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Forest Ecosystem Multifunctionality: A Systematic Review of Measures and Drivers

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Abstract

Purpose of Review Forest ecosystem multifunctionality, the capacity of forests to simultaneously deliver multiple ecosystem functions and services, is being increasingly affected by pressures stemming from anthropogenic activities and climate change. Here, we conducted a systematic literature review to explore how forest ecosystem multifunctionality was evaluated in the literature, and to identify its main drivers.

Recent Findings We found that the number of publications strongly increased in recent years, mostly focused on China and Europe. Abiotic drivers were most frequently examined, ranked in decreasing importance as soil properties, site features, and climate factors. Biodiversity-related drivers were the second most studied, encompassing species composition (i.e., species identity within the forest), species richness of trees, bacteria, and fungi, and stand structural diversity. Soil-related drivers were predominantly used to evaluate belowground multifunctionality, with less consideration given to their potential effects on aboveground multifunctionality. Conversely, the effects of tree and stand attributes have commonly been considered in both above- and belowground ecosystem multifunctionality. Forest ecosystem multifunctionality is often mediated by interactions among drivers, involving both above and below-ground components.

Summary Tree species and soil organism diversity (including species richness and functional diversity), stand age and stand structural diversity, emerged as crucial drivers enhancing multifunctionality both above- and belowground. Our results suggest that preserving old-growth forests, promoting long-term restoration, and expanding species-diverse forests is an effective strategy for achieving multifunctional forests. Current understanding is limited by a pronounced geographical bias, limited comparability of studies, and overlooked multifunctionally drivers, especially related to the effects of soil fauna and management practices.

Keywords Indicators · Ecosystem functions · Ecosystem services · Ecosystem multifunctionality · Biodiversity · Forest restoration

Introduction

Forests are facing increasing pressures and demands arising from both anthropogenic activities and the accelerating impacts of climate change. Moreover, forests play a pivotal role in climate change mitigation strategies, particularly through their capacity to sequester carbon in biomass and soils, but also for timber production and soil conservation [1–3]. Simultaneously, they contribute to biodiversity conservation, regulation of the water cycle, and the promotion of human well-being by providing recreational, cultural, and health-related services [4–8]. However, in the face of such growing pressures, including pest outbreaks, droughts, wildfires, and land-use changes, there is an increasing need

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for forest systems that are not only productive but also resilient and capable of delivering multiple benefits simultaneously. To address this, the concept of forest ecosystem multifunctionality (hereafter 'forest multifunctionality'), defined as the capacity of forests to simultaneously deliver multiple ecosystem functions and services [9–12], underpins the ability of a forest to perform these diverse roles effectively. In addition, multifunctional forests commonly exhibit enhanced resilience to various biotic and abiotic disturbances, including pest outbreaks, droughts, and wildfires [13]. This resilience reinforces the significance of forest multifunctionality as a fundamental objective in forest adaptation strategies under changing climatic conditions. However, forest multifunctionality has been measured based on various dimensions, indicators, and methods, which complicates rigorous assessments of the value of different forestry approaches and systems.

Over the past decade, ecosystem multifunctionality has attracted considerable interest within the scientific community [10, 14, 15]. It has been proposed that ecosystem multifunctionality can be defined either in terms of ecosystem functions alone ("ecosystem function multifunctionality") or in terms of ecosystem services ("ecosystem service multifunctionality"), which integrate the valuation of ecosystem functioning from a human perspective [10]. Although the concept of multifunctionality is now well established, the way it should be measured remains a matter of debate, particularly regarding which ecosystem functions should be incorporated into ecosystem multifunctionality indices [16, 17]. A recent review demonstrated that the rationale behind the integration of variables in the calculation of ecosystem multifunctionality was frequently lacking in the literature, as was their demonstrated relevance to actual ecosystem functioning [16]. Beyond this important debate, the study of ecosystem multifunctionality is further complicated by the considerable variation in the set of ecosystem functions and services used to compute multifunctionality indices across studies, particularly depending on whether the focus is on aboveground or belowground components of the ecosystem. Finally, there is active debate on the most appropriate methodologies for calculating these indices, with various approaches proposed to capture the complexity and interactions among multiple ecosystem functions [18]. Among them, the averaging approach has been the most used due to its simplicity and ease of interpretation [11, 19, 20]. However, the multiple-threshold approach, proposed by Byrnes et al. [18], emerged as a more powerful assessment of forest multifunctionality by better capturing the performance of individual functions, even in the presence of trade-offs and correlations among functions.

In parallel, a growing number of studies have sought to identify the key drivers of forest multifunctionality. Forest stand features [21, 22], forest management [23, 24], site conditions [25], and biotic and abiotic disturbances [26, 27] can substantially affect forest multifunctionality. For example, an expanding body of evidence indicates that forest multifunctionality is influenced by the diversity, abundance and composition of multiple trophic levels within forest ecosystems, ranging from canopy tree species to belowground soil biota [10, 14, 15]. Furthermore, several studies have shown that tree species diversity increases ecosystem productivity, improves resource use efficiency, and enhances ecological stability [11, 28–31]. Moreover, it supports the richness and abundance of forest-associated taxa across various groups, thereby fostering overall biodiversity [28, 32]. Importantly, the interactions among organisms occupying different trophic levels, such as primary producers, herbivores, and decomposers, play a critical role in regulating key ecosystem functions and forest multifunctionality (e.g., nutrient cycling) [21, 29, 33–36]. This underlines the relevance of indirect effects in shaping forest multifunctionality, mediated through the interdependence among multiple drivers [23, 25, 37, 38].

However, previous studies have often yielded inconsistent or inconclusive findings regarding both the magnitude and direction of the effects of different drivers on forest multifunctionality. For example, soil pH [25, 39, 40], microbial diversity [29, 40] and stand age [25, 38, 41] were reported to affect forest multifunctionality in ways that range from negative to non-significant to positive. This lack of consensus may stem from the fact that these drivers exhibit non-linear effects on forest multifunctionality. It may also stem from ongoing methodological debates regarding the construction of forest multifunctionality indices, as noted earlier. Finally, it may arise from the complexity involved in selecting which potential drivers to include and which modeling approaches to apply when analyzing the drivers-forest multifunctionality relationships. As with forest multifunctionality indices themselves, the drivers influencing forest multifunctionality can operate at multiple spatial and ecological scales, encompassing site-level factors as well as both aboveground, belowground biological components, operating at the forest ecosystem, landscape and regional scales. This overall complexity helps explain why we currently lack a comprehensive understanding of the major drivers of forest multifunctionality, which may encompass both environmental factors and human pressures. This is especially true for forest ecosystems, which have been comparatively less studied than herbaceous ones [16].

To address this knowledge gap, we conducted a systematic literature review of studies evaluating the drivers of forest multifunctionality across the broader forest biomes (i.e., tropical, temperate, boreal, and Mediterranean). Specifically, we aimed to answer three main questions: (1) Which ecosystem functions or services are used to assess forest multifunctionality, and what methods are used to integrate them into forest multifunctionality indices? (2) What are the primary drivers of forest multifunctionality explored in the literature, and what are the directions of their effects? and (3) Are the same set of drivers examined for belowground, aboveground, or ecosystem-scale forest multifunctionality? With this, we aimed to strengthen the scientific foundation for the management and conservation of multifunctional forests in the face of climate change, while also identifying key research gaps and proposing future directions for forest multifunctionality studies.

Survey Method

Literature Search

We conducted a systematic literature search on the Web of Science platform, restricted to peer-reviewed articles. We performed a search on 05 January 2025. The search was conducted across a wide time range, from 01 January 1900 to 31 December 2024. The following keywords in Table 1 were used for the search and organized into three groups, as recommended by the Collaboration for Environmental Evidence [42].

Only original papers in English were considered, and reviews were excluded. The search yielded a total of 1069 papers. After reading the title and abstracts of all of them, we selected only those that: (a) quantitatively evaluated the influence of drivers on multifunctionality, and (b) focused on forests. We excluded all studies conducted in grassland, shrubland, or greenhouse conditions, or when the papers only focused on the comparison between forest vs. grassland, or forest vs. shrubland on multifunctionality (Fig. S1, Table S1), because it was not possible to isolate the effect of drivers on forest multifunctionality in these cases. With this, our final dataset included 103 papers in this review (Table S2).

