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Words apart: Standardizing forestry terms and definitions across European biodiversity studies

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ABSTRACT

Forest biodiversity studies conducted across Europe use a multitude of forestry terms, often inconsistently. This hinders the comparability across studies and makes the assessment of the impacts of forest management on biodiversity highly context-dependent. Recent attempts to standardize forestry and stand description terminology mostly used a top-down approach that did not account for the perspectives and approaches of forest biodiversity experts. This work aims to establish common standards for silvicultural and vegetation definitions, creating a shared conceptual framework for a consistent study on the effects of forest management on biodiversity. We have identified both strengths and weaknesses of the silvicultural and vegetation information provided in forest biodiversity studies. While quantitative data on forest biomass and dominant tree species are frequently included, information on silvicultural activities and vegetation composition is often lacking, shallow, or based on broad and heterogeneous classifications. We discuss the existing classifications and their use in European forest biodiversity studies through a novel bottom-up and top-driven review process, and ultimately propose a common framework. This will enhance the comparability of forest biodiversity studies in Europe, and puts the basis for effective implementation and monitoring of sustainable forest management policies. The standards here proposed are potentially adaptable and applicable to other geographical areas and could be extended to other forest interventions.

1. Introduction

Forests cover almost 40% of the European Union territory (Forest Europe, 2020), and, with 75 forest types (EEA, 2006) and 85 habitat types (Directive 43/92/CE), represent a crucial asset for the conservation of biodiversity in Europe. About a quarter of European forest area is designated for biodiversity or landscape protection (Forest Europe, 2020); but only about 2% of forests are considered as primary (Sabatini et al., 2021), and mature and old-growth forest are scarce and decreasing (Morales-Hidalgo et al., 2015; Mikoláš et al., 2019).

The long history of land use by humans, especially in Europe, shaped the extent, distribution and stand structure of forests (Johann, 2004; Kaplan et al., 2009), with important consequences for biodiversity (e.g. Angelstam et al., 2020). Silvicultural treatments modify forest structure, and in turn forest biodiversity and resilience at both stand (e.g., Sitzia et al., 2012) and landscape scale (Pommerening, 2006).

Current European forest policies strongly rely on the concept of sustainable forest management, which should "contribute to enhancing biodiversity or to halting or preventing the degradation of ecosystems, deforestation and habitat loss" (Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020). These policies stimulated local and national efforts to evaluate the effects of different silvicultural management regimes on forest multi-taxon biodiversity (Johann, 2006; Bouvet et al., 2016; Doerfler et al., 2017; Ammer et al., 2018).

Silviculture, as a discipline, was developed in Europe, with the first silvicultural methods dating back to the 16th century (Fernow, 1911), while its application was more recent in other continents (Achim et al., 2022). European silvicultural practices (e.g. coppicing, shelterwood systems) were developed in an array of local environmental and socio-economic contexts (Szabó et al., 2015; Fabbio, 2016), over different geographical areas and across multiple human languages. This has favored the emergence of many silviculture terms with different, context-dependent meanings (Agnoletti, 2006; Johann, 2006). For instance, under 'shelterwood system' category we can count manifold variants and interpretations based on cutting frequencies and on the degree of stand canopy openness (e.g. Březina and Dobrovolný, 2011; Barna and Bosela, 2015), while intermediate cuttings like thinning may indicate treatments across a wide range of intensities (Gonçalves, 2020). The situation was further complicated by the inclusion of non-European systems (Bauhus, 1999; Bell et al., 2008; Palik et al., 2021; Rogers et al., 2022) and of additions related to societal changes and to forest multifunctionality (Achim et al., 2022). The wealth of terms and their definitions in forestry have caused much confusion among policy makers, practitioners and researchers (Pommerening and Murphy, 2004).

Attempts to address potential miscommunications include revising the definition of forest (Sasaki and Putz, 2009; Chazdon et al., 2016), defining specific silvicultural practices in different national and regional contexts (Gibbs, 1976; Lähde et al., 1999; Bell et al., 2008), and producing standardized vocabularies and classifications (e.g., EEA, 2006; FAO, 2020; IUFRO, 2000).

In general, the definitions that were developed for management purposes seldom provide indications of forests' ecological trajectories and dynamics, which are key to assess and monitor forest conditions (Chazdon et al., 2016). Moreover, many studies on forest biodiversity do not include specific forestry terms nor details on the silvicultural regime applied to the study sites (e.g., Janssen et al., 2018; Hofmeister et al., 2019). As a consequence, they focus on species diversity and its ecological interpretation, rather than on implications for conservation practices or economical constraints (see Zavala and Oria, 1995). Some studies refer to very local cases or are related to specific experimental treatments (e.g., Elek et al., 2018; Doerfler et al., 2020; Tinya et al., 2023), making it difficult to generalize their results at broader spatial scales. Similar issues are faced for vegetation classification, with descriptions ranging from a simple list of dominant trees to specific phytosociological syntaxa. Many studies from different geographical areas and time periods (e.g., Bell et al., 2008; Mason et al., 2022; Pach et al., 2018) have suggested that a conceptual framework and shared definitions for silvicultural interventions would help reduce the uncertainties associated with forest development and the effects of management on biodiversity. For instance, conclusions on the effects of different management systems on biodiversity at the landscape scale were debated also in relation to the context-dependency of some management definitions (Schall et al., 2020, 2021; Bruun and Heilmann-Clausen, 2021). Nevertheless, to our knowledge, there have been no attempts to define a common forestry and vegetation vocabulary to be used in biodiversity studies that accounts for both the information reported in scientific articles and an iterative discussion among forest biodiversity experts.

Here, we aim at improving the comparability of European forest biodiversity studies to reach broad-scale syntheses of forest management effects on multi-taxon diversity. Our specific objectives are to (i) harmonize the information related to silviculture and vegetation retrieved in studies focusing on forest biodiversity through the active engagement of the researches involved in them, (ii) propose a common standard for the classification of forest stands into silvicultural and vegetation categories.

2. Materials and methods

2.1. Overall methodological approach

This work stems from the networking activities of the COST Action "Biodiversity of Temperate Forest Taxa Orienting Management

Sustainability by Unifying Perspectives" (BOTTOMS-UP; CA18207: https://www.bottoms-up.eu/en/), which gathered and standardized European forest data encompassing multiple taxonomic groups, forest structure and management in a single harmonized platform, hereafter BOTTOMS-UP platform (Burrascano et al., 2021, 2023). The platform derives from field activities of several independent research groups that collected data at plot or stand level including: (i) detailed description of the sampling design and survey protocol, (ii) data on forest stand structure, (iii) data on a minimum of three taxonomic groups, representing at least Animalia, and either Plantae or Fungi. A 'research project' was defined as a multi-taxon dataset where data from a forest site were sampled by an independent research group through the same protocol.

