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Where are we now with European forest multi-taxon biodiversity and where can we head to?

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► To cite this version:

Sabina Burrascano, Francesco Chianucci, Giovanni Trentanovi, Sebastian Kepfer-Rojas, Tommaso Sitzia, et al.. Where are we now with European forest multi-taxon biodiversity and where can we head to?. *Biological Conservation*, 2023, 284, pp.110176. 10.1016/j.biocon.2023.110176 . hal-04185032

HAL Id: hal-04185032

<https://hal.inrae.fr/hal-04185032v1>

Submitted on 22 Aug 2023

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1 WHERE ARE WE NOW WITH EUROPEAN FOREST MULTI-TAXON BIODIVERSITY AND WHERE CAN WE HEAD TO?

2

3 ABSTRACT

4 Forestry implementation significantly impacts forest biodiversity. Despite the promotion of
5 Sustainable Forest Management (SFM) in Europe, sustainability assessments hardly account for
6 direct biodiversity indicators. We aim to i) gather and map the existing information on forest multi-
7 taxon biodiversity associated with stand structure and management in Europe; ii) identify knowledge
8 gaps for forest biodiversity research; and iii) discuss the research potential associated with multi-
9 taxon biodiversity data.

10 We established a research network focused on multi-taxon biodiversity, stand structure and
11 management data of European forests; and fitted species records, standing trees, lying deadwood,
12 and sampling unit metadata from 34 local datasets.

13 Suitable information was available for 3,591 sampling units, each surveyed for on average 4.6
14 taxonomic groups. Standing tree diameters, tree height deadwood and tree-related microhabitats
15 were sampled in respectively 2,889; 2,356; 2,309 and 1,388 sampling units. Sampling unit metadata
16 includes spatial coordinates, and compositional and management descriptors.

17 Available data cover all the 14 European forest compositional categories but are unevenly distributed
18 among them, with European beech forests being over-represented as compared to thermophilous
19 and boreal forests.

20 Overall, the available information has the potential to inform the development of conservation and
21 SFM strategies for European forests by supporting: (i) methodological harmonization and
22 coordinated monitoring; (ii) the definition and testing of SFM indicators and thresholds; (iii) data-
23 driven assessment of the effects of environmental and management drivers on multi-taxon forest
24 biological and functional diversity, (iv) multi-scale forest monitoring integrating *in-situ* and remotely
25 sensed information.

26

27 INTRODUCTION

28 Forests support about three-quarters of terrestrial plants, fungi and animal species (FAO, 2020),
29 and are at the base of other ecosystem services including the provisioning of raw materials and the
30 regulation of geochemical cycles. These services are threatened by climate change, forest loss and

31 degradation, invasions by non-native species, and over-harvesting (Felipe-Lucia *et al.*, 2020). The
32 increasing concern related to these threats has imposed a paradigm shift from single-objective forest
33 management (i.e., timber production-oriented) to the embracement of forest multifunctionality
34 (Mori *et al.*, 2017).

35 Sustainable Forest Management (SFM) is defined as the management that concomitantly
36 maintains forest biodiversity, productivity, regeneration capacity, and vitality, as well as forests'
37 potential to fulfill a wide range of functions and services (MCPFE, 1993). As such, SFM is globally
38 recognized as a crucial tool to counteract biodiversity loss, and to promote sustainable development
39 (UN, 2015). Managing forests sustainably is particularly relevant in Europe, where, although about
40 24% of forests are formally protected, only a small fraction (2% of total forest area) is not subject to
41 harvesting interventions (Forest Europe, 2020). Accordingly, the SFM definition reported in the
42 European Union regulation (2020/852) includes a criterion of biodiversity maintenance, reported as
43 the contribution to “enhancing biodiversity, halting or preventing the degradation of ecosystems,
44 deforestation and habitat loss”.

45 Nevertheless, the effects of SFM on the diversity of multiple taxonomic groups, hereafter multi-
46 taxon biodiversity, are not sufficiently known due to the high demands of multi-taxon biodiversity
47 sampling and analysis, which requires significant funding, time, and a broad range of expertise and
48 competences (Tomppo *et al.*, 2010). For these reasons, it remains uncertain to which extent, and for
49 which taxonomic groups could forest management for wood supply deteriorate biodiversity
50 compared to unmanaged forests, and how SFM can mitigate these effects.

51 The challenges of multi-taxonomic field sampling are being increasingly addressed at the local or
52 regional scales. In Europe, these efforts often consist of exhaustive species censuses across single- or
53 multiple sites to assess the effects of forest structure and management on the diversity of multiple
54 taxonomic groups (see references in Table 1). Relatively few examples of such studies can be found
55 in other continents within the temperate and boreal zones (Murray *et al.*, 2017; Bowd *et al.*, 2021;
56 Stokely *et al.*, 2022). The efforts of European researchers to test the effectiveness of SFM reflect the
57 long-lasting and widespread land-sharing approach to forest zoning that characterizes Europe, at
58 least since Möller (1922), as compared to regions where a sparing approach is more common (e.g.,
59 Australia, North America). However, compared to continent-wide health forest monitoring networks
60 (e.g., International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects

61 on Forests - ICP Forests), research activities related to European forest biodiversity remain
62 uncoordinated at the continental scale and suffer from a lack of harmonization and integration across
63 local studies.

64 Here we aim to i) review the existing information on forest multi-taxon biodiversity associated
65 with stand structure and management and ii) identify knowledge gaps in multi-taxon forest
66 biodiversity studies. Starting from this basis, we aim to iii) discuss future research challenges
67 associated with multi-taxon biodiversity in European forests. Ultimately, we intend to encourage new
68 institutional forms of broad-scale forest biodiversity data collection and usage to inform forest
69 conservation and management policies in Europe and elsewhere.

70

71 METHODS

72 DATA COLLECTION

73 We aimed at gathering forest biodiversity and stand structural data from many independent
74 research projects and studies on multi-taxon forest biodiversity performed across Europe in the last
75 20 years. We created a network connecting research groups that collected forest multi-taxon
76 biodiversity data in Europe from local to national scales. The initial network was progressively
77 enlarged by contacting researchers involved in past and ongoing forest multi-taxon biodiversity
78 projects identified through project databases (i.e., LIFE projects' database:
79 <https://webgate.ec.europa.eu/life/publicWebsite/search>), publications and personal information.

80 We defined a *forest* as an ecosystem in which tree cover was equal or greater than 40% (Sasaki &
81 Putz, 2009). We intended *multi-taxon* to include simultaneous information on a minimum of three
82 taxonomic groups, representing at least Plantae or Fungi, and Animalia. *Stand structure* data was
83 defined as tree species composition, volume and size distribution of standing trees (both living or
84 dead), and of lying deadwood when available.