Table 1 Combination of keywords used in the systematic literature review including the boolean operator "OR" divided in three groups. The operator "AND" was used between groups

Groups	Keywords and Operators Used
Biome/Vegetation	forest* OR rainforest OR tropical OR subtropical OR temperate OR boreal OR plantation* OR restoration* OR conserved* OR remnant
Multifunctionality	multifunctional*
Drivers	driver OR indicator* OR cause* OR influence* OR factor* OR effect* OR dynamic* OR determinants* OR consequences*

The following variables were extracted from figures, tables, and/or text: country, biome, geographic coordinates, explored drivers, effect direction of the driver on forest multifunctionality (positive, negative, or neutral) and whether the effect was direct or indirect (when the effect was indirect, we extracted the intermediate driver), ecosystem functions and/or services used to calculate forest multifunctionality index (i.e., measurements of biophysical aspects, not ecosystem services (social demands)), as well as the method used to calculate it. In addition, journal names and impact factor (JCR) metrics for 2024 were extracted from the Web of Science website. We categorized forests into four biomes: tropical (including tropical and subtropical forests), temperate, boreal, and Mediterranean. When authors did not provide information about the biome, we used geographical coordinates to determine it: latitudes between 0° and 33° N or S were classified as tropical forests; 33° to 66° N or S as temperate forests; and latitudes above 66° N or below 66° S as boreal forests.

Classification of Ecosystem Functions and Services

We classified the ecosystem functions used to calculate forest multifunctionality indices following Garland et al. [16]. According to these authors, abiotic soil properties (e.g., soil water content, soil pH, bulk density) should not be used to calculate multifunctionality indices, because they do not necessarily reflect ecosystem functions or services. Consequently, we excluded these indicators from our review of the functions used to calculate forest multifunctionality ($n = 6$ papers, Table S3). In addition, we classified forest multifunctionality functions as belowground, when only soil and surface drivers were used to assess multifunctionality; aboveground, when only aboveground drivers were used to access multifunctionality; and both, when both aboveground and belowground drivers were considered. Furthermore, ecosystem functions were considered in the context of the four main types of ecosystem services defined by the Millennium Ecosystem Assessment: supporting, provisioning, regulating, and cultural [43]. In addition, the different facets of forest biodiversity were considered as a separate category, because they are considered a service in themselves, but also crucial drivers and regulators of functions [44].

Driver Categories

We classified the drivers into four categories: abiotic factors, disturbances, soil organisms, and tree and stand features. Abiotic factors were further categorized into soil properties (e.g., soil pH, soil bulk density, soil fertility), site features (e.g., slope, elevation, longitude), and climate (e.g., mean annual precipitation, mean annual temperature, soil water content). The studied disturbances included (i) silvicultural operations, such as thinning, logging (i.e., any type of harvest, e.g., selective logging, thinning, clear-cutting), intensive land use intensity and fertilization manipulation, (ii) natural hazards, such as fire, alien species invasion, inundation, and (iii) stand fragmentation. Soil organisms were classified into fifteen categories, distinguishing between soil fauna and soil microorganisms, which were sometimes further distinguished between bacteria and fungi, with a focus on diversity, composition and abundance. Tree and stand features were classified into twelve categories, with the most frequently represented being functional composition, species richness, structural diversity, functional diversity, stand age, biomass stock and phylogenetic diversity.

Effects of the Drivers on Forest Ecosystem Multifunctionality

We identified whether the effect of drivers on forest multifunctionality was direct or indirect when authors used methodologies capable of making this distinction, such as Structural Equation Models (SEM) and Path Analysis [21, 45]. When the effect of forest multifunctionality drivers was assessed through other methods than SEM or Path Analysis, e.g. using linear regression, analysis of variance, or Pearson and Spearman correlations, we considered that the distinction between direct and indirect effects had not been tested [29, 46]. If a study used both types of methodology, we recorded both [47].

Statistical Analyses

To evaluate the interest and relevance of studies on forest multifunctionality and its drivers worldwide, we considered two criteria: (a) the number of publications per year, and (b) JCR metrics to assess the relevance of academic articles [48].

We determined the consistency of driver effects on multifunctionality based on the frequency of occurrences indicating whether the effect was positive or negative, following Borda-Niño et al. [49], which assessed the consistency of driver effects as the proportion of positive relationships among total positive and negative cases. Thus, consistency was calculated for each driver considering all observations as follows: consistency = positive/(positive + negative + neutral). For interpretation, we classified drivers as favorable when > 0.5, neutral when = 0.5, and non-favorable when < 0.5. Binomial tests were performed using the *binom.test* function from the stats package in R [50]. Consistency analysis was only performed for drivers with more than 20 observations, and only continuous drivers were tested (e.g., tree and microbial community composition were excluded).

Trends in Studies on Forest Ecosystem Multifunctionality Drivers

Our systematic review selected 103 published papers from 45 different peer-reviewed journals. We found that studies on forest ecosystem multifunctionality and its drivers were published in 15 countries on all continents, but were principally concentrated in China and Spain, which accounted for 74% (62% and 12%, respectively) of all studies (Fig. 1a, Fig. S2 and Table S4). We found an exponential increase in research papers on forest multifunctionality drivers from 2015 to 2024 ($R^2 = 0.99$, $p < 0.001$; Fig. 1b). Tropical forests were the most represented, accounting for 46.49% of the studies, followed by temperate forests (35.09%), Mediterranean (13.15%) and boreal (5.26%) forests (Fig. 1c).

The increasing number of publications in recent years exhibited a growth rate of 33.7%, which is ca. seven times higher than the 5% average annual growth reported for life sciences in general by Bornmann et al. [51]. This reveals a strong interest of the scientific community for the determinism of forest multifunctionality. Moreover, it is not only the quantity of studies that stands out, as the impact analysis of these publications indicates their high relevance in the field. These journals have an average JCR score of 5.56, where 40% have a very high JCR score (> 5) and 60% have a high JCR score (2 < JCR < 5). None of the journals listed have a JCR score lower than 2 (Table S5). These metrics suggest that the topic of drivers of forest multifunctionality has gained significant priority in scientific research, driven by a notable research effort in China.

Functions and Methods Used To Calculate Forest Multifunctionality Indices

Twenty-four ecosystem functions were identified in this review, which were associated with five categories of ecosystem services: cultural, regulatory, supporting, provisioning, and biodiversity (Fig. 2A). We observed a wide variability in the number of functions used to calculate multifunctionality indices, ranging from 2 to 32 across studies, with an average of 7 (±4.60) functions per paper. These functions also represented a wide range of ecosystem services, approximately 43% of the studies relied on a single ecosystem service, 31% on two services, 20% on three, and fewer than 1% included four or five services. Among the ecosystem services, supporting services were the most