To map the heterogeneity of the forestry terminologies and stand-related information used in biodiversity studies, we applied two parallel processes of analysis (Fig. 1): a bottom-up (blue flowchart in Fig. 1) and a top-driven process (orange flowchart in Fig. 1).

For the bottom-up process, we collected 120 peer-reviewed articles published in international journals up to 2021, referring to 29 research projects belonging to the BOTTOMS-UP platform and including analysis on at least one of the most commonly sampled taxonomic groups, i.e., vascular plants, beetles, arachnids, lichens, birds, fungi, bryophytes or bats (see Burrascano et al., 2021). We analyzed in detail 67 articles (Supplementary Material SI 01), which involved 95 sites across 10 European countries (Fig. 2).

In parallel, for the top-driven process, we asked data custodians (i.e. the responsible for data preparation and handling within the platform) of each research project to provide the forestry and stand-related information through standardized data forms. The top-driven approach included an iterative analysis through all steps of the process, according to a combination of two techniques, the Decision Delphi and the Nominal Group Technique (Mukherjee et al., 2015). These techniques firstly (Fig. 1, section a, orange flowchart) involved the core of the platform research network (i.e., those experts who worked since the beginning to data and metadata collection) and secondly all data custodians (Fig. 1, section c, orange flowchart), through continuous discussions aimed at the progressive refinements of data standardization using a specific set of defined terms. Finally, we compared the data deriving from these two approaches, and then proposed a common standard of shared classifications by integrating and harmonizing the information included in the scientific literature.

2.2. Bottom-up data collection

Terms and information on forestry and stand-related information were organized as in Table 1. By silvicultural system we refer to the process by which the trees constituting a forest are tended, removed, and replaced by the regeneration or planting of trees: the process results in the production of stands of distinctive forms (Matthews, 1989). By management information we mean information on forest stand structural conditions at the time of the sampling. Forest vegetation classification refers to any kind of description of the forest community of vascular plants. All information was aggregated at the level of research project.

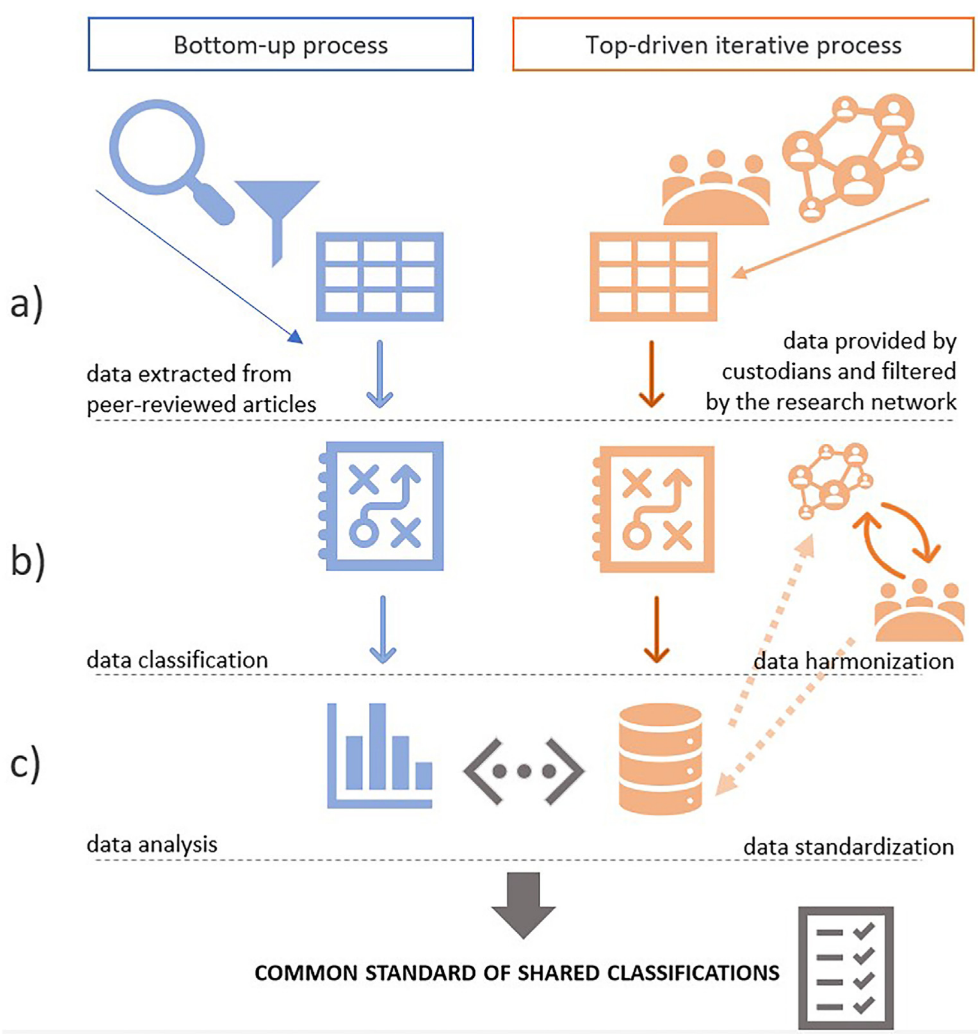


Fig. 1. Workflow summarizing the two processes (bottom-up and top-driven iterative) of analysis: a) data collection: data extracted from 120 peer-reviewed articles (blue, left) and data provided by data custodians (orange, right), b) data classification (blue, left) and harmonization (orange, right), c) data analysis of peer-reviewed articles (blue, left) and standardization of data provided by data custodians (orange, right). Data standardization resulted both from evidences of data analysis and from the iterative refining of definitions and classifications with the platform network. The final outcome: common standard of shared classifications. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