85 To test the comprehensiveness of the platform, we surveyed the research network on relevant
86 literature and gathered 117 published articles (Trentanovi *et al.*, submitted). We added further
87 articles found through a literature search on ISI Web of Science (accessed on November, 17, 2022
88 and limited to articles published before 2022) with the formula (TS= (forest AND multi-tax* AND
89 biodiversity)). This search resulted in 130 additional articles, of which 61 describe studies performed

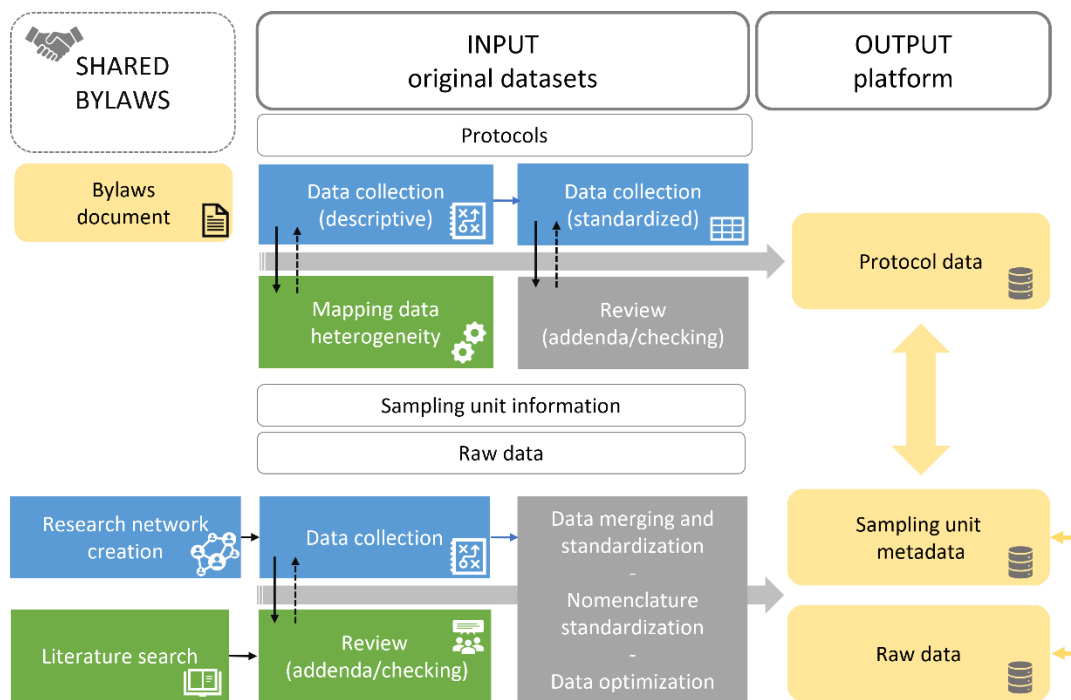
90 in Europe. Among these, 17 focused on non-forest habitats (e.g., wood pastures, urban or agricultural
91 areas), 17 did not fit the multi-taxon or stand structure requirements, five had a different focus
92 (sampling methods, biotic disturbance). Only 22 articles fitted the platform requirements, among
93 which 11 were already listed in the literature gathered through the research network, and five were
94 relative to datasets already included in the platform. Based on this literature assessment we deemed
95 the platform as significantly representative.

96 For each dataset in the platform, we firstly gathered and harmonized the information on sampling
97 designs and protocols (see the 'protocols' of Fig. 1) into three ancillary tables that include
98 standardized sampling protocol descriptions of: standing trees, lying deadwood, and biodiversity
99 data. (i.e., 'protocol data' in the output section of Fig. 1).

100 The spatial hierarchy of the platform encompasses plots (i.e., delimited forest areas of known
101 geographical coordinates) that are nested into stands (i.e., management spatial units), and stands
102 that are nested into sites (i.e., environmentally homogeneous geographical areas). We generally refer
103 to sampling units to include both plots and stands, since in a minority of cases (about 15% of the
104 stands do not have plot IDs but stand IDs), data were sampled at the stand scale, without specific
105 sampling plots. It is also relevant to point out that for most of the collected datasets, several
106 ecosystem components, i.e., taxonomic groups and stand structure, were sampled in the same *plots*,
107 but in a minority of cases different components were sampled using various designs across a forest
108 stand, allowing for cross-taxon analysis only at the stand scale (see Burrascano *et al.*, 2021 for a
109 thorough discussion of the pros and cons of the two approaches).

110 The studies included in the platform were mainly observational but some experimental studies
111 were also included. In both cases, we collected information on stand age and/or development stage,
112 a categorical definition of the silvicultural system adopted, and many other associated quantitative
113 management data (e.g., time since last harvesting).

114



115

116 Figure 1. Workflow of the platform building process. Blue boxes identify in-progress products; green
 117 boxes identify phases of common decisions, brainstorming and comparison with scientific literature;
 118 gray boxes indicate data processing; yellow boxes are the outcomes.

119

120 DATA MANAGEMENT

121 Each original dataset was associated with one data custodian, responsible for data preparation
 122 and handling within the platform, and for communication with the dataset contributors. The
 123 heterogeneity in sampling designs, measurement methods, spatial scales, target variables and
 124 taxonomic groups required the definition of standardized procedures to harmonize raw information
 125 and produce a common data structure.

126 We built a relational structure encompassing several tables whose organization and templates
 127 derived from an iterative process of proposals and refinements carried out through a wide and open
 128 discussion (see connections between boxes in the ‘Input’ section in Fig. 1).

129 The core of the platform (i.e., ‘Sampling unit metadata’ and ‘Raw data’ in Fig. 1) consists of four
 130 tables: one containing sampling unit metadata and the others containing the raw data separately for
 131 standing trees, lying deadwood, and multi-taxon species composition.

132 The sampling unit metadata includes location, ownership, structure, regeneration and
 133 management type. Two key variables within this table are the forest compositional category and the

134 silvicultural system. The former refers to the classification into 14 categories of ecologically distinct
 135 forest communities in Europe dominated by specific assemblages of tree species (SI-1). These
 136 categories were designed to facilitate the interpretation and communication of indicators on the
 137 status and trends of forests in Europe (EEA, 2006; updated by Barbati et al., 2014). The classification
 138 into broad silvicultural systems was based on the type of regeneration cut according to Matthews
 139 (1989) and refined through an extensive discussion within the network (Tab. 1).

140

Silvicultural systems	Treatment description
Unmanaged	No silvicultural interventions applied in the recent past, stands currently under natural development
Selection cutting	Single-tree and group selection cutting are uniformly distributed across the stand.
Shelterwood	Overstorey trees in a forest stand are completely removed through multiple progressive cuts designed to promote regeneration making use of the shelter and seed source of remaining trees
Clearcutting with retention	The forest stand is clear-felled in a single harvesting operation except for solitary trees or tree groups that are deliberately spared
Clearcutting	The forest stand is entirely harvested in a single operation, resulting in a treeless open area mostly artificially regenerated
Coppice with standards	The two vertical strata of the forest stand (even-aged coppice as the understorey, and an overstorey of standards which are trees of seed-rather than sprouting origin) are harvested respectively by a clearcutting and a selection cutting. Standards can be uneven-aged and the two components have quite different rotation periods. This category also includes the combination of coppice and high forest (i.e. compound coppices)

141 Table 1. Definitions of the silvicultural systems used in the platform.

142 Data were processed in the R programming environment (R Core Team, 2021, R version 4.1.1)
 143 using version control to ensure the widest possible hands-on collaboration and data cross-checking.
 144 Data inconsistencies that may have originated from data entry errors (e.g., typographical errors), data
 145 type storage, species nomenclature, and adherence of datasets to the table structure (e.g., column
 146 names, list of possible and plausible values) were qualitatively checked through several validation

147 rules. These (semi)automatic rules were based on data range, length, column reference name, list
148 values, null values, blank values, and data types. After this validation process, data have been
149 corrected or integrated mostly through back-checking to data providers.