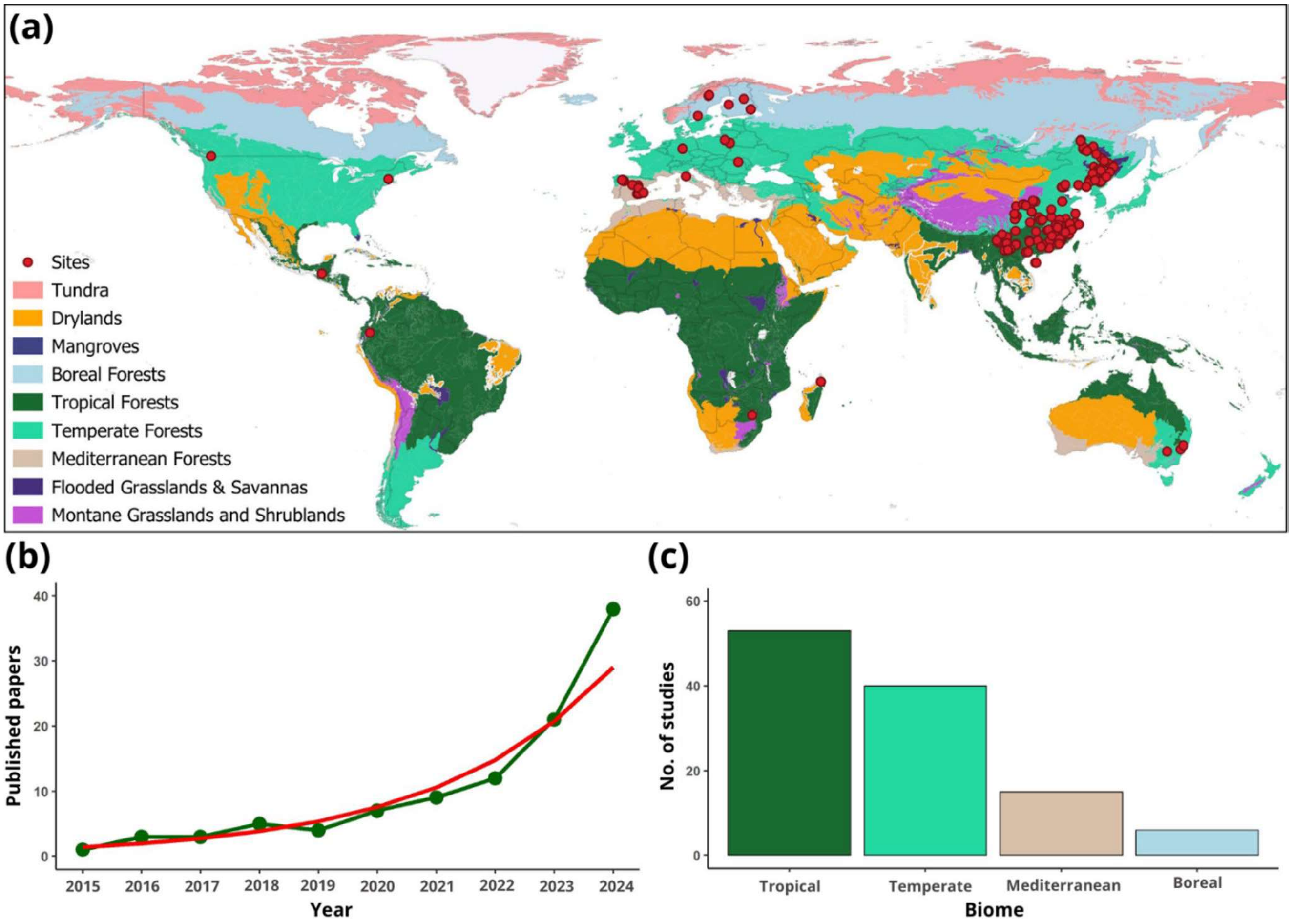
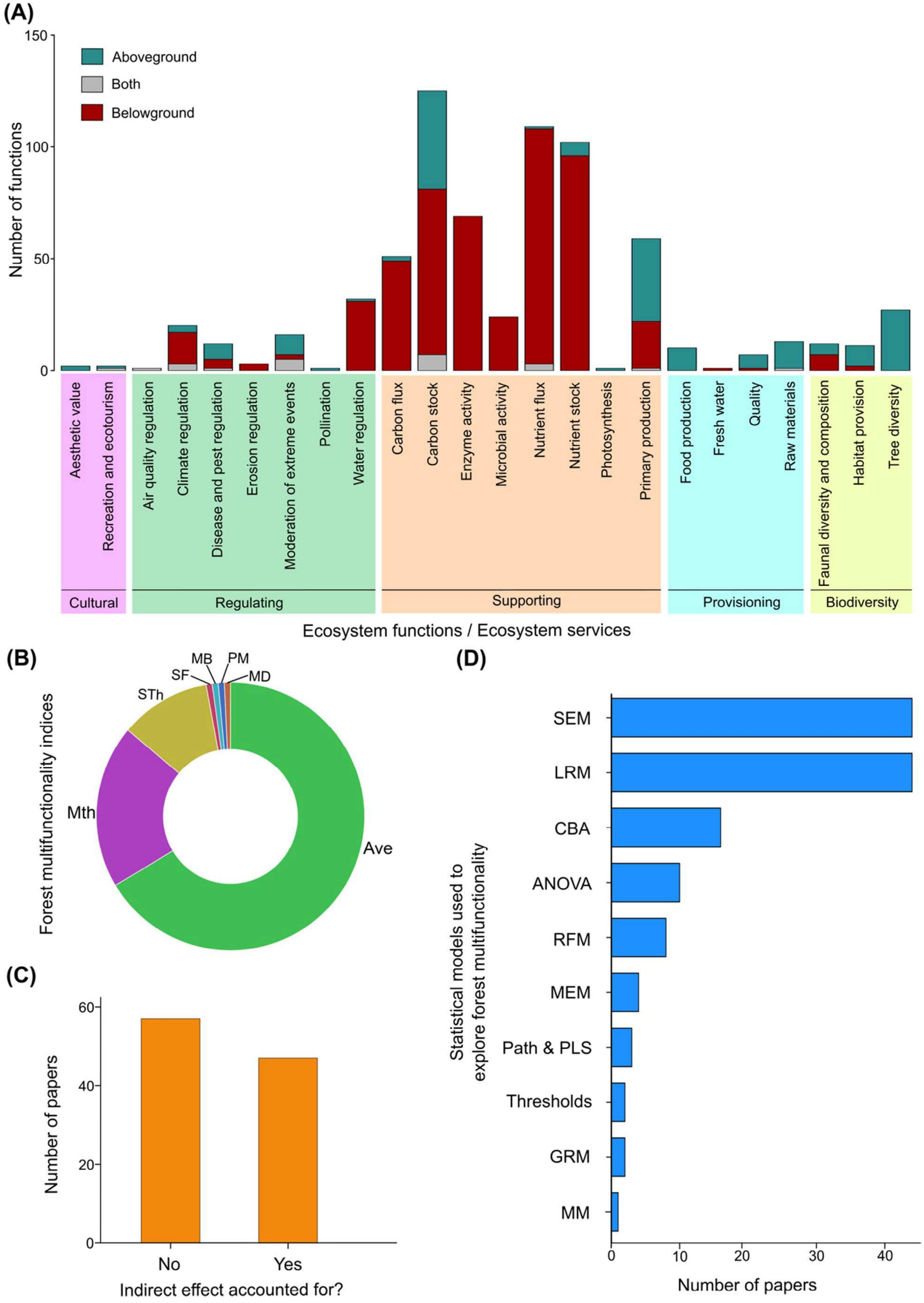


Fig. 1 Overview of the published studies on the drivers of forest multifunctionality. (**a**) Spatial distribution of 159 study sites from 103 papers on the drivers of forest multifunctionality. Each site is represented only once, regardless of how many publications used data from that site. (**b**) Exponential growth (red line show $R^2 = 0.99$; $p < 0.001$) in the number of studies on forest multifunctionality drivers published between 2015 and 2024. (**c**) Number of published papers for each biome

frequently used, appearing in 79% of studies, followed by regulating (13%), biodiversity (5%), provisioning (3%), and cultural services (< 1%).

Furthermore, we found that 72% of the individual functions used to calculate forest multifunctionality indices were related to belowground functions, while 25% were associated with aboveground functions, and only 3% involved both compartments (Fig. 2A). Among the main belowground functions, the most frequently assessed were nutrient stock and nutrient flux, followed by enzyme activity and carbon stock. In contrast, aboveground functions were more often linked to primary production and plant diversity, as well as to raw materials and carbon stock (Fig. 2A). Furthermore, carbon and nutrient stocks and fluxes, enzyme activity, and primary production were the main contributors to supporting ecosystem services, whereas cultural, regulating, provisioning and biodiversity services were less frequently addressed.