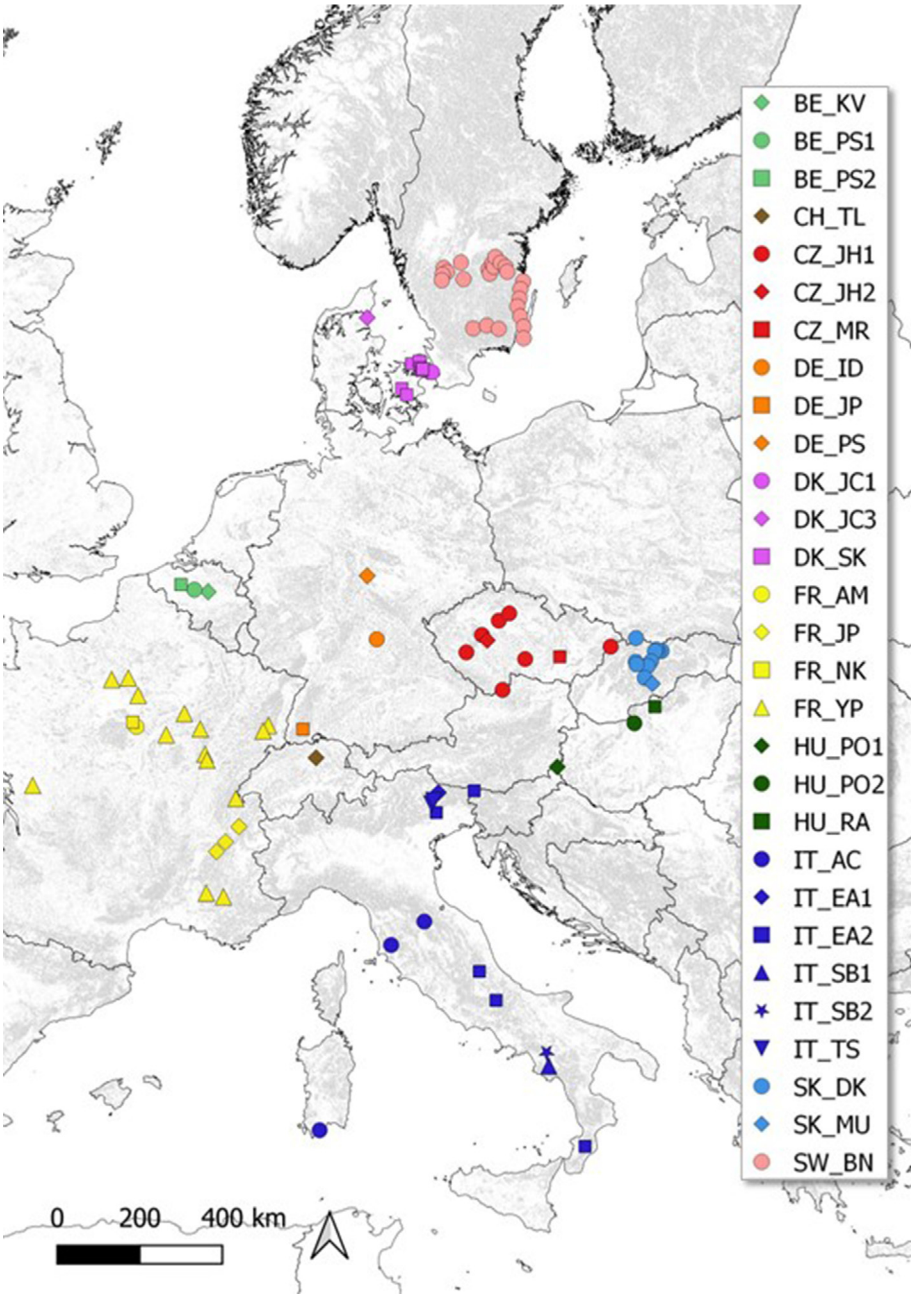


Fig. 2. Research project distribution (total number of sites = 95) throughout Europe. Projects are uniquely identified by a specific combination of symbol and color, and by the acronym of the country where the data were mostly sampled plus the initials of the data custodian. Reference number and detail for each project are reported in Supplementary Material SI 01. Gray areas are covered by forests with a tree cover greater than 40% according to the European Forest Institute Forest Map of Europe (Kempeneers et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Tree plant origin was recorded as important background information, which is mainly related to the silvicultural system. For 'Forms of treatment', the quality evaluation was ranked as: *good* (if based on international standards, i.e., scientific articles, official reports, international manuals of silvicultural practice); *fair* (commonly used terms or original definition of the research project, but with comprehensive explanations); *poor* (original definition of the research project, without deep explanations); *none* (absence of information). The presence of information on 'Stand vertical structure' and 'Regeneration type' was recorded to supplement information on the silvicultural system.

For management information, we recorded the presence of officially ongoing silvicultural practices within the stand (e.g., by management plans or authorized cutting activities). 'Indicators of woody biomass and productivity' and 'Intensity of intervention' are quantitative information that, coupled with qualitative ones (i.e. those reported for sylvicultural systems), could help the interpretation and comparisons of results (Müller et al., 2019). We recorded the presence of indicators of woody biomass and productivity, such as growing stock or living trees basal area, and deadwood biomass as well as indicators of intensity of management activities like harvest utilization rates, frequency of cuts and size of cutting areas. Finally, the 'Time since last intervention' was recorded since it provides further insights on the disturbance effect on stand structure at the time of sampling (Nolet et al., 2017).

2.3. Top-driven data provision

Custodians of each research project were asked to provide data on silvicultural systems and management information for each sampling unit, according to the proposed scheme of harmonized classes, and to the type of last intervention (Table 2). These classes have been established by coupling key findings from the above-mentioned literature review process with a thorough review of seminal works on silvicultural theory and practice (for example, see Matthews, 1989; Smith et al., 1997; Nyland, 2002; Savill, 2004; Härkönen et al., 2019; Palik et al. 2021).

Table 1
Information on forestry and stand-related terms extracted from peer-review articles. Numbers on the left refer to main topic (1: silvicultural systems; 2: management information; 3: vegetation classification). For each type of information and definition we reported the type of record: presence-absence (p/a), or categorical (classification into different 'levels of detail'). For 'Forms of treatment' the quality evaluation of the information is also reported (see text).

	Type of information	Definition	Type of record
1	Tree plant origin and age	The main origin of stand trees (e.g. from sprouts or seeds). Tree stand age as mean tree age for even-aged stands or age of different diameter classes for uneven-aged stands.	p/a
	Forms of treatment	Current (or last, if active management is over) treatment applied.	Level of detail and quality evaluation
	Stand vertical structure	Height stratification of the tree layers (*sensu* Lundqvist, 2017): multi-storied, two-storied, single-storied.	Level of detail
	Regeneration type	Current (or last, if active management is over) method applied for the stand regeneration.	p/a
2	Active management	Presence of ongoing silvicultural practices (planned through forest management plans or other planning instruments).	p/a
	Indicators of woody biomass and productivity	Quantitative data on living and dead woody biomass.	p/a
	Indicators of utilization intensity	Amount of timber harvested (e.g., in terms of basal area, cubic meter, number of trees) during any type of intervention within the applied silvicultural system; indications on the size of cutted areas.	Level of detail
	Time since last intervention	Time since last silvicultural intervention at the time of sampling.	Level of detail
3	Vegetation classification	Can be a general description (e.g., main tree species forming the forest stand) or a formalized classification as European Forest Type (EEA, 2006; Natura 2000 classification of habitat types (Annex I to Directive 92/43/EEC), phytosociological syntaxon.	Level of detail

The harmonization step resulted in six classes of treatment. Group, strip, wedge, and edge systems were considered as variants of the three basic high forest systems (i.e. simple clearcutting, shelterwood, and selection cutting). Finally, custodians were also asked to classify sampling units into forest categories or types (EEA, 2006) and (when possible) into Natura 2000 habitat.

