	0.020	0.019	0.019
EUAP1136	Riserva naturale orientata Monti di Palazzo Adriano e Valle del Sosio	6	0.097	0.117	0.059	0.092	0.040	0.073
EUAP1140	Riserva naturale orientata Monte Genuardo e Santa Maria del Bosco	2	0.099	0.112	0.104	0.104	0.034	0.049
EUAP1143	Riserva naturale orientata Sambuchetti-Campanito	1	0.151	0.151	0.067	0.067	0.060	0.060
EUAP1154	Riserva naturale orientata Rossomanno-Grottascura-Bellia	2	0.167	0.181	0.081	0.096	0.125	0.137
EUAP1155	Riserva naturale orientata Bosco di Santo Pietro	1	0.122	0.122	0.042	0.042	0.051	0.051
EUAP1158	Parco nazionale dell'Appennino Tosco-Emiliano	13	0.165	0.212	0.060	0.089	0.107	0.181
EUAP1169	Riserva naturale statale Gola del Furlo	4	0.142	0.157	0.082	0.107	0.068	0.100
EUAP1171	Riserva naturale statale Tenuta di Castelporziano	6	0.189	0.220	0.046	0.097	0.139	0.196
EUAP1173	Sistema territoriale di interesse naturalistico—ambientale Monte Peglia Selva di Meana (STINA)	3	0.159	0.181	0.063	0.087	0.075	0.105
EUAP1177	Riserva naturale orientata Bosco Ronchetti	1	0.116	0.116	0.040	0.040	0.053	0.053
EUAP1184	Zona di salvaguardia del Monte Fenera	3	0.156	0.168	0.057	0.106	0.123	0.183
EUAP1194	Parco naturale regionale Litorale di Ugento	1	0.139	0.139	0.031	0.031	0.060	0.060
EUAP1195	Parco naturale regionale Fiume Ofanto	2	0.113	0.120	0.066	0.089	0.048	0.066
EUAP1196	Riserva naturale Monte Faverghera	1	0.159	0.159	0.047	0.047	0.107	0.107