Among the approaches used to measure multifunctionality, the averaging approach was the most common, accounting for 66% of the cases, followed by the multiple-threshold approach (19%) and the single-threshold approach (11%) (Fig. 2B, Table S6). The single-function, multidimensional, model-based and maximin approaches were the least used, each representing less than 1%. The averaging approach has been more commonly used because it is simpler to calculate and interpret [11, 19]. In this approach, the forest multifunctionality index is calculated as the average of all functions, typically with equal weights [18, 52, 53]. However, some authors have assigned different weights to specific functions [10, 40, 54]. Authors generally selected the method that best fit their research objectives (e.g., using weighted vs. unweighted average approaches). This reflects two contrasting assumptions: on one hand, weighting functions implies that certain ecosystem functions are more important than others; on the other hand, treating all functions


(A)
150
100
50
0
Number of functions
Aboveground
Both
Belowground
Aesthetic value
Recreation and ecotourism
Air quality regulation
Climate regulation
Disease and pest regulation
Erosion regulation
Moderation of extreme events
Pollination
Water regulation
Carbon flux
Carbon stock
Enzyme activity
Microbial activity
Nutrient flux
Nutrient stock
Photosynthesis
Primary production
Food production
Fresh water
Quality
Raw materials
Faunal diversity and composition
Habitat provision
Tree diversity
Cultural
Regulating
Supporting
Provisioning
Biodiversity
Ecosystem functions / Ecosystem services
(B)
Forest multifunctionality indices
MB
PM
SF
MD
STh
Mth
Ave
(C)
60
40
20
0
Number of papers
No
Yes
Indirect effect accounted for?
(D)
Statistical models used to explore forest multifunctionality
SEM
LRM
CBA
ANOVA
RFM
MEM
Path & PLS
Thresholds
GRM
MM
0
10
20
30
40
Number of papers

◀ **Fig. 2** Functions and methods used to calculate forest multifunctionality indices. (**A**) The diversity of functions used to calculate forest multifunctionality indices. We only considered functions that were measured at least twice. The full list of functions is available in Table S3. (**B**) Proportion of the different methods ($n=7$) used to calculate forest multifunctionality indices, with the averaging approach (Ave) being the most common, followed by the multiple-threshold (MTh), single-threshold (STh), single-function (SF), multidimensional (MD), model-based (MB) and potential maxima (PM) approaches. (**C**) Proportion of studies that explicitly tested for indirect effects of drivers on forest multifunctionality. (**D**) Statistical models used to assess the effects of drivers on forest multifunctionality. SEM: structural equation models, LRM: linear regression models, CBA: correlation-based analyses, ANOVA: analysis of variance, RFM: random Forest models, Path & PLS: Path analysis & partial least squares modeling, MEM: mixed-effects models, GRM: generalized regression models, Thresholds: single or multiple-thresholds approach

equally assumes that they contribute equally to ecosystem performance.

Moreover, the multiple-threshold approach evaluates the performance for various functions across several thresholds (e.g., 25%, 50%, 75%, 90%), offering a more detailed view of trade-offs and synergies among functions [18]. By contrast, the single-threshold approach counts the number of functions that exceed a predefined performance threshold (e.g., 50% of the maximum observed value), providing an index of how many functions are performing simultaneously [55]. This latter method is generally considered less robust than the multiple-threshold approach [18]. In our review, only five papers directly compared the averaging and multiple-threshold approaches [56–60]. Four of those papers [56–59] report that the 50% threshold method closely mirrors the averaging approach in terms of effect direction. Moreover, Zhou et al. [61] also found a high correlation between these methods and chose to perform their analysis using the threshold approach, considering it more robust and informative, especially for understanding how many functions exceed critical performance levels. Conversely, Yuan et al. [60] reported that the effects of several drivers on forest multifunctionality varied between positive and negative depending on how the multifunctionality index was calculated, suggesting that discrepancies among methods may be site-specific and warrant further investigation.

Importantly, single-function (SF), multidimensional (MD), model-based (MB) and potential maxima (PM) approaches were each used only once (Fig. 2B). SF assesses the relationship between biodiversity and each ecosystem function individually, without combining them into a composite multifunctionality index [18, 20], and the MD approach treats functions as independent response variables analyzed together using multivariate techniques [62]. MB estimates multifunctionality by jointly modelling multiple functions in a hierarchical framework, capturing the effects of ecological factors on overall ecosystem functioning [63]. By contrast, PM measures multifunctionality as the point at which all ecosystem services and biodiversity are simultaneously closest to their potential maximum levels [64]. As SF, MD, MB and PM approaches were scarcely used for quantifying forest multifunctionality, their implications for resulting indices and comparability with standard methods deserve further consideration.

What Are the Drivers of Forest Multifunctionality?

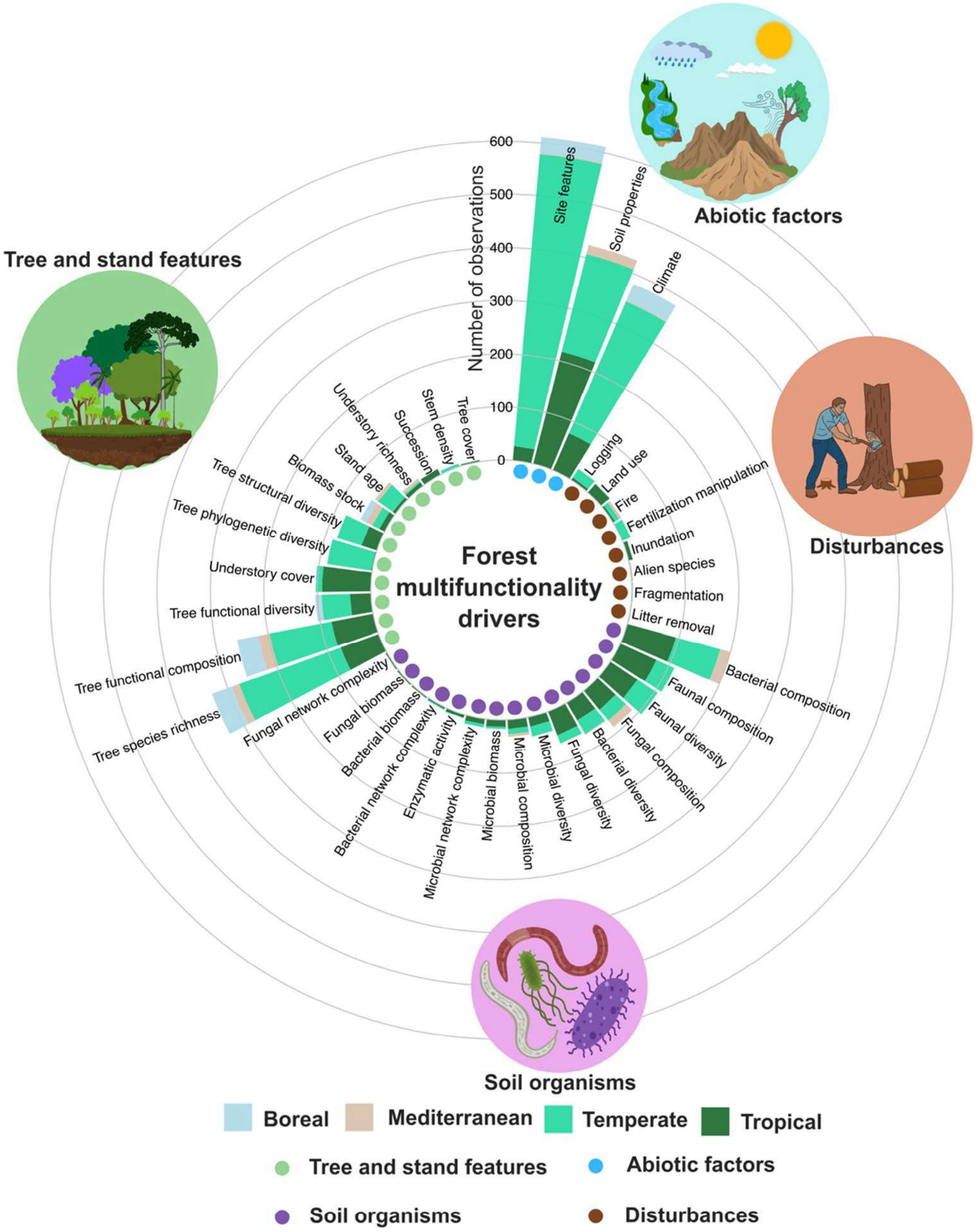
Methods Used To Explore the Drivers of Forest Multifunctionality

Our review showed that less than half of the studies assessed the dependencies of forest multifunctionality indices using statistical models capable of distinguishing direct from indirect effects by testing alternative causal pathways (Fig. 2C). Those models mainly include structural equation models and path analysis, which were used in 45% of the surveyed studies (Fig. 2D). Identifying whether driver effects are direct or indirect is crucial for understanding the ecological interactions driving forest multifunctionality [45, 47]. Moreover, clarifying this distinction in future publications will help prevent misinterpretations of the results and their implications for management.