2.4. Data analysis and visualization

We used bar charts to visualize the proportion of research projects with the most comprehensive information; concentric donut chart was used to visualize the range of treatment definitions that were used in scientific literature. We used an alluvial chart to compare data deriving from the bottoms-up process and those defined through the top-driven process. We visualized descriptive statistics using R statistical software (R Core Team, 2022); "ggalluvial" (Brunson, 2020) package was used for the alluvial plot.

3. Results

3.1. Evidences from literature review

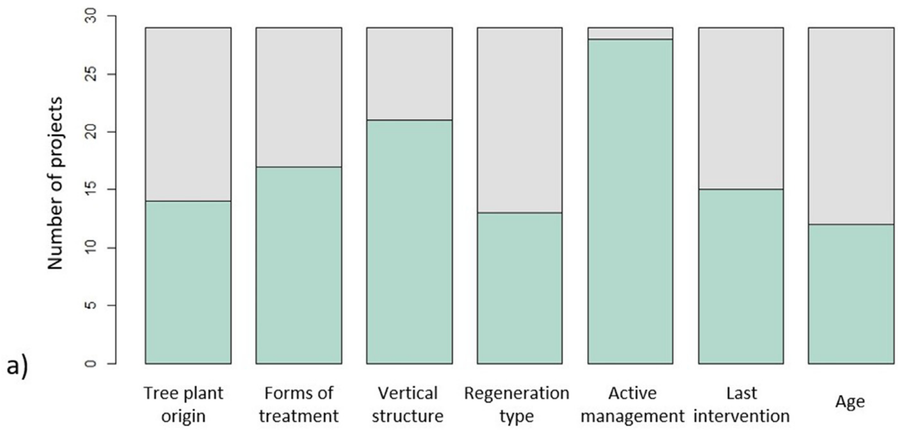
All projects were conducted over the last 20 years and cover different environmental and management conditions of European sites (six out of nine biogeographical regions), representing a timely overview of the silvicultural practices and vegetation classifications currently in use in the forest biodiversity literature.

Table 2
Harmonized terminology used in our study. For each type of information, there are one or more predefined classes as defined with a specific description.

Type of information	Predefined classes	Specific description
Tree plant origin	Sprouts, seeds	The main origin of stand trees.
Form of treatment	Clear-cutting	The forest stand is entirely harvested in a single operation, leaving a treeless open area.
	Clear-cutting with retention	The forest stand is entirely harvested in a single harvesting operation with the exception of specific solitary trees or groups of trees (living or dead) that are deliberately spared.
	Shelterwood	Trees in a forest stand are completely removed using a limited number of progressive cuts designed to promote regeneration making use of the shelter and seed source of remaining trees.
	Selection cutting	Felling and regeneration areas are not restricted to certain parts of the forest, but uniformly distributed. Here are included both single-tree and group selection cutting.
	Simple coppice	All trees originating from stool shoots are entirely harvested by a single operation. This category also includes former abandoned coppices if the cut aims at restoring the coppice system.
	Coppice with standards	The two components of the forest stand (simple even-aged coppice as the under-story, and an over-story of standards which are normally trees of seed rather than sprouting origin) are harvested respectively by a simple clearcutting and a selection cutting. Standards can be uneven-aged and the two components have quite different rotation lengths. This category also includes the combination of coppice and high forest (i.e. compound coppices).
Type of last intervention	Final felling	It refers to the final stage felling within the regeneration cycle of an even-aged stand.
	Partial felling	It refers to felling within the rotation period of a stand (excluding final felling). It includes both those aimed at improving the growth and timber quality (e.g. thinning operations) and those aimed at tree regeneration (e.g. seeding felling, secondary felling).
	Selection felling	Felling continuously distributed over the whole stand (mainly aiming at irregular stand structure).
Regeneration type	Planting	Artificial regeneration by planting juvenile trees.
	Direct seeding	Artificial regeneration by sowing of seeds directly into the forest.
	Natural regeneration	Seedlings or sprouts (from coppice) are produced by trees left on or near the site.

In the articles we reviewed, relevant silvicultural information was mostly lacking (Fig. 3a). Despite most of the projects reported on the presence or absence of ongoing silvicultural activities in the surveyed forest stands, half of the projects did not report on tree plant origin, regeneration type, time since the last silvicultural intervention and age. However, 75% of projects reported information on the stand vertical structure.

Most of the projects reported on the presence (or absence) of ongoing silvicultural activities (column 'Active management' in Fig. 3a). Regarding management history (column 'Last intervention' in Fig. 3a), only Janda et al. (2017) refer to primary forest where no human activity



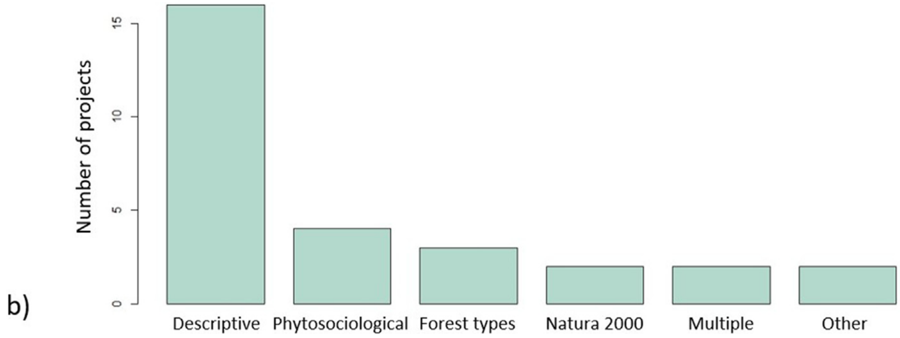


Fig. 3. Number of projects reporting data on silvicultural system and management information (a) and on the type of vegetation classification (b) within the reviewed articles. Information is reported also for 'unmanaged' stands with relatively recent cutting activities (i.e. within the last 50 years). In Fig. 3a, gray bars indicate the number of projects not reporting specific silvicultural system and management information. In Fig. 3b, 'Descriptive' indicates a general description with no international reference classification, 'Phytosociological' the use of a phytosociological syntaxa classification, 'Forest types' the use of the European Forest Type classification, 'Natura 2000' the use of the Natura 2000 habitat type classification, 'Multiple' the use of two or more classification types (phytosociological syntaxa, Natura, 2000 habitat types or Forest types) and 'Other' the use of other types of referenced classification.