150 Species names and higher taxonomic information were extracted from databases and
151 corroborated by experts. All species names were firstly checked using the `gnr_resolve()` function in
152 the 'taxize' package (Chamberlain & Szöcs, 2013). The species names obtaining scores greater than
153 0.90 were accepted, while those with lower scores were sent to experts for corroboration. For
154 vascular plants, a further screening was performed through the 'WorldFlora' package (Kindt, 2020).
155 Finally, species names that could not be corroborated by experts were checked against the GBIF
156 database (<https://www.gbif.org/>). Complete taxonomic classification was extracted with the
157 `taxonomy()` function in the 'myTAI' package (Drost *et al.*, 2018).

158 Relationships across tables operate at different spatial scales through univocal IDs for sites, stands,
159 and plots. The templates of the tables for contributing data to the platform are available at: XXX to
160 promote further implementation of the data.

161 Data management is coordinated by a governing board elected by the consortium involving all
162 data contributors according to common bylaws that were discussed and accepted by all the
163 consortium participants (XXX). The bylaws are composed of eight regulation articles partly based on
164 previous experiences of shared datasets (e.g., Biurrun *et al.*, 2019). As it is always the case in the
165 beginning of these sharing processes, a give-and-take approach has been chosen (Kattge *et al.*, 2020;
166 Bruelheide *et al.*, 2019); therefore, joining the consortium is possible for researchers that provide a
167 dataset complying with the bylaws requirements. Data usage is open to anyone proposing a research
168 project involving at least one consortium member by following the instructions at: XXX. A Shiny Web-
169 App (XXX) was created to smooth the proposal of projects by allowing for data exploration and
170 filtering based on the sampling unit metadata (SI-2).

171

172 DATA ANALYSIS AND VISUALIZATION

173 The proportion of sampling units for each compositional category was compared with the share of
174 such categories in the European Union forest area as reported in Barbati *et al.* (2014). Similarly,
175 sampling unit distribution across broad regeneration strategies (high forest and coppice), and
176 unmanaged areas were compared with the share of forest area under these conditions as reported

177 in McGrath *et al.* (2015). Sampling unit metadata were visualized through alluvial plots using the
178 'ggalluvial' R-package (Brunson, 2020).

179 The distribution of species and species records across higher taxonomic ranks (phyla and classes) was
180 represented through a phylogenetic tree, encompassing 7,335 out of the 8,724 species of the
181 platform. The tree was obtained through PhyloT (<https://phylot.biobyte.de/>) in Newick format and
182 imported in R through the 'ape' package (Paradis & Schliep, 2019). To each species in the tree we
183 associated its higher taxonomic ranks derived through the 'myTAI' package (Drost *et al.*, 2018) and
184 the number of occurrences across sampling units (SI-3). The combined information was visualized by
185 using the 'ggtree' package (Yu *et al.*, 2017).

186 In addition to the mentioned check for plausible ranges of values, structural data were subjected to
187 specific integration processes. Heights of standing trees were integrated by means of height-
188 diameter relationships (hypsometric models); whereas deadwood fragments measurements were
189 integrated through data imputation performed using the 'mice' package (van Buuren & Groothuis-
190 Oudshoorn, 2011). Data integration was performed individually for each dataset by applying the
191 predictive mean matching (PMM), i.e., assessing imputation uncertainty through the examination of
192 the variation in imputed values when treated as real, and including forest compositional categories
193 and types, and spatial variables (plot and site). Few datasets lacked any measures of height/length
194 and were integrated by using the whole data platform. A total of 42,643 tree heights out of 178,098
195 were calculated by means of hypsometric models; and 5,011 diameters and 9,317 lengths were
196 imputed out of 58,824 lying deadwood fragments. Based on these data, the distributions of sampling
197 unit mean of Diameter at Breast Height (DBH) for standing trees and of diameter for lying deadwood
198 were calculated (SI-4, SI-5).

199 Biodiversity and stand structure indices may be related to environmental conditions by using
200 parameters published in the framework of other research projects. For instance, each sampling unit
201 was spatially associated with data on soil characteristics that were obtained from the European
202 topsoil physical properties map (Ballabio *et al.* 2016). Among the multiple soil properties available in
203 this dataset, those currently linked to each forest multi-taxon sampling unit over a 1000 m buffer
204 from the center of the sampling unit are: Available Water Capacity, Bulk density (derived from soil
205 texture datasets), Soil textural classes derived from clay, silt, and sand maps. Similarly, climatic data
206 were obtained from CHELSA v.2.1 (Karger *et al.* 2017), at 1000 m resolution. Bioclimatic variables

207 were derived as long-term means or sums over the 1981–2010 period, and included mean annual
 208 temperature, annual range of air temperature, annual precipitation amount, and precipitation
 209 seasonality. Each sampling unit is also associated to a heat load index (HLI) expressing the
 210 topographic influence on incident solar radiation (McCune and Keon 2002).

211

212 RESULTS

213 OVERVIEW OF THE EXISTING DATA

214 *Sampling units*

215 A total of 3,591 sampling units across 220 sites in 12 European countries were gathered (SI-2,
 216 <https://zenodo.org/record/7886698#.ZFES7HZBxD8>), ranging from Sweden to southern Italy in
 217 latitude, and from France to Lithuania in longitude (Fig. 2). The harmonization involved 34 local
 218 datasets (Tab. 2) and 185 researchers.

219

220 Table 2. General descriptors of the local datasets. Dataset ID: ID of dataset, Country: country where
 221 the study has been made, N sites: number of sampled sites, N units: number of sampling units,
 222 Reference: main literature references of the 34 datasets collected for this work.