Table 10 B-N-OG mean estimates in Natura 2000 network habitats

Natura 2000 habitat code	Habitat name	n plots	Mean B	Max B	Mean N	Max N	Mean OG	Max OG
91	European temperate forests	646	0.157	0.296	0.085	0.403	0.102	0.422
9110	Luzulo-Fagetum beech forests	315	0.168	0.327	0.088	0.403	0.122	0.422
9120	Atlantic acidophilous beech forests with Ilex and sometimes also Taxus in the shrublayer (Quercion robori-petraeae or Ilici-Fagenion)	8	0.134	0.172	0.080	0.159	0.060	0.123
9130	Asperulo-Fagetum beech forests	292	0.174	0.327	0.086	0.333	0.131	0.422
9140	Medio-European subalpine beech woods with Acer and Rumex arifolius	49	0.167	0.266	0.090	0.288	0.122	0.275
9150	Medio-European limestone beech forests of the Cephalanthero-Fagion	131	0.170	0.259	0.072	0.271	0.118	0.356
9160	Sub-Atlantic and medio-European oak or oak-hornbeam forests of the Carpinion betuli	37	0.172	0.270	0.063	0.271	0.116	0.274
9180	Tilio-Acerion forests of slopes, screes and ravines	646	0.158	0.296	0.082	0.360	0.102	0.365
9190	Old acidophilous oak woods with Quercus robur on sandy plains	1	0.118	0.118	0.045	0.045	0.103	0.103
91AA	Eastern white oak woods	452	0.139	0.296	0.082	0.403	0.075	0.266
91B0	Thermophilous Fraxinus angustifolia woods	14	0.150	0.205	0.084	0.171	0.077	0.118
91D0	Bog woodland	71	0.179	0.284	0.130	0.333	0.154	0.322
91F0	Riparian mixed forests of Quercus robur, Ulmus laevis and Ulmus minor, Fraxinus excelsior or Fraxinus angustifolia, along the great rivers (Ulmenion minoris)	89	0.152	0.270	0.044	0.203	0.092	0.217
91H0	Pannonian woods with Quercus pubescens	32	0.150	0.194	0.059	0.156	0.075	0.216
91K0	Illyrian Fagus sylvatica forests (Aremonio-Fagion)	188	0.171	0.259	0.095	0.360	0.122	0.356
91L0	Illyrian oak-hornbeam forests (Erythronio-Carpinion)	201	0.160	0.284	0.059	0.194	0.089	0.282
91M0	Pannonian-Balkanic turkey oak –sessile oak forests	406	0.149	0.327	0.088	0.293	0.088	0.372
9210	Apeninne beech forests with Taxus and Ilex	830	0.149	0.296	0.082	0.293	0.087	0.365
9220	Apennine beech forests with Abies alba and beech forests with Abies nebrodensis	319	0.154	0.327	0.081	0.293	0.100	0.372
9250	Quercus trojana woods	25	0.103	0.184	0.026	0.104	0.040	0.097
9260	Castanea sativa woods	753	0.153	0.327	0.075	0.403	0.092	0.372
92A0	Salix alba and Populus alba galleries	641	0.143	0.271	0.078	0.293	0.079	0.273
92C0	Platanus orientalis and Liquidambar orientalis woods (Platanion orientalis)	13	0.124	0.182	0.057	0.171	0.071	0.151
92D0	Southern riparian galleries and thickets (Nerio-Tamaricetea and Securinegion tinctoriae)	123	0.126	0.220	0.093	0.273	0.059	0.180
9320	Olea and Ceratonia forests	78	0.119	0.200	0.097	0.273	0.048	0.146
9330	Quercus suber forests	234	0.131	0.293	0.083	0.280	0.066	0.245
9340	Quercus ilex and Quercus rotundifolia forests	925	0.140	0.293	0.073	0.293	0.075	0.267
9380	Forests of Ilex aquifolium	110	0.131	0.212	0.114	0.280	0.067	0.183
9410	Acidophilous Picea forests of the montane to alpine levels (Vaccinio-Piceetea)	249	0.175	0.284	0.100	0.360	0.139	0.356
9420	Alpine Larix decidua and/or Pinus cembra forests	231	0.174	0.284	0.108	0.403	0.137	0.322
9430	Subalpine and montane Pinus uncinata forests (* if on gypsum or limestone)	31	0.162	0.255	0.098	0.271	0.121	0.274
9510	Southern Apennine Abies alba forests	16	0.189	0.284	0.074	0.121	0.137	0.210
9530	(Sub-) Mediterranean pine forests with endemic black pines	190	0.163	0.271	0.103	0.360	0.112	0.356
9540	Mediterranean pine forests with endemic Mesogean pines	141	0.138	0.247	0.066	0.203	0.071	0.183
9560	Endemic forests with Juniperus spp.	25	0.140	0.244	0.081	0.164	0.077	0.254
9580	Mediterranean Taxus baccata woods	99	0.129	0.212	0.126	0.280	0.061	0.155
95A0	High oro-Mediterranean pine forests	19	0.144	0.238	0.096	0.249	0.084	0.197

Table 11 B-N-OG results per Natura 2000 site types

		n° plots	B mean	N mean	OG mean
Site type	A	542	0.149	0.080	0.093
	B	1035	0.148	0.076	0.088
	C	347	0.153	0.073	0.097

Appendix D: Analysis of variance (ANOVA)

See Table 12.

Table 12 *P*-values of plots located inside or outside protected areas (both EUAP and Natura 2000), and between "conifers" and "broadleaves"

Protected areas		Indicator	*p*-value	Significance
Inside	Outside	B	0.487	ns
		N	< 0.001	***
		OG	0.004	**
Forest categories		Indicator	*p*-value	Significance
Conifers (Forest categories 1–7, 20)	Broadleaves (Forest categories 8–19)	B	< 0.001	***
		N	< 0.001	***
		OG	< 0.001	***

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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