directly affected the tree layer for some centuries ('SK_DK' project). Nine projects included some stands defined as 'unmanaged', but all of them are still affected by past cutting activities. Indeed, three of these projects (i.e. 'BE_KV1', 'CH_TL' and 'FR_YP'), described in Vandekerkhove et al. (2016), Haeler et al. (2021) and Paillet et al. (2015), referred to forests that became integral reserves (i.e. with no more management activity) 20 years before the survey. Haeler et al. (2021) mentioned that some portions of the stand were left untouched for decades. Hofmeister et al. (2019) and Ujházy et al. (2017) reported that some portions of the forest stand had been unmanaged since the first half of the 20th century. When reported, we also found a heterogeneous level of detail for the 'time since last intervention': from very precise management histories of the forest (e.g. in 'BE_KV1' or 'DE_ID' according to the management experiment in action) and accurate indications retrieved from management plans (e.g. 'FR_YP' project) to broader indications (e.g. a very general range of years of ceasing activities).

Most of the analyzed projects reported a broad description of forest vegetation (Fig. 3b), mostly based on the presence of dominant tree species, with or without information on the presence of secondary tree species. Four projects reported the European Forest Types categories, but just one of these in combination with its phytosociological syntaxon (Blasi et al., 2010). Three projects reported only Natura 2000 habitat types, while six just the phytosociological syntaxa.

Overall, information on the forms of treatment was highly heterogeneous: from generic 'intensively' or 'extensively managed stand', to detailed descriptions encompassing frequency of cutting activities, stand age and, in some cases, eventual biodiversity enrichment operations (e.g., Ujházy et al., 2017; Bombi et al., 2019; Lelli et al., 2019; Byriel et al., 2020). Only 8 out of 17 projects (i.e. those projects that reported at least some data on the treatment, according to Fig. 3a) provided a good quality information (Supplementary Material SI 02), using terminologies and classifications (e.g., Király and Ódor, 2010; Elek et al., 2018; Schall et al., 2018; Brunialti et al., 2020; Doerfler et al., 2020) consistent with those reported in international manuals (e.g., Matthews, 1989) and recent international publications (e.g., Chianucci et al., 2016; De Cinti et al., 2016). The level of detail of the information of more than 50% of the projects was fair or poor (Supplementary Material SI 02). Storch et al. (2020) from the 'DE_JP' project were the sole reporting detailed descriptions of the silvicultural systems applied at landscape scale (i.e., the Black Forest in Germany) but without specifying the silvicultural treatment applied in the sampled area. In four projects 'continuous cover forestry (or management)' was used in connection with one of the more specific applied silvicultural systems such as shelterwood system, single-tree selection or group shelterwood. For a few cases, more precise information can be retrieved from national scientific journals written in the local language (e.g., Lelli et al., 2019).

The semi-standardization of silvicultural system definitions (Fig. 4) enabled the organization and categorization of the wide array of silvicultural categories observed in the selected projects. Management systems that predominantly result in single-storied forest stands encompass a broader range of categories, from specific and well-known definitions (e.g., clear-cutting with artificial regeneration) to simplified or local terminology and classifications (e.g., a sort of 'selective cutting' followed by 'Femelschlag' system). Many projects used very general, although commonly used, poorly informative categories (e.g., 'even-aged system'). In contrast, multi-storied forest stands were described by a narrower range of definitions. These descriptions are often non-conventional (e.g., thinning operations associated with selective cuttings) or, again, very general (e.g., 'continuous cover management', 'partial cutting'). In the 'DE_ID' project, Doerfler et al. (2020) thoroughly documented the application of a series of treatments based on forest age. Partial cuttings like thinning are also reported as a specific treatment *per se*, independent of any additional information on the applied silvicultural system.

Most of the projects reported basic information on indicators of living tree biomass and deadwood (Supplementary Material SI 02). In most cases, these indicators were calculated from the data collected during the

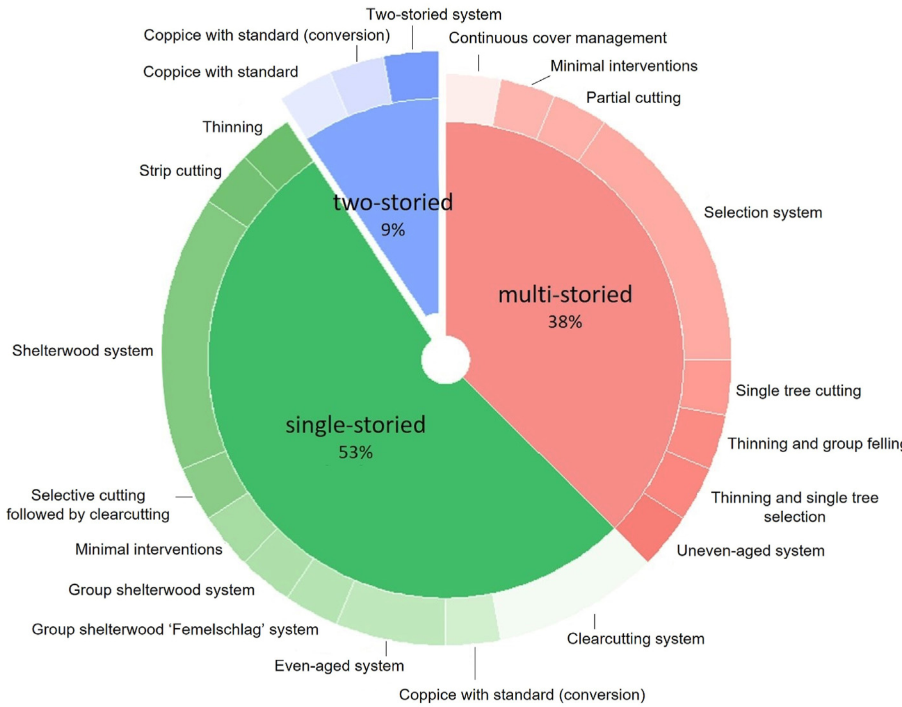


Fig. 4. Correspondance between the assigned silvicutural treatment (outer circle) and the structural description (inner circle) in the reviewed articles. Definitions were coarsely standardized to visualize the manifold definitions used in the articles. Articles previously classified as without specific information (i.e. 'absence' of information in Fig. 3a) are here detectable because they refer to the very general classifications as 'uneven/even aged systems' or 'continuous cover management'.

field surveys (e.g., basal area of living trees, deadwood volume), while some others were gathered from the existing literature (e.g., growing stock from forest management plans). The projects that provide indicators of harvesting intensity (e.g., timber yield, logged volume,