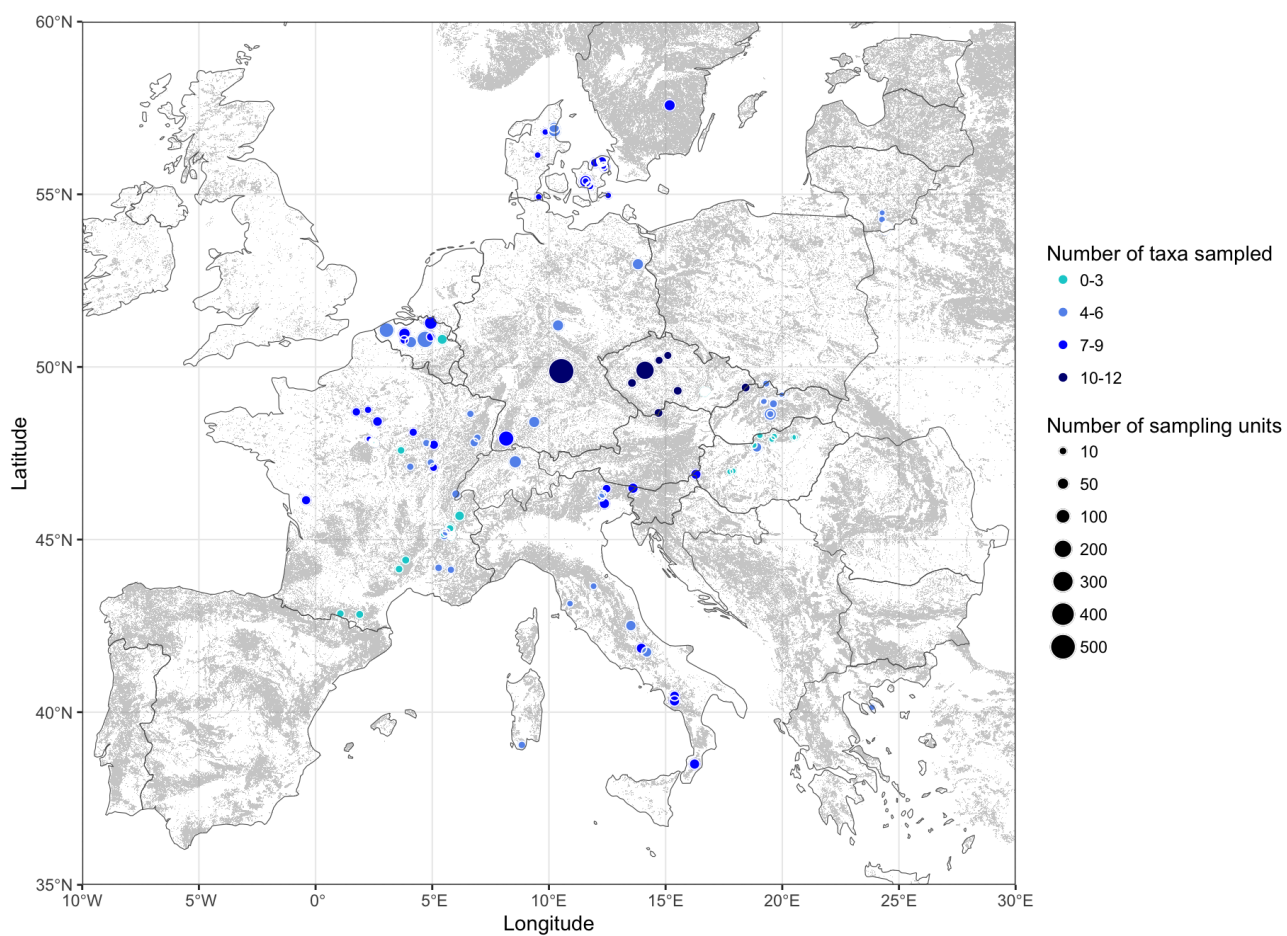
Dataset ID	Country	N sites	N units	Reference
BE_PS1	BE	2	32	De Smedt et al., 2019
BE_PS2	BE	1	53	De Groote et al., 2017
BE_KV1	BE	5	462	Vandekerkhove et al., 2016
CH_TL	CH	1	69	Haeler et al., 2021
CZ_JH1	CZ	6	106	Hofmeister et al., 2019
CZ_JH2	CZ	1	230	Hofmeister et al., 2013
CZ_MR	CZ	1	45	Chamagne et al., 2016
DE_ID	DE	1	526	Doerfler et al., 2017
DE_JP	DE	1	135	Storch et al., 2020
DE_PS	DE	3	150	Schall et al., 2018
DK_JC1	DK	6	40	Lelli et al., 2019
DK_JC2	DK	2	107	Mazziotta et al., 2017
DK_JC3	DK	1	30	-
DK_SK	DK	16	386	Byriel et al., 2020
FR_AM	FR	12	33	Cocquelet et al., 2019

FR_JP	FR	3	70	Janssen et al., 2018
FR_NK	FR	35	43	Korboulewsky et al., 2021
FR_YP	FR	24	300	Paillet et al., 2015
GR_FX	GR	1	4	-
HU_FT	HU	1	36	Horváth et al., 2023
HU_PO1	HU	1	35	Tinya et al., 2021
HU_PO2	HU	1	30	Elek et al., 2018
HU_RA	HU	8	22	-
IT_AC	IT	3	18	Cutini et al., 2021
IT_EA	IT	6	199	D'Andrea et al., 2016
IT_SB1	IT	1	36	Blasi et al., 2010
IT_SB2	IT	2	66	Sabatini et al., 2016
IT_TS	IT	2	20	Sitzia et al., 2017
LT_GB	LT	20	143	-
SK_DK	SK	3	18	Kameniar et al., 2021
SK_MM	SK	3	22	Kozák et al., 2021
SK_MS	SK	3	18	Langbehn et al., 2021
SK_MU	SK	1	65	Ujházy et al., 2018
SW_BN	SW	25	50	Götmark, 2013

223

224

225



226

227 Figure 2. Distribution of the platform sampling sites in Europe. Grey areas are covered by forests with a tree
 228 cover greater than 40% according to the European Forest Institute Forest Map of Europe (Kempeneers *et al.*,
 229 2011). Number of taxa are represented by color, while number of sampling units by dot size.

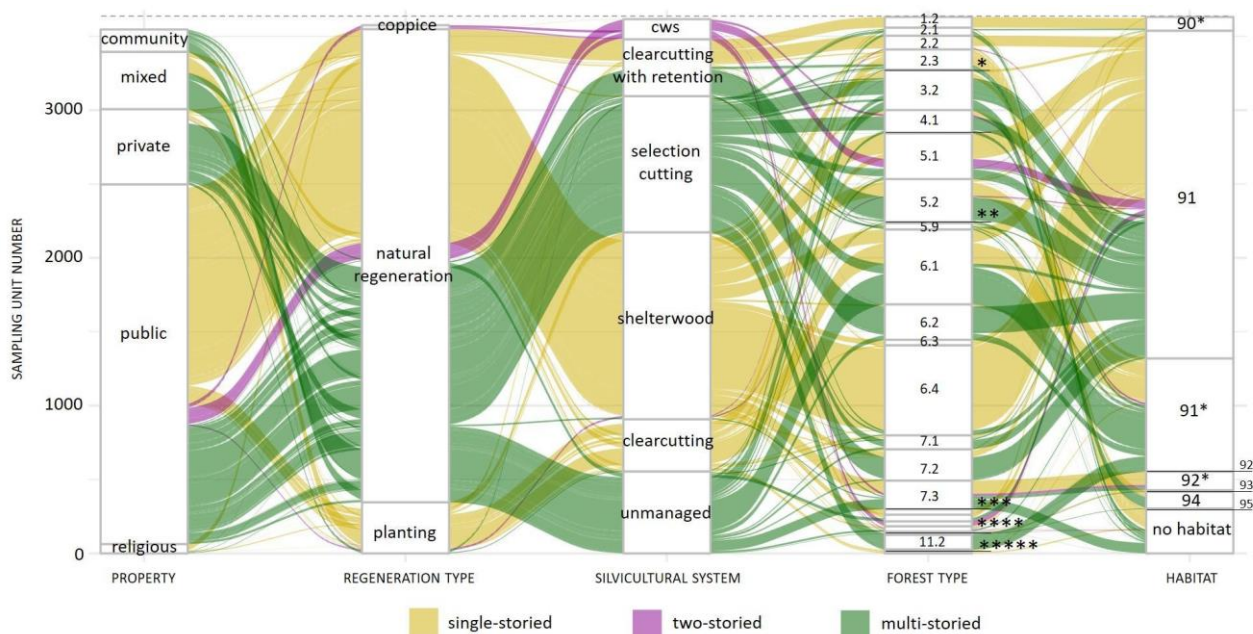
230

231 In general, no clear pattern of association appears between silvicultural systems and forest
 232 compositional categories. For instance, shelterwood is applied to almost all compositional categories
 233 (Fig. 3); even though coppice with standards were associated mostly with mesophytic and
 234 thermophilous deciduous forests.

235 Importantly, most sampling units (94%) were referred to a habitat type of conservation concern
 236 according to the European cornerstone of biodiversity conservation, the Habitats Directive
 237 (92/43/EEC). The highest representation (82%) was found for the forests of temperate Europe (group
 238 91). About a quarter (27%) of the total number of sampling units referred to as priority habitat types,
 239 with, in order of decreasing frequency, 91H0*- Pannonian woods with *Quercus pubescens*, 91G0*-

240 Pannonic woods with *Quercus petraea* and *Carpinus betulus*, 91E0*- Alluvial forests with *Alnus*
 241 *glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae).