Drivers across Biomes

Across the 103 papers included in our review, we identified 38 distinct groups of drivers, which we organized into four main categories (Fig. 3, Table S7). Additionally, we explored the distribution of drivers of forest multifunctionality across biomes for all studies included in the review. In temperate forests, abiotic factors and tree and stand features were the most frequently investigated drivers influencing multifunctionality. Among these, site features, climate, tree species richness, and tree functional composition were particularly common. In tropical forests, research more often focused on soil properties and soil organisms, highlighting the importance of belowground processes for ecosystem functioning in these regions. Research in boreal and Mediterranean forests was limited. Mediterranean studies primarily explored tree and soil traits, while boreal studies focused on tree and stand features (Fig. 3). Additionally, most studies assessing forest multifunctionality were conducted at the stand scale, whereas only a few (12 studies with only 39 observations, Table S7) examined drivers at the landscape level. These landscape-scale studies mainly focused on variables such as land use composition, landscape heterogeneity, and forest cover, highlighting that spatial structure can also influence

Fig. 3 Drivers of forest multifunctionality explored in the literature across four biomes. Bars represent the number of observations for each driver in all biomes (total = 3376 observations). Driver categories include abiotic factors (blue circles), disturbances (brown circles), soil organisms (purple circles) and tree and stand features (light green circles). Bar colors represent boreal (blue), Mediterranean (brown), temperate (light green) and tropical (dark green) forests



forest multifunctionality [23, 64–66]. For instance, a large-scale analysis encompassing over 2000 ha of temperate and boreal forests in Finland revealed that intensive management practices can create long-lasting constraints on forest multifunctionality at the landscape level, making forest multifunctionality not resilient to intensive forestry [64]. However, the limited number of studies prevents broader generalizations, emphasizing the need for more research integrating multiple spatial scales.

Furthermore, the most frequently studied drivers were abiotic, including, by decreasing order of frequency, soil properties, site features and climate factors (Fig. 4, Table S7). The second most studied drivers were related to the composition (i.e., the identity of the species found in the forest) and the diversity of trees and soil organisms. This underscores the growing scientific interest in the relationship between biodiversity and forest multifunctionality in recent years [45, 67]. This interest also extends to stand structural diversity, defined as the heterogeneity of tree size within a stand [11, 31] and stand age. In contrast, drivers related to anthropogenic and natural disturbances have been less explored (Fig. 4, Table S7).

Abiotic Factors

Abiotic factors are well-studied drivers of forest multifunctionality (*n* = 671 observations, Fig. 4). They generally exhibit a comparable proportion of negative, neutral,

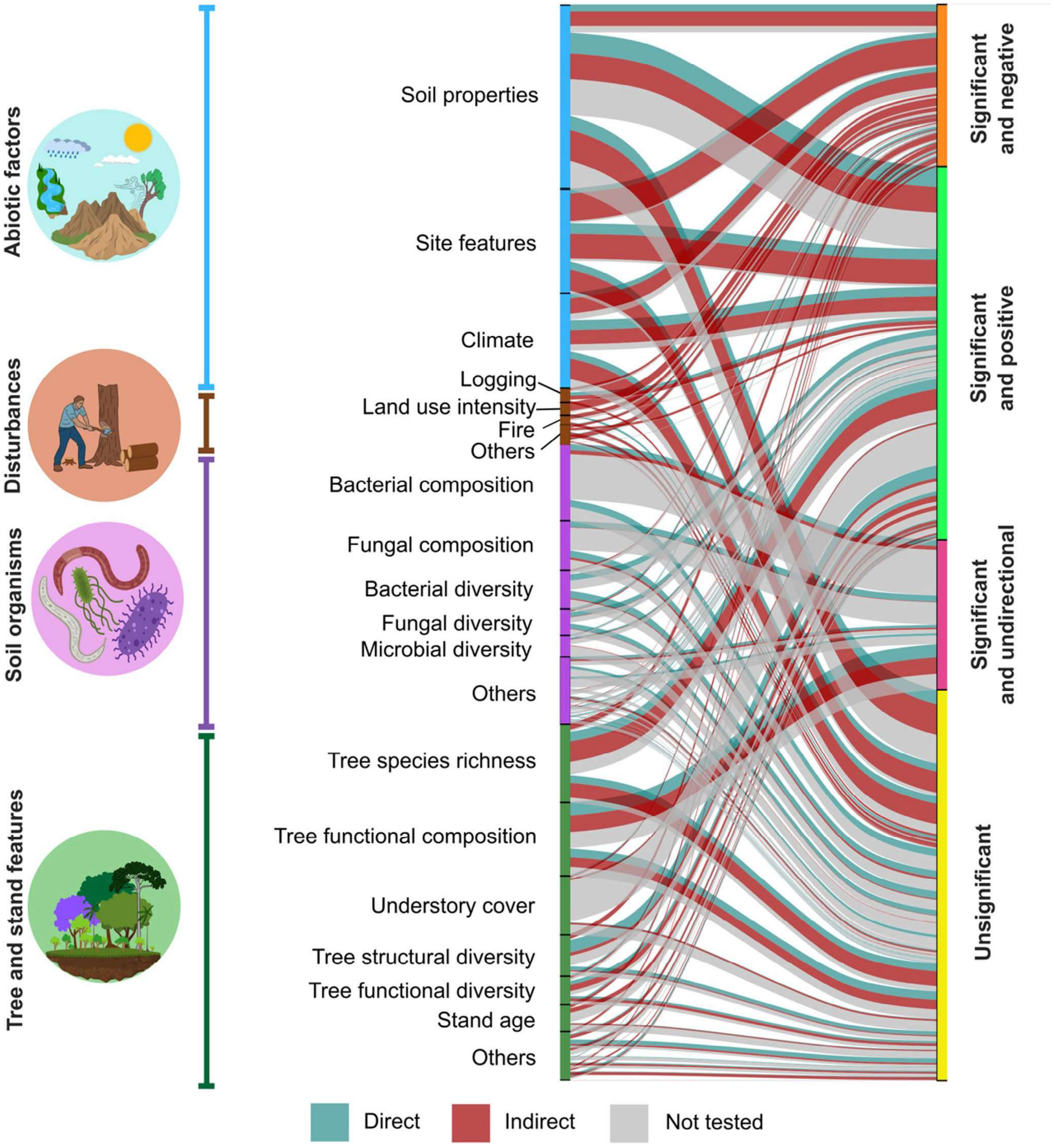


Fig. 4 Sankey diagram linking drivers of forest multifunctionality (observations = 1881) to effect direction. Direct, indirect and not tested effects are represented by green, red and gray, respectively. For better readability, less frequent drivers have been grouped under "Others" in each ones of the four categories

and positive effects on forest multifunctionality (Fig. 4). This is in line with many previous studies reporting that the effects of abiotic factors on forest multifunctionality are often inconsistent across large ecological gradients [68–70]. This inconsistency arises because many abiotic factors do not have a linear relationship with forest multifunctionality. Instead, they tend to follow a Gaussian pattern, where intermediate values are associated with maximum forest functions (e.g., as observed for pH, soil water content, and bulk density [16]). Therefore, the inconsistencies found in this study likely reflect the broad scope of our analysis, which encompasses a variety of forest ecosystems where abiotic factors vary significantly. Moreover, such inconsistencies may stem from the inherent ecological complexity and context dependence of forest systems, as well as from interactions among variables and methodological differences in modelling approaches.

Moreover, our survey revealed that soil properties influence forest multifunctionality through both direct and indirect effects, while the impact of site features and climate on forest multifunctionality was primarily driven by indirect effects [19, 25, 35, 40, 60, 71]. In a recent meta-analysis on the effects of belowground multifunctionality on ecosystem restoration, Tian et al. [54] showed that soil properties such as soil carbon, total nitrogen, and phosphatase play a key role in determining the recovery of ecosystem multifunctionality in restoration areas. This finding aligns with several studies from our review that demonstrated strong effects of these drivers on forest multifunctionality [72–75]. Furthermore, these authors emphasized the importance of adopting an overall ecosystem-functioning perspective, rather than focusing on isolated functions, in order to consider interactions among functions and achieve a more integrated view of ecosystem performance. Nevertheless, some studies have shown that climatic factors, such as mean annual precipitation and temperature, can exert a strong direct effect on forest multifunctionality due to their ability to significantly alter environmental conditions [27, 38]. This reflects the complexity of abiotic control over forest multifunctionality, as soil properties, site features, and climate often influence a wide range of functions and taxonomic levels, resulting in interacting effects on forest multifunctionality [38].