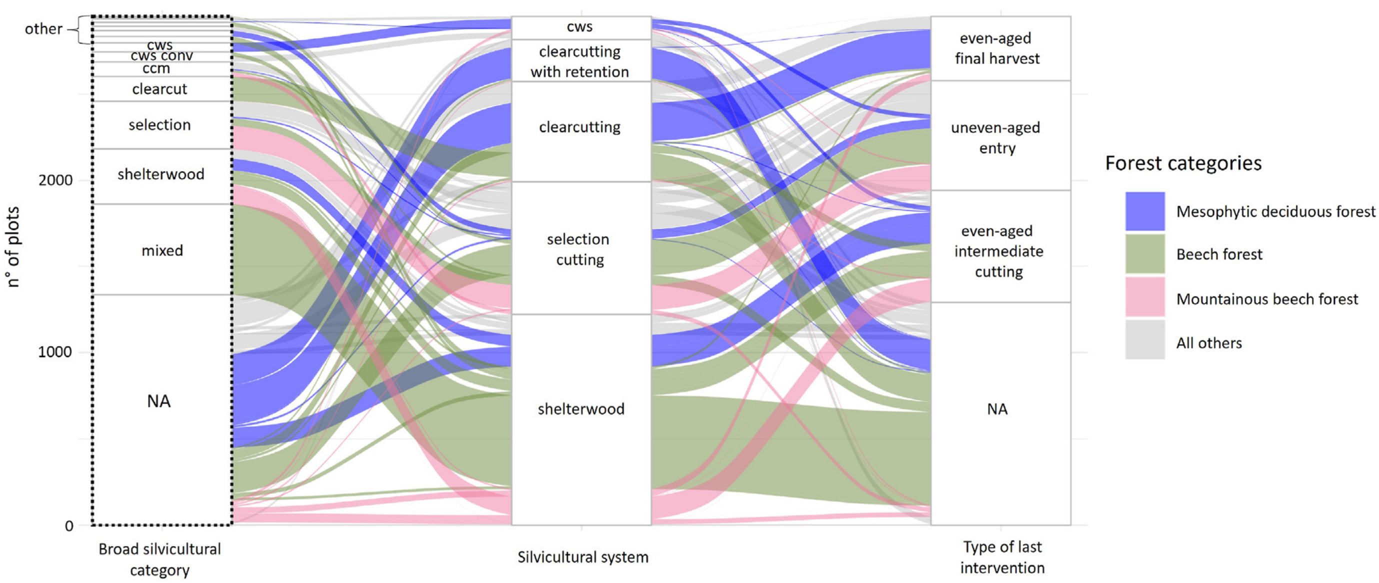


Fig. 5. Alluvial plot comparing the silvicultural information in peer-reviewed articles, i.e., bottoms-up process (first column on the left with dashed outline, "Broad silvicultural category"), with those (the second, "Silvicultural system", and third column, "Type of last intervention") requested by the platform during the first step (letter a) of Fig. 1 of the top-driven iterative process. The number of plots ($n = 2950$, forest categories with less than 30 plots are not included) is reported on the y axis. The analysis excludes plots with 'NA' on a silvicultural system or classified as 'unmanaged' ($n = 555$). 'Other' refers to nine additional silvicultural system categories with fewer than 40 plots: even-aged management, group shelterwood system, partial cutting, strip cutting, thinning and group felling, thinning and single tree selection, two-storied management, uneven-aged management, selective cutting followed by clearcutting. 'Mixed' refers to 'mixed situations' described in the previous section, 'cws conv.' means coppice with standard conversion to high forest, 'cws' means coppice with standard, 'ccm' means continuous cover management. 'NA' in 'type of last intervention' column represents the number of projects where the requested information (i.e., type of last intervention) was not available (e.g. data that are not detectable by custodians). The most commonly sampled forest categories (total number of plots for each forest category >200) are highlighted in color: Mesophytic deciduous forest (5); Beech forest (6); Mountainous beech forest (7); All others forests categories (2 - Hemiboreal forest and nemoral coniferous and mixed, 3 - Alpine coniferous forest, 4 - Acidophilous oak and oak-birch forest, 8 - Thermophilous deciduous forest, 11 - Mire and swamp forest, 14 - Introduced tree species forest) are in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

frequency of intervention, dimension of logged areas) are predominantly those that exhibit the most accurate description (i.e. quality level classified as "good") of the implemented silvicultural system (e.g. 'DE_PS', 'IT_EA', 'HU_PO2' projects). Some of these projects involve the application of experimental treatments (e.g., 'HU_PO2').

3.2. Applying a common standard of silvicultural definitions

In several instances, research projects lacking a clearly defined silvicultural system in reviewed articles were successfully associated with one or more of the proposed silvicultural system categories (Fig. 5). Most of considered stands were high forests (98%), with only a small fraction as coppice (2%). Some of the classifications used in published articles were consolidated with others, resulting in the creation of a more comprehensive category within the standardized classification system.

In some cases, the association between published and standardized information was complex due to the use of terminology with multiple interpretations depending on the historical or geographical tradition. The most relevant example is the so-called 'Femelschlag system', which was reported for projects located in Denmark and Belgium. In the first phase of the top-driven process, this form of treatment has been forced into the shelterwood system according to Matthews (1989) and Raymond et al. (2009). But this choice was followed by an articulated discussion throughout the phases of the iterative process (see Discussion section). Out of the plots that reported the silvicultural system, the associated type(s) of the latest intervention was reported in 56% of cases. However, for plots associated with the shelterwood system, data custodians could not retrieve this type of information in 47% of the cases. For 64% of the plots, information regarding the time elapsed since the last intervention was also unavailable.

For all the forest stands, it was possible to retrieve forest categories according to EEA (2006) as well as forest types (data not shown). The most frequent category was lowland beech forest (code = 6, 40%), followed by mesophytic deciduous forest (code = 5, 24%). Coppiced stands were mainly formed by thermophilus deciduous forests (i.e. Downy oak/Turkey oak, Hungarian oak/Sessile oak forest types).

4. Discussion

The long history of forest management in Europe has produced a heterogeneous set of practices, and hence of silvicultural vocabulary. Our work provides a comprehensive overview of forest management and vegetation classifications employed in the biodiversity research conducted in Europe. We standardized the information retrieved in peer-reviewed articles through the active engagement of the researchers involved in them. Through this process, we were able to develop a harmonized terminology for vegetation and management-related information that will facilitate the comparability of results among research projects. This effort resulted in: (i) increasing the awareness on the relevance of the terminology used in research projects relating forest management and biodiversity; (ii) proposing a common set of terms and data classification; (iii) highlighting the need to integrate specific terminologies with in-depth descriptions and supporting data.