242



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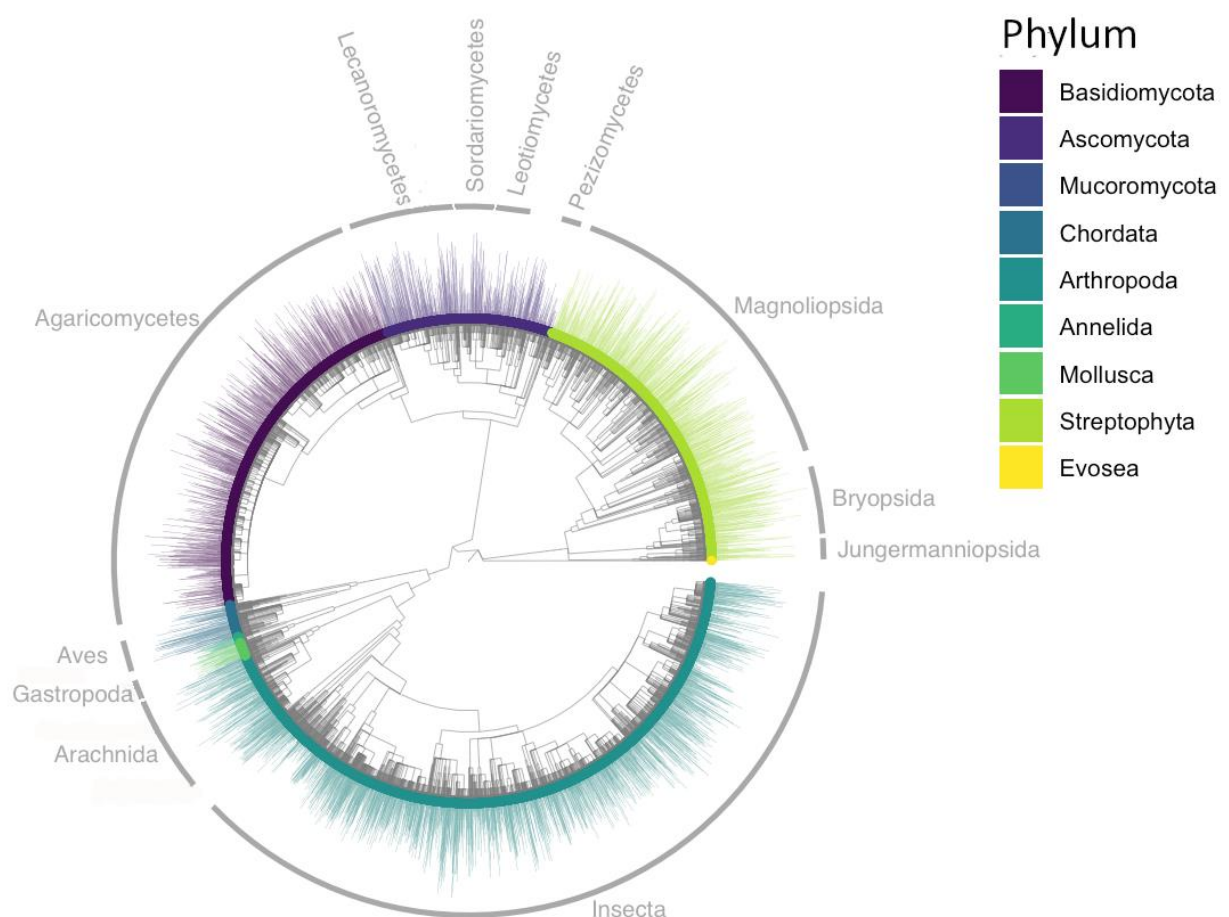
244

245 Figure 3. One-, two-, and multi-storied forest sampling unit distribution across type of ownership,
 246 regeneration, silvicultural system (cws: coppice with standards), forest type, and habitat type. Vertical blocks
 247 represent clusters of sampling units for which the same condition (e.g., natural regeneration) occurs, with
 248 block height depending on the number of sampling units for which that condition occurred across structural
 249 types (single-, two- and multi-storied). Flows between the blocks show the combination of values for different
 250 structural types (e.g., number of one-storied plots within a public property originated from planting). In the
 251 forest type column, left numbers refer to the forest categories as reported in SI 1 and in EEA (2006), while the
 252 number after the dot refers to a specific type within that category (please refer to EEA, 2006). Forest types
 253 represented by less than 50 sampling units are identified by stars (* 3.1; ** 4.2; *** 7.4, 7.5; **** 8.1, 8.2, 8.7,
 254 8.8, 9.1, 10.1, 11.1; ***** 11.3, 11.4, 12.1, 13.2, 14). In the Habitat column, sampling units are gathered in
 255 groups of habitat types divided among those having priority (followed by “*”) or not, and referred to the codes:
 256 90: Forests of Boreal Europe, 91: Forests of Temperate Europe, 92: Mediterranean deciduous forests, 93:
 257 Mediterranean sclerophyllous forests, 94: temperate mountainous coniferous forests, 95: Mediterranean and
 258 Macaronesian mountainous coniferous forests.

259

260 *Taxonomic information*

261 The dataset comprises a wide range of taxonomic groups across the kingdoms of fungi, plants,
262 and animals (SI-3, <https://zenodo.org/record/7886698#.ZFES7HZBxD8>), with 8,724 species, 2,979
263 genera, 729 families, 193 orders, 44 classes, and nine different phyla (Fig. 4). The taxonomic groups
264 originally considered in each study include heterogeneous taxonomic ranks, from kingdom to order,
265 and, in some cases, include only specific morphological or ecological groups commonly used in
266 sampling and identification (e.g., macrofungi, epiphytic lichens, saproxylic beetles). Most plots have
267 information on four or more different taxonomic groups, with an average of 4.6 groups per plot.
268 The plots with information on only one or two taxonomic groups have information on at least three
269 taxonomic groups at the stand level, as required by the platform bylaws.



270

271 Figure 4. Phylogenetic tree of the species enclosed in the data platform (7,335 out of the 8,724
272 could be included). The colored sectors refer to phyla; external bars show the log-transformed

273 number of records for each species; gray circular sectors show the representation of the classes for
274 which more than 50 species occur.

275

276 The classes that are represented by the highest number of species are also those represented by
277 the highest number of records (Fig. 5), i.e., *Insecta* (3,244 species across 88,338 records),
278 *Agaricomycetes* (2,077 species across 44,418 records), *Magnoliopsida* (1,182 species across
279 71,458). However, this pattern differs for *Bryopsida*, which are represented by only 280 species in a
280 very high number of records (27,551). This means that some *Bryopsida* species occur in a very high
281 number of sampling units; for instance, *Hypnum cupressiforme* is the species occurring in the
282 highest number of sampling units (5,082) among all species in the platform (see also Blasi et al.,
283 2010). On the other hand, *Insecta*, *Magnoliopsida* and *Agaricomycetes* are the most represented
284 classes among species singletons (i.e., species occurring only once in the platform) with respectively
285 35%, 29% and 13% of singletons vs. less than 3% for *Bryopsida*.

286 *Structural attributes*

287 Being required by the bylaws, diameters of standing trees are available for all sampling units,
288 either at the plot or stand scale, with a total 2,889 sampling units, with additional data on tree
289 height, deadwood and tree-related microhabitats in respectively 2,356, 2,309, and 1,388 plots.