Disturbances

In general, we found that land use intensification decreases forest multifunctionality (Fig. 4). Most studies have evaluated the effects of land use intensity (i.e., cropping frequency and management intensity) primarily regarding soil multifunctionality and indicate that soil organisms play a crucial role in this relationship [23, 40]. Conversely, the effects of logging on forest multifunctionality were predominantly positive and appear to depend on the interaction between soil biodiversity and canopy structure [19, 24]. Yuan et al. [56] showed that logging of low to moderate intensity can enhance soil biodiversity and promote multifunctionality, while simultaneously reducing aboveground plant diversity. Similarly, Bastida et al. [76] observed that thinning can mitigate the negative impacts of drought on multifunctionality by altering soil microbial communities. These findings suggest that forest management strategies should carefully balance the complex, indirect effects of disturbances on the variety of ecosystem compartments and trophic level to promote forest multifunctionality.

Soil Organisms

The composition and diversity of bacterial and fungal communities were the most frequently evaluated drivers of forest multifunctionality (n = 335 observations, Fig. 4 and Table S7). Approximately 72% of the observations reported that bacterial composition influences forest multifunctionality, while 28% found no such effect (Fig. 4). In contrast, fungal composition exhibited a more balanced distribution of effects, with 59% of observations indicating an influence on forest multifunctionality, and 41% reporting no effect (Fig. 4). Several studies have highlighted the role of both bacterial and fungal composition in enhancing water-holding capacity [77], soil respiration [78], enzymatic activity [76], and plant diversity [21]. Notably, these studies also emphasize that such effects are interconnected: microbial communities interact with forest structure, soil properties, and climate conditions, leading to synergistic improvements in forest multifunctionality. This suggests that forest multifunctionality is tightly linked to the biological activity of soil bacteria and fungi, and that the diversity of these microorganisms provides a direct pathway toward higher multifunctionality in forests. However, this relationship requires further investigation, as most studies focus primarily on microorganisms, overlooking soil fauna, providing an incomplete picture of soil biodiversity and its role in soil functioning and forest multifunctionality.

Tree and Stand Features

In most cases, tree species richness, stand biomass, and tree structural diversity exerted a positive effect on forest multifunctionality, either directly or indirectly (Fig. 4). Tree structural and functional diversity and composition tend to have direct impacts on forest multifunctionality [12, 27, 59, 60, 79]. While several studies have reported that tree species richness increases forest multifunctionality [21, 22, 39, 57], our findings additionally suggest that tree species richness primarily exerts indirect effects [80, 81]. Indeed, tree species richness on its own appears insufficient to enhance forest multifunctionality [79], and this is especially true in the context of restoration practices [82]. This supports the notion that tree species richness alone may not only drive ecosystem functioning directly [83, 84], but also promote functional diversity among trees or soil organisms, which in turn enhances resource acquisition, ecological functioning, and overall forest performance [11, 24, 25, 85]. Studies show that restoration is more effective when multi-trophic interactions, such as those between plants, soil microbes, and soil fauna, are considered, due to their cascading effects on ecosystem processes [22, 55, 81, 86]. For instance, synergies between tree species richness and soil properties can directly shape microbial community composition and abundance, thereby supporting ecosystem recovery [55]. Moreover, interactions across trophic levels and taxa importantly drive forest multifunctionality across the successional stages in restoration forests. As restoration progresses, increases in functional tree diversity tend to emerge [82], along with more complex stand spatial structures and more integrated trophic-level interactions in later successional phases [61], which increases forest multifunctionality. This reinforces the view that focusing solely on one taxon group (e.g., tree species) may be inadequate for effective forest multifunctionality restoration.

Consistency of Driver Effects on Forest Multifunctionality

We tested the consistency of the effects of the most studied drivers on forest multifunctionality to determine whether common patterns could be identified beyond the specific context of each study (Table 2). The consistency analysis revealed that bacterial and fungal diversity, stand biomass, stand age, tree functional diversity, tree species richness, tree structural diversity and understory cover had a consistently positive effect on forest multifunctionality (Table 2). Therefore, our review suggests that more diverse stands and older trees exhibit higher forest multifunctionality. Protecting old-growth forests and promoting long-term restoration along with diverse planted forests is therefore an effective approach to achieving multifunctional forests [87–89].

Table 2 Consistency measures whether positive effects occur proportionally more frequently than negative and neutral effects: values indicate the proportion of positive effects relative to the total number of observations. A binomial test was used to assess whether the number of positive effects was significantly higher than the number of negative effects. Only continuous drivers with more than 20 observations were included in the test

Categories of drivers	Subcategory	Total	Consistency
Disturbances	Logging intensity	25	0.56
Soil organisms	Bacterial diversity	67	0.40*
	Fungal diversity	46	0.39*
	Microbial diversity	37	0.32
Tree and stand features	Stand biomass	21	0.67*
	Stand age	47	0.51*
	Tree functional diversity	50	0.50*
	Tree phylogenetic diversity	29	0.28
	Tree species richness	135	0.55*
	Tree structural diversity	72	0.63*
	Understory cover	103	0.74*

* $p < 0.05$ in the binomial test

Indirect Drivers of Forest Multifunctionality

Many listed drivers exhibited an indirect effect on forest multifunctionality, i.e., an effect mediated by the interactions among abiotic factors, disturbances, soil organisms, and tree and stand features [12, 57]. Several studies reported that site features strongly influence forest multifunctionality by shaping tree species richness, phylogenetic diversity, and functional diversity and composition (Fig. 5) [12, 25, 57]. Climatic factors have also been investigated, mainly through their effects on tree composition and functional diversity, but no clear relationship has been established (Fig. 5) [12, 41, 90]. Conversely, tree species richness exerts a strong effect on forest multifunctionality via its influence on functional diversity (Fig. 5) [12]. Markedly, only a limited number of studies explored indirect effects involving soil organisms on forest multifunctionality. Despite the fact that indirect effects among soil organisms and soil trophic relationships play an important role in driving forest multifunctionality [77, 78], these aspects have not been studied enough to allow drawing of a robust pattern of these dependencies or to warrant further studies (Figs. 4 and 5).

Contrasting the Drivers of Above and Belowground Multifunctionality

In our review, we found that many studies calculated forest multifunctionality index using only belowground functions [20, 23, 33, 35, 73, 91–93], rather than combining multiple types of functions to adopt a more holistic view of forest multifunctionality, as recommended by previous studies [9, 10, 16]. Nonetheless, a smaller part of the studies has successfully integrated both above- and belowground functions to assess multifunctionality more comprehensively (e.g., [38, 63, 67, 68, 94–96], demonstrating that such an approach is not only conceptually sound but also practically feasible. Notably, none of the listed studies relied solely on aboveground functions to calculate forest multifunctionality indices (Fig. 6).

We observed that the effects of aboveground drivers were examined in relation to both above- and belowground forest multifunctionality (e.g., [71, 72]), whereas belowground drivers were primarily studied in the context of their effects on belowground forest multifunctionality only [28, 97]. For instance, approximately 69% and 55% of the reported