4.1. Silvicultural and vegetation information in European forest biodiversity research projects

Recent studies have primarily drawn their conclusions by examining the relationships between forest biodiversity and specific management regimes or silvicultural systems (Kerr, 1999; Torras and Saura, 2008). However, most forest biodiversity projects inadequately summarized the management regime, and lacked comprehensive information on current active or non-intervention management. This result is in line with the findings of Mason et al. (2022), who reported difficulties faced by respondents (i.e., foresters and researchers) in providing accurate data on the silvicultural system in an European wide survey. On the one hand, the lack of information in the scientific literature may derive from a limited expertise of biodiversity researchers in silvicultural practices, or from their deliberate choice to omit technical aspects of forest management. Overall, this results in a focus on forest ecology rather than on conservation practices, economical constraints, and forest management. On the other hand, most European forests lack detailed management plans (Forest Europe, 2020), and even when a management plan exists, it is seldom publicly accessible. Further causes of this lack of information are: (i) the text length limitations set by scientific journals that may discourage the inclusion of information not strictly related with the main objective of the article, (ii) the fact that biodiversity data are collected at a finer scale (e.g., 1000 m^2) than silvicultural information (e.g., compartment scale).

Within the literature we analyzed, just a few articles reported detailed qualitative information on the adopted silvicultural system, along with crucial ancillary information like time elapsed since the last treatment or frequency and intensity of interventions. Notably, these research projects were conducted within the framework of national and European projects (e.g., EU LIFE programme) that prioritize the integration of scientific knowledge with practical applications (Cistrone et al., 2015), or include experimental treatments (e.g., Doerfler et al., 2017; Elek et al., 2018).

Our synthesis shows that detailed information on current and past stand silvicultural practices is essential to understand their impact on biodiversity (Paillet et al., 2010) but still widely neglected in biodiversity studies. The reviewed articles often reported deep analysis of current biomass, but rarely referred to legacy effects (Muurinen et al., 2019), missing the link between past and present silvicultural regimes (Bergès and Dupouey, 2021). Information on thinning operations and other intermediate treatments can provide valuable information on the frequency of interventions, as well as on biomass or other structural properties necessary for the calculation of indices of forest management intensity (Schall and Ammer, 2013). Moreover, the broad range of silvicultural categories and definitions reported hampers the comparability of the results of different research projects.

As stressed by Oettel and Lapin (2021), a crucial step towards enhancing sustainable forest management in Europe is to establish a connection between management indicators related to management intensity (e.g., harvesting method, amount of timber harvested, management history) and conservation-oriented silvicultural practices. The absence of this prerequisite hampers the assessment of the impacts of different silvicultural systems on forest biodiversity, which is essential for policymakers and stakeholders to monitor forest functions (Mason et al., 2022), as emphasized in the recent EU forest strategy (COM(2021) 572 final). In this view, our work serves as a link between research suppliers and users, a need already stressed by Coll et al. (2018).

Rigorous vegetation classification was included in the most comprehensive research projects, some of which used multiple classifications, e.g., forest types and habitat types. The combination of these specific vegetation classifications with detailed management information and structural data is extremely valuable for the implementation of forest biodiversity conservation and restoration practices (Kovac et al., 2018; Trentanovi et al., 2018) and for the fine tuning of indicators of sustainable forest management (Barbati et al., 2014). Similarly, reporting the phytosociological associations provide readers with a deeper understanding of the surveyed forest stand and of the forest dynamics (Barbati et al., 2014). However, most of the projects reported only a general description based on the dominant tree species, often without details on secondary species.

4.2. A common standard for forest biodiversity research projects

The iterative discussion resulted in the proposal of a standardized framework (Fig. 6) of harmonized information that should be reported in biodiversity research projects.

Our standard scheme deliberately excludes the silvicultural category of 'coppice in conversion to high forests'. This decision was influenced by