290 The mean diameters of standing trees (both living and dead) and lying deadwood within each
291 sampling unit across the platform vary across silvicultural regimes. The former shows a left-skewed
292 distribution for clearcutting and clearcutting with retention and a bimodal distribution for coppice
293 with standards. The lying deadwood mean diameters have a peak at lower values if compared with
294 standing tree DBH distributions, and often show a wider range, in some cases with a bimodal
295 distribution (Fig. 6).

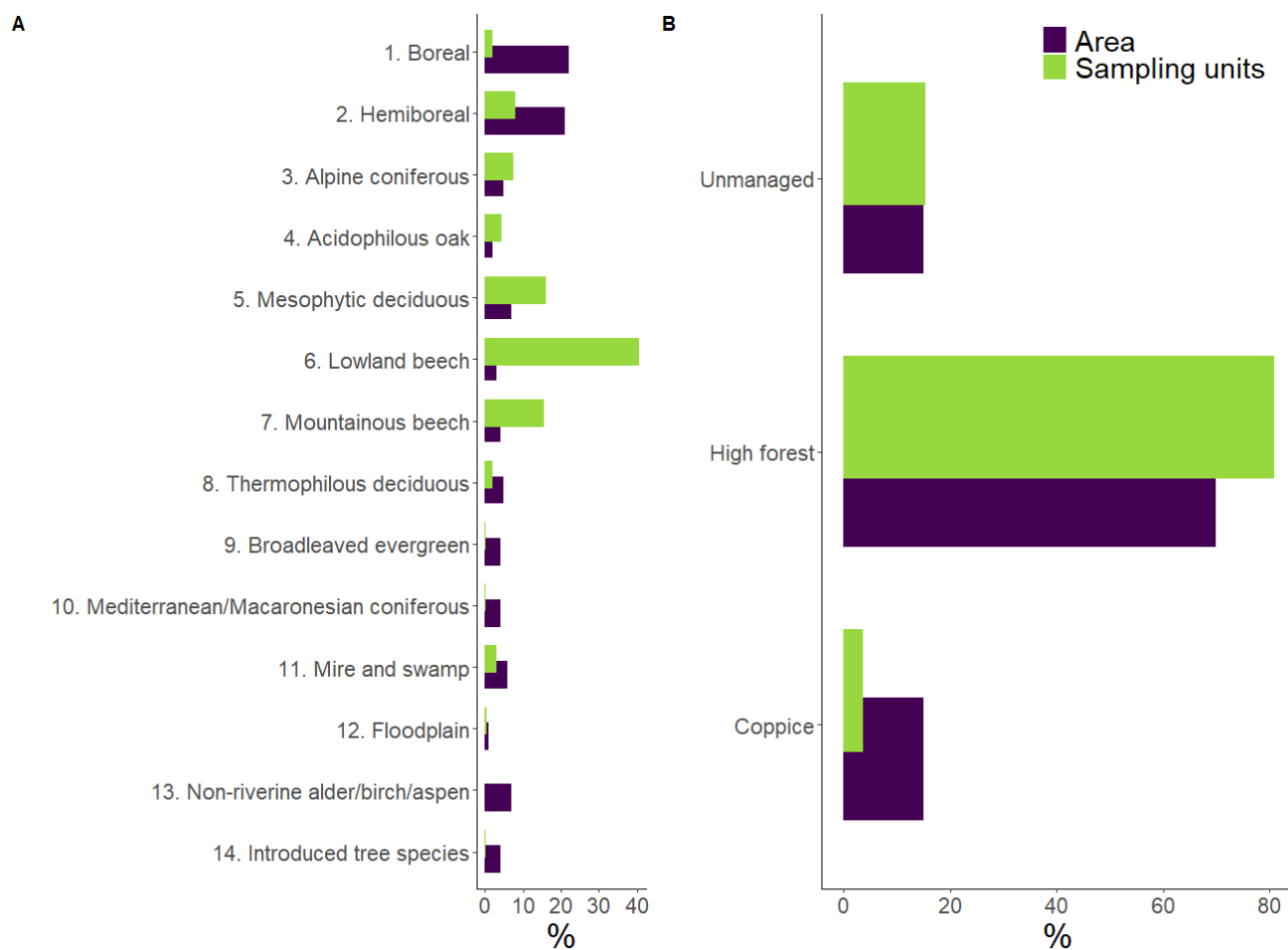
296

297 GAPS IN KNOWLEDGE

298 *Sampling units*

299 Sampling units with multi-taxon biodiversity data associated with stand structure and management
300 information (SI-2) are available for all the 14 European forest compositional categories (Barbati et al.,
301 2014) although unevenly distributed among them. European beech forests are over-represented with
302 respect to the area they occupy (Fig. 5A), with lowland and mountainous beech forests representing

303 more than 55% of the sampling units (Barbati *et al.*, 2014) (Fig. 5A). The distribution of sampling units
 304 across management systems, i.e., timber harvesting relying on resprouting (coppice) or seed
 305 regeneration (high forest) or no harvesting (unmanaged), differed from their area extent (McGrath
 306 *et al.*, 2015) only for coppices (Fig. 5B).



307
 308 Figure 5. A: Share of the number of sampling units and of forest area across different forest compositional
 309 categories (A) in EU-28 based on Barbati *et al.* (2014); and across two broad methods of regeneration (coppice
 310 and high forest) and the absence of silvicultural intervention (B) based on McGrath *et al.* (2015) .

311
 312 Relevant gaps remain for some crucial management information, for instance type and year of last
 313 intervention were not available for about 40% of sampling units. This indicates that detailed
 314 management information is often not available to forest biodiversity researchers. However, the
 315 sampling unit metadata allow a close look into the management and composition of the forests
 316 included in the platform. Most of the available sampling units are within public forests, naturally

317 regenerated, with shelterwood and selection cutting systems being by far the most represented, and
318 single- and multi-storied forests being similarly frequent (Fig. 3).

319

320 *Taxonomic information*

321 Some taxonomic classes are underrepresented both in terms of species and records, and this is
322 especially true for fungi other than Agaricomycetes. For instance, Eumycetozoa, Mucoromycetes and
323 Pucciniomycetes are represented by only one species that occurs in less than 5 sampling units. The
324 rarity of these classes is even more striking if we account for the fact that fungi were among the most
325 commonly sampled groups of organisms.