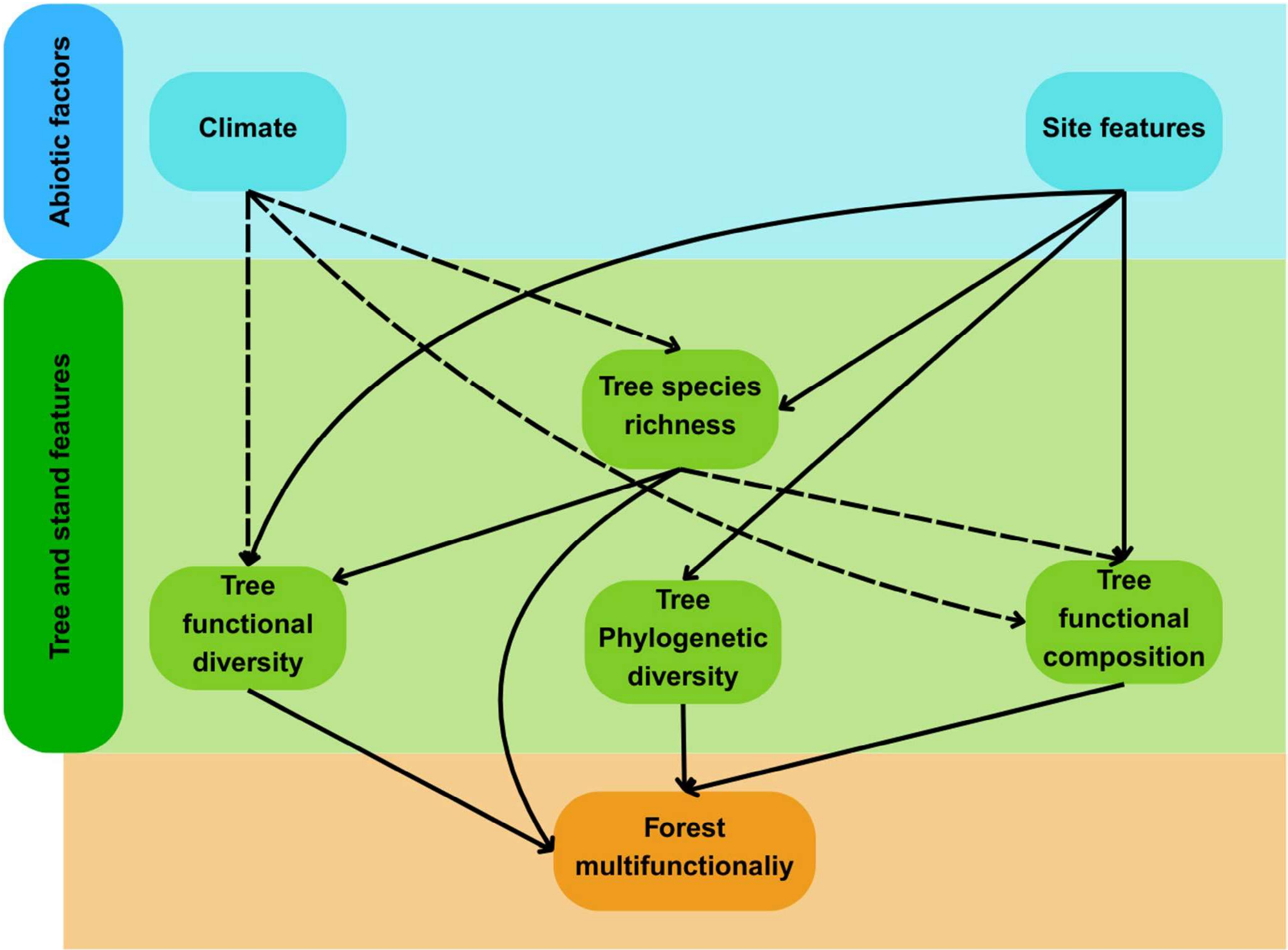


Fig. 5 Most frequent indirect drivers ($n>20$ observations) of forest multifunctionality reported in the studies included in this review. Solid arrows indicate that more than 50% of the reported effects of a given driver on forest multifunctionality were significant (either positive or negative), whereas dashed arrows indicate that most reported effects were neutral

effects of soil organism and disturbance drivers were exclusively assessed on belowground forest multifunctionality, respectively. In contrast, the effect of tree and stand feature and abiotic factors drivers were explored on both above- and belowground forest multifunctionality in 72% and 62% of the observations, respectively. This suggests that studies focusing on tree-related drivers tend to investigate their impact on the entire ecosystem, including soil biodiversity, a pattern not observed in soil-related studies. This result aligns with our findings on ecosystem functions, indicating a clear tendency to assess belowground multifunctionality primarily using belowground functions and drivers (Figs. 2A and 6).

Given the broad and integrative nature of multifunctionality [10, 15, 17], a comprehensive assessment requires a multidisciplinary approach that bridges biotic and abiotic drivers related to soil, stand, and climate. For example, a recent global meta-analysis showed that elevated ozone decreases forest multifunctionality in different belowground ecosystem types, including forests [98]. This shows that the effects of abiotic factors (here ozone concentration) and belowground drivers clearly affect ecosystem-scale multifunctionality. Indeed, studies suggest that integrating aboveground and belowground indicators can enhance ecological monitoring by balancing accuracy and cost-effectiveness [99]. Yet, changes in aboveground vegetation structure are often paralleled by similar trends in belowground biodiversity, underscoring the interdependence of these components in ecosystem monitoring [99, 100], which reinforces the importance of holistic assessments in ecological management [99, 101]. Additionally, the increasing availability of LIDAR data in forest science may increase the characterization of aboveground functions in the futures, e.g., by better characterizing carbon cycling dynamics [102], as well as other key functions such as tree-related microhabitats [103].

Fig. 6 Sankey diagram linking driver categories of forest multifunctionality (observations = 1881) to how multifunctionality was measured in 103 studies reviewed. We defined how multifunctionality was measured by considering the functions (if above, below or both) used to calculate the multifunctionality index. Colors means the type of multifunctionality considered: green represents above- and belowground multifunctionality, and orange represents belowground multifunctionality only

Limitations and Perspectives on our Current Understanding of the Drivers of Forest Multifunctionality

Geographical Gaps

A striking observation revealed by our systematic review is the limited geographical coverage of forest multifunctionality studies, and the near absence of data from Africa, North and South America, and Oceania. The studies were mainly conducted in Asia, predominantly come from China. In this country, studies are limited to a small number of authors (Fig. S3). In contrast, Europe shows a higher number of publishing research groups and authors, although the total number of publications is lower. Moreover, several European studies are derived from the same project and dataset (FunDivEUROPE, Fig. S3 [63, 67, 68, 104]). This largely questions the genericity of the patterns revealed in our study and calls for further research to better identify the drivers of global multifunctional forests.

Improving the Construction of Multifunctionality Indices

One challenge in identifying general patterns in multifunctionality determinism is the limited comparability across studies, due to substantial variability in how multifunctionality indices are constructed. This variability stems from the often arbitrary selection of ecosystem functions, the diverse methods used to measure or estimate them, and the different approaches used to aggregate these functions into indices [16, 18]. This issue has been discussed elsewhere [10, 16], highlighting the need for standardized measurements of a consistent set of ecosystem functions, ideally defined solely on process rates across forest ecosystems [17].

Moreover, the choice of functions used to calculate indices can influence what is considered high or low forest multifunctionality. Functions related to greenhouse gases emissions and those related to soil carbon stabilization have opposite impacts for climate regulation, thus limiting the comparability of indices that would include one or the other as a proxy for C cycling. In turn, the implications of high values for certain functions on overall ecosystem performance are not always clear. For example, rapid litter decomposition was once seen mainly as evidence of quick carbon mineralization and release to the atmosphere, whereas it is now understood that fast decomposition can also promote greater soil carbon stabilization [105], although this remains debated [106].

Finally, the methods used to measure functions can themselves influence the calculated multifunctionality values and the perceived effects of drivers on forest multifunctionality. To illustrate this issue, we found that many studies used the decomposition of standard material, such as flat wooden sticks [67, 104], as proxies of litter decomposition as proposed by methodological frameworks [17]. Yet, it was recently found that standard litter decomposition was not informative at all of the decomposition rates of the site-specific litter [107]. Collectively, the absence of a consistent way of measuring and calculating index makes it difficult to pin down important drivers of forest multifunctionality. We thus encourage further conceptual and methodological development to provide a new standardized framework to study multifunctionality in forest ecosystems.