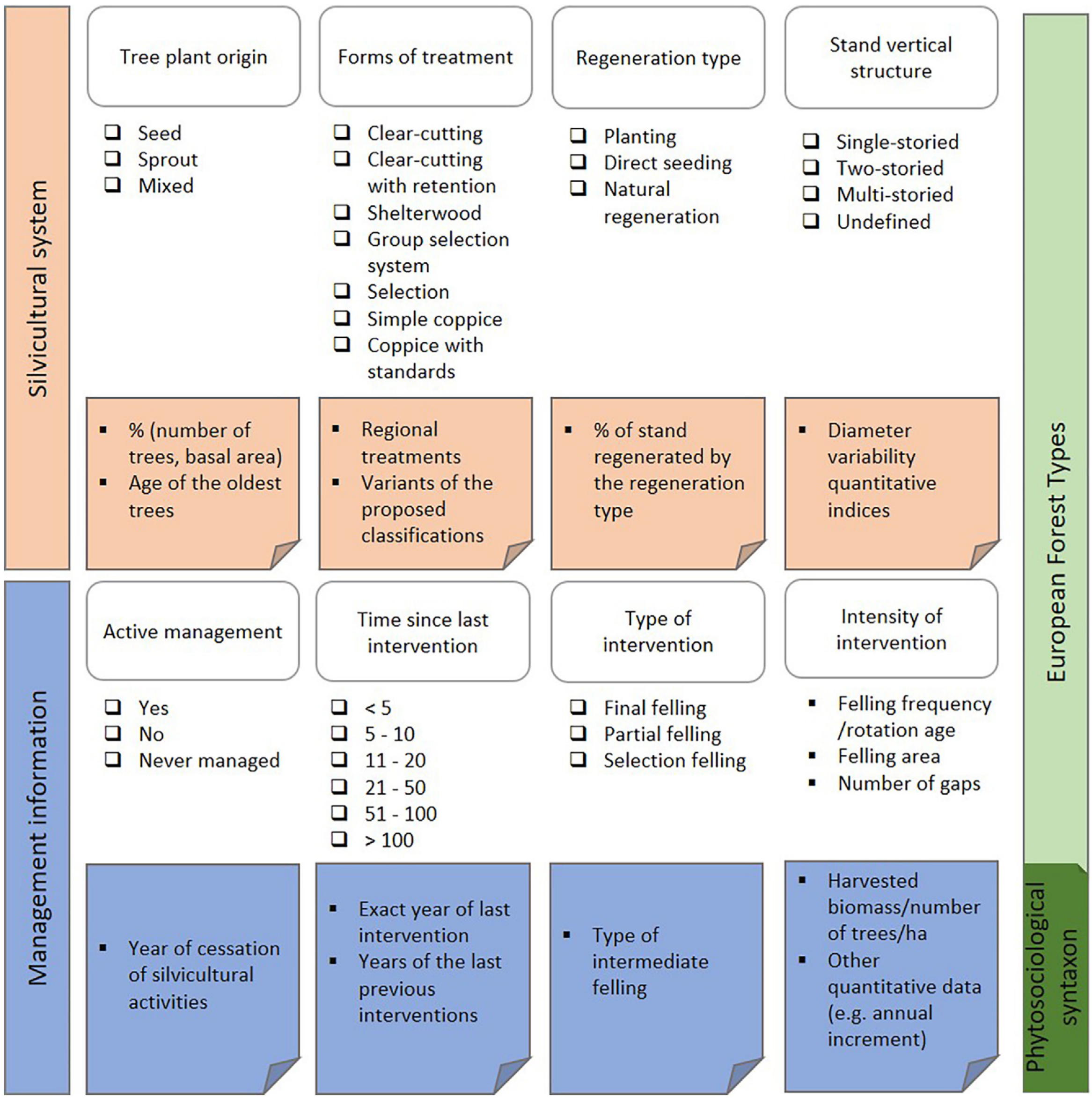


Fig. 6. Proposed standard on forestry and stand-related information. Primary information and classification are reported in the upper part of the framework, optional data within the box at the bottom. A worked-out example is reported in Supplementary Material SI 03.

the scarcity of records found in the literature review and by discussion with experts. Instead, we focused on indicating the prevailing silvicultural system based on the main tree plant origin, regardless of the heterogeneous transitory phases associated with coppice conversion. Conversely, we stress the need to include information on the current stand structure and possible dynamics, such as the type and time since the last intervention, and quantitative data on current biomass distribution as well as intensity of interventions.

During the discussion with researchers, the interpretation of silvicultural approaches associated with diverse meanings across geographical and historical contexts was challenging. For instance, the 'Femelschlag' system was originally developed and implemented in the beech forests of Switzerland (Heiri et al., 2009). It was progressively adopted across different countries with applications deviating from its initial form and resulting in a variety of silvicultural systems (Sagheb-Talebi, 1995; Röhrig et al., 2006; Raymond et al., 2009; Puettmann et al., 2009). American foresters refer to it mainly as an irregular shelterwood method with flexible applications at smaller spatial scales (Puettman et al., 2008). Irregular shelterwood differs from regular shelterwood and its variants in that the forest cover is retained during a long period of time to accommodate special management objectives (Nyland, 2002) and establish mixed forests (Gayer, 1886). Indeed, the 'Femelschlag' system, as understood by European foresters, is far from the shelterwood system, as the former aims at the establishment of uneven-aged forest stands with cohorts of different age classes (Mohr and Schori, 1999). Based on this discussion and scientific literature, in our scheme we included a stand-alone system called 'group selection system' (Knoke, 2012), where Femelschlag and other tree group-related approaches could fit. By coupling this term with additional information on stand vertical structure and the size of the cutting area (see primary information section in Fig. 6), the international reader will gain a closer and clearer understanding of the applied silvicultural system and its objectives.

While traditional terminology can be useful at the local scale to facilitate implementation and dissemination among stakeholders, conceptual frameworks are needed at the European level (MPFE, 2003; Duncker et al., 2012). To promote understanding across different scales and contexts, it is advisable to provide comprehensive descriptions of forest stands that incorporate both local or specific silvicultural practices and broader categories with extensive explanations on their meaning and goals (e.g. secondary information section in Fig. 6).

The classification of recently set aside forest stands poses another significant challenge for categorization and terminology. This issue often arises when management activities cease due to the establishment of a new strictly protected area or the absence of ongoing management through planning instruments. In the articles reviewed, these forest stands were often defined as "unmanaged" even when the effect of past activities was still significant. In our scheme, the term 'unmanaged' refers to the lack of management plans (where required) or of specific harvesting authorizations issued by local authorities. However, we acknowledge the existence of forest stands that, despite legally requiring a management plan, are either set aside or subjected to occasional cutting for years or decades. For this reason, when classifying a stand as 'unmanaged' we strongly recommend indicating the time since the last intervention. This information can be retrieved through field observations (e.g., presence and decay stage of artificial stumps) or more precisely through forest management planning instruments (see Maksin et al., 2018; Trentanovi et al., 2018). Collecting information on the historical uses of a forest stand can be facilitated through interviews with local stakeholders (see Mason et al., 2022) and by taking advantage of online sources. The proposed scheme limits the misinterpretation of the term 'unmanaged forests', which we often found in forest biodiversity research projects, but without essential specifications.

5. Conclusions

The primary objective of this work was to establish a unified and standardized set of classifications that can facilitate the assessment of the impact of forest management practices on biodiversity. Such standardization will benefit all the stages of forest biodiversity studies, from the design of monitoring programs that encompass forest stands with diverse management approaches and intensities, to the scaling up of local research findings to the European context. Establishing a common ground is necessary to fill the gap between science and practice in sustainable forest management (Ammer et al., 2018), since forest management and silviculture are multi-faceted topics that lie between traditional practices and evidence-based approaches. Multidisciplinary collaboration between conservation biologists, forest ecologists and foresters is crucial to understand relationships between management and biodiversity in forest ecosystems.

Researchers should increase their efforts of including data of forest stands that can have significant implications on biodiversity (Zavala and Oria, 1995) to strengthen the link between forestry and ecology. Human-induced or natural disturbance intensity and frequency, together with the silvicultural system, should be accounted for in order to define relevant indicators to measuring the effects of forest management (Pretzsch, 2019; Aszalós et al., 2022) and enhancing biodiversity conservation efforts in sustainable forest management (Oettel and Lapin, 2021).

Although primarily focused on the European experience, the proposed standard represents a valuable starting point to be tested and adapted to the requirements of other continents and extended to other types of forest interventions (e.g. post-disturbance salvage logging, Thorn et al., 2020). Adopting a standardized approach to describing and categorizing silvicultural systems and their effects on biodiversity would be highly beneficial in producing global summaries and assessments of the impacts of silviculture on biodiversity.

Conflict of interest

All authors declare that they have no conflict of interest.

Author contribution

GT, TC and SB developed the idea of the manuscript. TS, FC, YP, KV, AC, ED, PS, ID, JHC, JH, JH, PJ, NK, DK, TL, AM, MR, MM, BN, PO, PS, MS, FT, MU and SB contributed the data. GT, TC, TS, FC, and SB collected and harmonized the data. GT realized the graphs and performed the analysis. GT, TC and SB developed the first draft of the manuscript. TS, FC, GV, CA, MC, TAN, MdR, YP, SM, KV, ABO and EDA revised the first draft, providing substantial contributions to the further development of the manuscript. All the authors contributed to the text.

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Appendix A. Supplementary data

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