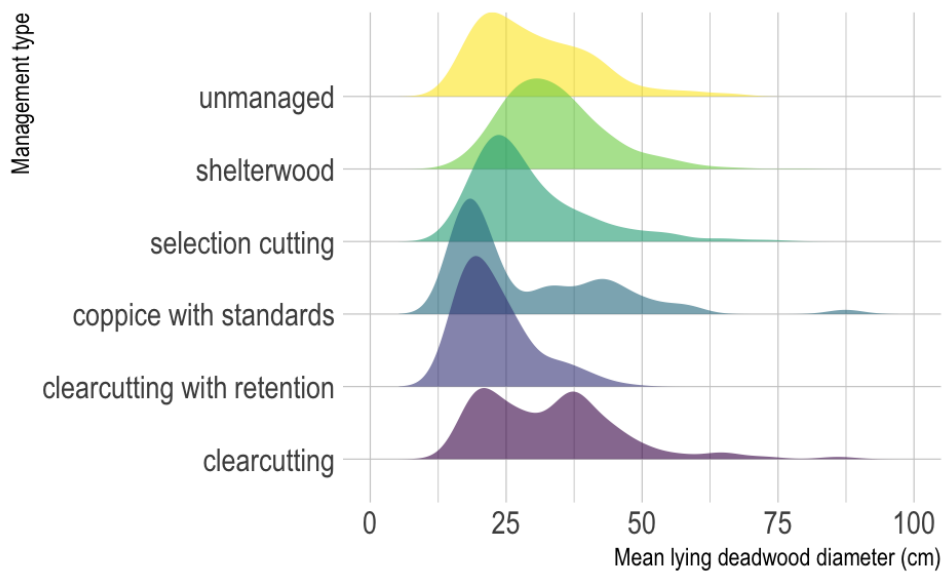
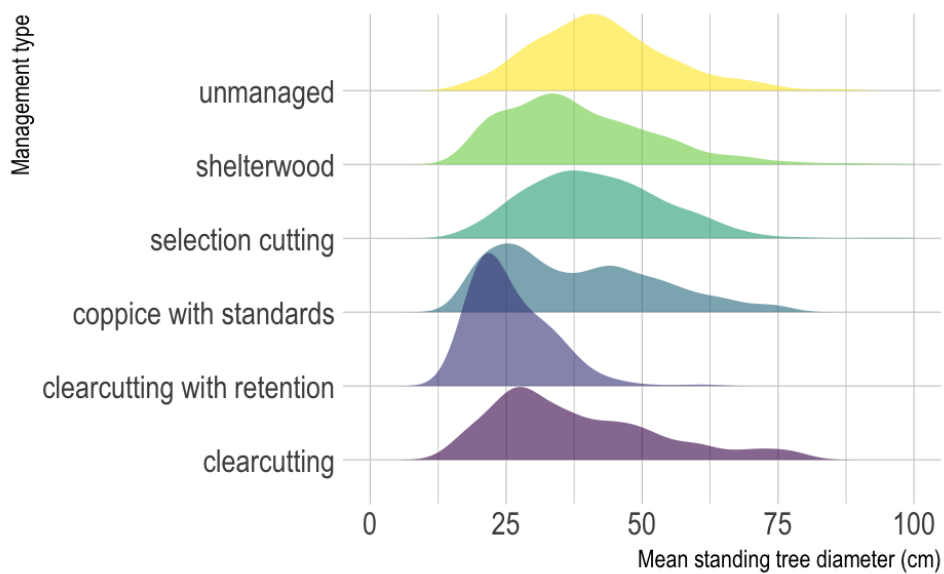
326

327 *Structural attributes*

328 Notwithstanding differences in the forest definition adopted and in DBH threshold, the diameter
329 distributions of the data within the platform reflect the distribution of growing stock across
330 diameter classes at the European level (Forest Europe, 2020), with most sampling units having a
331 mean DBH between 20 and 40 cm (Fig. 6). On the other hand, in European multi-taxon studies, the
332 share of trees over 40 cm is higher than the share below 20 cm. This means that multi-taxon studies
333 are partly biased towards mature developmental phases, with consequences on the representation
334 of species related to different phases of the forest succession (Hilmers *et al.*, 2018), especially of
335 the earliest.

336

337



338

339 Figure 6. Distribution of sampling unit's mean diameters for living (Diameter at Breast Height – DBH) and
 340 dead standing trees (upper portion) and lying deadwood (lower portion) across different silvicultural systems.
 341 Mean diameters were calculated after applying a lower threshold of 15 cm to limit the effect of different
 342 sampling protocols within the platform.

343

344 DISCUSSION

345 SOLIDS AND VOIDS OF THE EXISTING DATA

346 This study is the first attempt, both in Europe and globally, to encompass extensive and
347 comprehensive information on forest management, structural attributes, and multi-taxon
348 biodiversity in a single, harmonized and publicly explorable platform.

349 Although we collected most data deriving from forest multi-taxon studies performed in Europe,
350 the resulting data is unevenly distributed across compositional categories. Further efforts should thus
351 focus on attaining a good representation for boreal, hemiboreal, thermophilous and Mediterranean
352 compositional categories, as well as for mire, swamp, and floodplain forests. Among these, boreal
353 and hemiboreal forests are widespread in Europe, thus their underrepresentation in the platform is
354 a clear knowledge gap. Other categories, instead, have a limited extent across Europe, with floodplain
355 forests displaying the lowest cover (Barbati *et al.*, 2014). Although floodplain forests are considered
356 as biodiversity hotspots (Przepióra & Ciach, 2022), these habitats are nowadays not only rare in
357 European landscapes, but occur in settings that have been profoundly altered by humans, thus
358 characterized by high habitat fragmentation and low ecosystem integrity. For these reasons,
359 floodplain forests should be primarily addressed by biodiversity studies, especially in view of
360 restoration actions (Dufour *et al.*, 2019). On the other hand, the share of sampling units referred to
361 as priority habitat types (27%) is higher than what is reported in terms of area, i.e., 23% according to
362 European Commission (2019), showing a great potential of the existing data in the assessment of the
363 conservation status and relation with management of forests of primary conservation concern in
364 Europe.

365 The distribution of the existing data across silvicultural systems shows a tendency among
366 researchers to perform multi-taxon biodiversity studies in forests that are perceived as less
367 intensively managed, such as those under selection or shelterwood management regimes.
368 Clearcutting is represented mainly in plots related to experimental studies testing novel harvesting
369 practices as this silvicultural system is perceived as strongly threatening forest depending species
370 (Savilaakso *et al.*, 2021). Unmanaged forests have often been sampled as a relevant reference in
371 comparison to managed forests, especially if strategies that are generally perceived as sustainable
372 are applied (Paillet *et al.*, 2010). However, it should be noted that the unmanaged sampling units in
373 the platform may not be associated with old-growth condition since they vary widely in terms of time

374 passed since the last management intervention, i.e., from 20 to more than 100 years, and these
375 differences have to be accounted for when contrasting managed and unmanaged forests within the
376 platform.

377 The distribution across unmanaged, coppiced and high forests confirms that coppicing systems
378 are relatively understudied, particularly for multi-taxonomic biodiversity. This may be partly related
379 to the perception of these forests as less relevant for biodiversity and related ecosystem services.
380 Nevertheless, some studies suggest the opposite (Hédli *et al.*, 2010) and demonstrated a certain
381 degree of association of species of conservation concern with actively coppiced stands (Kosulic *et al.*,
382 2016). This uneven distribution may also be related to the progressive reduction of coppiced forests
383 in Europe, which are gradually being actively or passively converted into high forests, or simply
384 abandoned (Burrascano *et al.*, 2017). In general, the lack of multi-taxon biodiversity information from
385 coppices represents a knowledge gap for supporting policy decisions on coppice forest management,
386 which is especially relevant in view of their renewed prominence in climate adaptation policies and
387 forest multifunctionality (Cutini *et al.*, 2021).

388

389 RESEARCH POTENTIAL AND WORKING HYPOTHESES

390 Conversely to other data sharing platforms focusing on individual aspects of ecosystems, e.g.,
391 vegetation (Bruehlheide *et al.*, 2019), forest multi-taxon studies put in place different expertise and
392 data on the three main components of ecosystems: species composition, structure and function. As
393 such, these data collectively have the potential to promote interdisciplinary studies and to unveil
394 the outcomes of different conservation and management policies on the biodiversity of multiple
395 taxonomic groups as mediated by structural stand features, e.g., the diameter distributions of
396 standing trees and lying deadwood.