Overlooked Drivers of Forest Multifunctionality

The fact that soil organisms were considered almost as frequently as stand properties in driving both below- and aboveground forest multifunctionality highlights the growing recognition of the importance of above–belowground interactions (Fig. 6). Yet, the characterization of soil communities was strikingly restricted to microorganisms, while soil fauna was rarely considered. This is critical because soil fauna represent a key component of soil organism diversity, contributing to soils being the largest reservoir of biodiversity [100], and exerting a disproportionate influence on soil functioning relative to their biomass [101]. Some studies included in this review have shown the important role soil fauna in supporting soil multifunctionality [81, 108–110]. Notably, Kou et al. [108] showed that the land-use intensity strongly affects both macro- and mesofauna. Moreover, their relationships with soil multifunctionality appear to diverge. For instance, the composition of macrofauna responds differently than that of mesofauna to increasing forest disturbance, ultimately influencing soil multifunctionality. This divergence has recently been linked to differences in body size, which may determine whether a group is more affected by stochastic (e.g., dispersal-driven) or deterministic (e.g., selection-based) processes [111]. Similarly, Wang et al. [110] observed a significant positive relationship between soil organism body size and soil multifunctionality, suggesting that body size could be a useful predictor for evaluating multifunctionality in forests. However, it remains unclear how the behavior and dynamics of soil fauna, particularly under frequent land-use changes, may alter forest multifunctionality. We thus encourage future studies to expand their characterization of soil communities to include soil fauna. Beyond this specific issue, it is important to stress that our review can only identify the roles of drivers on multifunctionality from those that have been measured and published. Other environmental variables, such as microclimate conditions, soil physical properties, management intensity, and biotic interactions, may be even more important drivers of forest multifunctionality, yet they remain largely unexplored due to a ‘streetlight effect’.

Strikingly, disturbance-related drivers were among the least explored in this review. Yet, it is now firmly established that increases in disturbance associated with global change can drastically affect multifunctionality, often in connection with ongoing biodiversity loss. Indeed, strong effects have been reported from climate change [112], pollution [113], urban expansion [114], timber exploration [115], invasive species [116], land use changes [117] or wildfire [118].

Similarly, only very few studies have investigated how management practices, including logging and land-use intensification influence forest multifunctionality [19, 56, 76]. However, this warrants further research, especially beyond European and Chinese temperate forests. In particular, tropical forests, which account for approximately 45% of the global forest area [119], were addressed in only four studies (outside China), conducted in Mexico, Ecuador, South Africa, and Madagascar [66, 120–122]. No studies were found for Brazilian tropical and subtropical forests, even though these ecosystems are increasingly affected by strong anthropogenic disturbances, including deforestation [123, 124] and wildfires [125], which may lead to unexpected ecosystem collapse [126]. By comparison, the only study conducted in South America, Eguiguren et al. [66] found a strong impact of logging on forest multifunctionality in the Ecuadorian Amazon, particularly affecting ecosystem functions such as timber provisioning and carbon stocks. Therefore, identifying the drivers of forest multifunctionality in tropical forests is an urgent priority to improve forest management and support climate change mitigation efforts.

Implications for Management and Policy

The evidence summarized in this review reinforces the perspective that native old-growth forests maximize multifunctionality and that protecting them should be a priority to safeguard biodiversity and the broad ecosystem services they provide to society. At the same time, the option for reforestation approaches that mimic someway native forest structure and composition, like when more species are used and tree cover is maintained for longer periods of time, enhances the likelihood of achieving multifunctionality [127–129]. This assumption supports the use of ecological restoration – rather than other reforestation methods – for offsetting environmental damages when they cannot be avoided and when the main objective of reforestation is to deliver broader societal benefits, like in the restoration of riparian buffers and environmentally fragile areas [130].

Furthermore, the use of mixed plantings in commercial forestry is highlighted as an opportunity to integrate other ecosystem functions into timber production, thus enabling commercial plantations to expand their portfolio of benefits to society and increase resilience [131]. Alternatively, as reforestation has also been used to address one or a few utilitarian benefits, our review sheds light on the mechanisms and strategies that could be used to maximize these desired outcomes, by integrating different facets of biodiversity (structural and functional diversity, and species richness), scales, and varied functions (e.g [31, 37, 121, 132, 133]). , . Tree diversity tends to show positive or neutral effects and represents a 'no-regret' strategy to enhance multifunctionality [134]. Moreover, our synthesis indicates that several facets of diversity, such as structural and functional diversity, can substantially contribute to multifunctionality. This implies that even ecosystems with lower tree species richness may achieve high multifunctionality if management practices effectively increase canopy structural complexity.

Importantly, the role of management becomes even more critical given the solid evidence that forest multifunctionality potential is high but largely unrealized at continental [135] and local scales [136]. However, multifunctionality is not consistently higher in protected areas compared to forests outside protected zones in Europe [135], highlighting that conservation status alone is insufficient and that targeted management actions are essential to unlock this potential. In line with this, a long-term restoration plantation in Brazil demonstrated high multifunctionality by explicitly incorporating socioecological objectives into its design from the outset, ultimately providing multiple ecosystem services to the local community [137]. All these issues are critical for planning, implementing, and monitoring multifunctional forests, which have been increasingly demanded by society to address the polycrisis of our time.

Conclusions

This systematic review showed that multifunctionality indices in forest ecosystems were most calculated using belowground functions. Tree species and soil organism diversity (including species richness and composition effects), as well as stand structural diversity, emerged as crucial drivers enhancing forest multifunctionality both above- and belowground. In general, our results suggest that preserving old-growth forests, promoting long-term restoration, and expanding species-diverse forests is an effective strategy for achieving multifunctional forests. Importantly, soil-related drivers are predominantly used to evaluate belowground multifunctionality, with less consideration given to their potential effects on aboveground multifunctionality. Understanding forest multifunctionality demands not only isolated evaluations of above- or belowground processes but also a holistic perspective that considers their interconnected roles in shaping overall ecosystem dynamics. These insights are also relevant to the growing application of soil health indices in forest contexts, where soil multifunctionality constitutes a core component of soil health and is considered nearly synonymous with it by some authors [138]. Our findings highlight that approaches focused solely on belowground metrics may overlook important aboveground–belowground linkages that are essential for evaluating ecosystem performance as a whole. Finally, we observed that the vast majority of the studies reviewed focuses on "ecosystem function multifunctionality" (*sensu* [10]), i.e., they calculate multifunctionality indices based on fluxes or stocks of energy and matter in the ecosystem. Although those are fundamental metrics of ecosystem performance, it is also crucial to develop a deeper understanding of the drivers of "ecosystem service multifunctionality" in forests [10], i.e., where multifunctionality is defined and appraised based on human-oriented criteria [139]. It seems especially important to further explore the bioeconomic implications of multifunctionality and the trade-off and synergies between supply services of timber and non-timber products and other services [140–144]. In addition, we showed that future research needs to focus on the way forest management practices can enhance multifunctionality in the different environmental contexts. Together, these research avenues pave the way for a better integration of multifunctionality in sustainable and economically viable forest management guidelines and environmental decision-making.

Key References

Here, we provide a short list of the key references that have guided our discussion throughout this review, with a brief explanation of why each reference was chosen:

- Manning P, Van Der Plas F, Soliveres S, Allan E, Maestre FT, Mace G, et al. Redefining ecosystem multifunctionality. Nat Ecol Evol. Nature Publishing Group; 2018. p. 427–36. DOI: https://doi.org/10.1038/s41559-017-0461-7.

  This paper purposes a refined concept of ecosystem multifunctionality, emphasizing the need to consider the simultaneous maintenance of multiple functions at high levels. It provided the conceptual backbone for our discussion by clarifying how multifunctionality should be framed when linking biodiversity to ecosystem functioning.

- Garland G, Banerjee S, Edlinger A, Miranda Oliveira E, Herzog C, Wittwer R, et al. A closer look at the functions behind ecosystem multifunctionality: A review. J. Ecol. Blackwell Publishing Ltd; 2021. p. 600–13. DOI: https://doi.org/10.1111/1365-2745.13511.

  This review provides an overlook on ecosystem functions most commonly used to measure multifunctionality and highlighted biases toward certain ecosystem indicators.

- Byrnes JEK, Gamfeldt L, Isbell F, Lefcheck JS, Griffin JN, Hector A, et al. Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. Methods Ecol. Evol. 2014. p. 111–24. DOI: https://doi.org/10.1111/2041-210X.12143.

  This review provides a deeper look at multifunctionality indices as well as their pros and cons.

- Trogisch S, Schuldt A, Bauhus J, Blum JA, Both S, Buscot F, et al. Toward a methodical framework for comprehensively assessing forest multifunctionality. Ecol Evol. 2017;7:10652–74. DOI: https://doi.org/10.1002/ece3.3488.

  This study proposed a comprehensive framework for assessing forest multifunctionality, integrating multiple ecological, silvicultural, and management dimensions.

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Data Availability All data is available in appendix.

Declarations

Conflict of interest The authors declare no competing interests.

Competing interests The authors declare no competing interests.

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