397 HARMONIZING METHODS AND SCHEMES

398 The joint assessment of existing forest multi-taxon biodiversity data already stimulated a
399 harmonization effort for sampling protocols (Burrascano *et al.*, 2021). Similarly, a harmonized
400 platform may serve as a pilot dataset to assess the effort needed in terms of number of sampling
401 units and sites (Guerra-Castro *et al.*, 2021) to investigate how European forest species richness and
402 composition changes along management and environmental conditions, respectively included in the
403 platform and associated from external datasets. This will inform integrated European projects that

404 could be able to provide useful information for the newborn FISE platform (Forest Information
405 System of Europe - <https://forest.eea.europa.eu/>).

406 Harmonized sampling protocols and design are relevant in view of the monitoring and
407 conservation status assessment of forest habitat types for the implementation of the EU Habitats
408 Directive. Important assessment criteria include the actual status and the prospects of structures and
409 functions and typical species (Campagnaro et al., 2019). Up to date, the interpretation manual of
410 European habitats as only a limited descriptions of typical species that mainly include vascular plants,
411 also due to the lack of datasets and methodological frameworks for the consideration of additional
412 taxonomic groups. Nevertheless, the need for a multi-taxon approach to habitat types' typical species
413 has already been indicated (Tsiripidis et al., 2018) and this platform steps towards this direction.

414 IMPLEMENTING INDICATORS AND THRESHOLDS OF FOREST MANAGEMENT SUSTAINABILITY FOR BIODIVERSITY CONSERVATION

415 The existing knowledge paves the way to directly test biodiversity indicators of SFM and their
416 thresholds, and to overcome the current approach of assessing forest management sustainability
417 through proxies that mostly showed weak correlation with the *indicandum* (Gao et al., 2015). For
418 biodiversity sustainability, these proxies include tree composition, size and age distribution, gap
419 structure, deadwood amount and tree-related microhabitats (Müller & Bütler, 2010; Larrieu et al.,
420 2018). Their indirect indication is intrinsically limited (Barton et al., 2020; Zeller et al., 2022) and
421 would need to be complemented with a direct analysis of several taxonomic groups (Burrascano et
422 al., 2018). Recently, in addition to the usual set of indicators of forest management impact on
423 biodiversity (MCPFE, 1993), 34 bird species were accounted for (Forest Europe, 2020), but still, most
424 taxonomic groups contributing to forest biodiversity remain neglected. This is the case for extremely
425 species rich groups including species of high conservation concern, such as fungi (Halme et al., 2017),
426 and saproxylic beetles (Calix et al., 2018). The broad-scale tree level dendrometric information
427 included in the platform may be linked to environmental factors, i.e., climate and soil, and thus
428 contribute to the calibration of habitat-based indicators of forest ecosystem condition (Jucker et al.,
429 2022).

430 FOREST FUNCTIONING AND RESILIENCE

431 Forest functions depend not only on tree species characteristics, but also on the ecological roles
432 of several species across multiple taxonomic groups. For instance, understorey vegetation and
433 saproxylic organisms play a key role in nutrient cycling (Landuyt et al., 2019; Seibold et al., 2021). To
434 maintain forest functions in the face of major environmental changes, these specific functions have

435 to be accounted for in management plans and forest policies. The recent advances in functional traits
436 measurement and harmonization, and their increasing availability for multiple taxonomic groups
437 (e.g., Bernhardt-Römermann *et al.*, 2018; Moretti *et al.*, 2017) allow to trace back the effects of
438 different management approaches and environmental scenarios on different guilds and taxonomic
439 groups and on their role for ecosystem functioning. Accounting for species interactions, also when
440 studying the effect of environmental or management drivers on ecosystem biodiversity and
441 functioning, is emphasized in recent approaches on joint species distribution modelling that could be
442 applied to the platform data (Ovaskainen & Abrego, 2020).

443 INTEGRATION WITH REMOTE SENSING APPROACHES

444 The continent-wide information on important components of forest biodiversity that are not directly
445 visible by means of remote sensing devices is highly valuable to test and integrate information
446 acquired through remote sensing techniques, such as Airborne Laser Scanning. For instance, the
447 3,591 points of the platform may serve to discriminate the probability of occurrence of different
448 forest types that currently represents the most detailed information in Europe (Mücher &
449 Hennekens, 2019). The platform information may be used to integrate and improve multi-scale
450 ecosystem assessment by fine-tuning the links between structural diversity measured by means of
451 Airborne Laser Scanning and multi-taxon biodiversity (Moeslund *et al.*, 2019). Furthermore, specific
452 habitat variables that could be derived from Airborne Laser Scanning were recently identified to
453 improve species distribution models (Moudrý *et al.*, 2023), and to model dark diversity (Moeslund *et al.*,
454 2022), and such advancements would highly benefit from broad-scale harmonized multi-taxon
455 information.

456 CONSERVATION IMPLICATIONS

457 The European Union Biodiversity Strategy for 2030 is focused on protected areas and its main
458 objectives are to legally protect a minimum of 30% of land area, which should be effectively managed
459 and appropriately monitored, and to strictly protect at least a third of such protected areas. In this
460 view, gathering and harmonizing the available information on forest multi-taxon biodiversity can
461 promote the widespread collection of forest biodiversity data through shared approaches and
462 methodologies, with a special emphasis on understudied forest types, which are often also
463 particularly relevant for biodiversity conservation, e.g., floodplain or thermophilous forests.

464 The availability of widespread forest multi-taxon biodiversity and stand structure information at the
465 continental scale will allow to prioritize forest areas to be protected, or strictly protected, and will
466 set the basis for their appropriate monitoring, in line with the current Biodiversity Strategy.

467 On the other hand, the European Union Forest Strategy for 2030 is focused on the sustainability of
468 forest management, within and outside protected forests. This would start from the identification of
469 additional indicators, as compared to those assessed by Forest Europe, with thresholds or ranges for
470 SFM concerning forest ecosystem conditions, including biodiversity.

471 The availability of extensive multi-taxon biodiversity data would allow to define such indicators of
472 management sustainability, as well as their thresholds and ranges, based on their direct links with
473 the diversity of multiple taxonomic groups with different functions in forest ecosystems. This would
474 represent a crucial step forward from the current criteria and indicators whose effectiveness for
475 biodiversity is questionable.

476 The EU Forest Strategy also stresses how management sustainability indicators, and their
477 thresholds and ranges, should be built on existing work and take into account forest variability,
478 biogeographic regions and forest typology. Our work is perfectly in line with this statement, since
479 we reviewed and valued existing data on forest biodiversity by accounting for different forest
480 habitats, compositional and management categories. Refining indicators of SFM will feed guidelines
481 on closer-to-nature forestry that will be translated into voluntary certification scheme, so that the
482 most biodiversity friendly management practices could benefit from an EU quality label.

483 Europe has a leading role in the improvement of forest protection and management standards
484 globally. By supporting the objectives of the EU biodiversity and forest strategy, we think that, in the
485 long-term, our work may lead to the improvement of indicator schemes across multiple regions and
486 support an increased sustainability of forest management globally.

487

488 DATA AVAILABILITY STATEMENT

489 All the data used in this manuscript are provided in the supplementary material available at this link
490 <https://zenodo.org/record/7886698>.

491 An interactive tool for their exploration and filtering, as well as instructions for proposing a project with
492 the data here used are available at: XXX. Additional data may be requested for specific projects as
493 described at this link: XXX.

494

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