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# Managing Global Forests in View of Multiple Goals: An Evidence-Based Perspective

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**Abstract:** Forest ecosystems are increasingly facing challenges related to overexploitation and climate and land-use change, thereby posing a threat to the myriad benefits they provide. Forest management is the only tool for ensuring that adaptation, mitigation, and biodiversity conservation in forest ecosystems are maintained and further enhanced over time. However, forest managers might not have clear guidance on how to ensure these goals are achieved through their practices, which is why a goal-driven management framework is proposed and discussed in this study. The proposed framework provides an overview of the possible effects of alternative forest management practices on climate services, biodiversity conservation, and wood extraction and production. Based on this framework, the following "should-haves" for forest management towards achieving multiple goals are outlined: consideration of the trade-offs between biodiversity and other benefits; the need to reflect on time and space variability; and incorporation of climate sensitivity. The suggested actions are as follows: improve the monitoring framework; implement more robust modeling tools; and further consider policy trajectories.

**Keywords:** sustainable forest management; mitigation; adaptation; biodiversity conservation; wood production; ecosystem services

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## 1. Introduction

Forests are essential components of the Earth's biosphere and support human well-being in countless ways; however, forests are threatened worldwide by overexploitation, land-use change, and climate change [1]. These drivers inevitably lead to the loss of forest-dependent species and habitats and a reduction in the availability of goods and services for people [2]. Furthermore, the functionality and resilience of forests in many parts of the globe have been progressively declining because of climate-induced effects, such as large-scale drought and the increased frequency and severity of natural disturbances [3].

Global forest cover continues to decrease, with subsequent dramatic biodiversity losses [1]. In addition, the value of forest ecosystem services has fallen in recent decades by as much as USD $3.3 \cdot 10^{12}$ for boreal and tropical forests [4]. The combined effects of climate and land-use change are increasingly undermining the capacity of forests to continue sustaining our daily lives. The main causes of deforestation and forest degradation are well documented and mostly relate to socio-economic pressures triggering the conversion of forests to other land uses (e.g., agriculture and pasture), especially in the tropics [5]. Prolonged drought periods result in faster reductions in primary production and evapotranspiration (e.g., temperate forests [6]), as well as decreased tree growth and increased physiological stress [7]. Changes in temperature and precipitation also exacerbate the effects of natural disturbances (e.g., wildfires and wind throw [8]), including abrupt changes in stand structure and higher susceptibility to external driving forces [9,10].

Beyond climate and land-use changes, what happens within forests? On average, only half of the world's forests have management plans (ranging from 17% in South America to 96% in Europe), and forest management is mostly oriented towards wood production (30%

of the total forest area), leaving multi-purpose forest management at less than 20% of the total forest area [1].

From an ecosystem perspective, forests need adaptive capacity and resilience to face external impacts, both natural and anthropogenic. Forest ecosystem structures and processes are naturally driven and may require decades or even centuries to return to a new equilibrium state [11]. Moreover, ecosystem dynamics vary across space, and they influence large landscape transformations through tree species migration and the recolonization of abandoned or unused lands [12]. From a human perspective, sustainable forest management is key to ensuring that forests continue to deliver economic, social, and environmental benefits to present and future generations [13]. Forest management indeed contributes to the adaptation of forests to climate change, carbon sequestration and storage (which is part of climate regulation), and the preservation of valuable habitats and species, as well as to the availability of fundamental goods and services, e.g., wood and non-wood products, freshwater supplies, soil stabilization, and cultural values and esthetics [14]. Sustainable forest management also helps alleviate poverty, increase economic returns, promote working opportunities, and improve human health and wellbeing [15]. Social needs and market dynamics have historically driven forest management towards a production-oriented approach [16]. However, only recently, forest management has regained a pluralistic role encompassing climate change mitigation and adaptation and biodiversity conservation (see, e.g., integrated forest management [17]).

In the last few decades, both policymakers and the scientific community at various levels have emphasized on the roles of forests and forest management in climate change adaptation and mitigation, biodiversity conservation, and ecosystem services provision (for a comprehensive overview, see [18]). Worldwide, the UN Strategic Plan for Forests [19] provides a reference framework for further strengthening the role of sustainable forest management and the contribution of forests to sustainable development. At the European scale, the recent Bonn Ministerial Decision [20] has reported countries' pledges to step up the implementation of policies, tools, and measures for improving forest resilience, and calls for the implementation of risk management approaches in forest strategies, plans, and programs. Nevertheless, the UN report on Global Forest Goals [21] highlights several remaining challenges for the effective implementation of sustainable forest management, ranging from general aspects, such as the impact of climate change, biodiversity loss, and forest degradation, to nationwide aspects, such as forest financing, illegal trade, and capacity building. Other obstacles derive from the fact that countries have not yet reached a global consensus for a legally binding forest convention [18]. Despite more recent advances in international agreements (some of them legally binding) on reversing deforestation and forest degradation and strengthening climate change mitigation and nature conservation, the implementation of forest management remains the exclusive responsibility of national authorities, in some cases thus limiting the global progress towards rapidly meeting sustainability targets. Moreover, some national or supra-national policies are still too sectorial and partially driven by the market (e.g., timber commodity), thus further hampering the dialog between actors with different interests and goals (e.g., timber provision vs. biodiversity conservation). These aspects explicitly call for a more comprehensive integration of actions between the forest and other sectors [18].

Despite the holistic view of the sustainable forest management concept, some knowledge gaps hinder its effective implementation. Current forest management lacks consideration of synergies and trade-offs among biodiversity and ecosystem service provision [22]. There is indeed poor information on suitable recommendations for forest managers on how to handle multiple services [23]. On the other hand, forest management practices do not robustly capture the vulnerability and adaptability of forests to climate change, as they require predictions for the effects of changing climate conditions on forest productivity and resilience, as well as the embedding of related uncertainties [24].

Forestry research provides important support to practitioners, but it is weak in comprehensively exploring the trade-offs in service provision when alternative management practices are considered [25]. For this reason, forest managers do not always have a full understanding of how to balance multiple goals through forest management practices [26]. Moreover, forest managers are not yet completely ready to implement adaptive practices to cope with the uncertainty related to the effects of changing climate on health, resistance, and the stability of forest stands [27].

The aim of this study is to shed light on the potential effects of forest management practices on management goals, such as climate actions (adaptation and mitigation), biodiversity conservation, wood production, and other benefits. To this end, a goal-driven management framework is built based on a systematic review, and the following three perspectives (here called "should-have(s)") are ultimately drawn for management practices towards safeguarding the multiple benefits forests provide while incorporating spatial and time dependencies and climate sensitivity: practices mimicking natural disturbances are beneficial for a broader set of goods and services; practices targeting more benefits are less dependent on time and space; and practices lacking the incorporation of the effects of climate on the future evolution of forest stands are less effective in meeting management goals.

## 2. Approach

### 2.1. Literature Review

I carried out a systematic review (e.g., [28]) of peer-reviewed and indexed records in the SCOPUS and Web Of Science (WOS; Core Collection) databases. The review is based on a by-topic search of all document types (articles, reviews, book chapters, etc.) written in English from 1945 (WOS) and 1960 (SCOPUS) to now (Review date: September 2024). The following search strings were used in both databases: (i) forest management AND adapt*; (ii) forest management AND mitigat*; (iii) forest management AND biodiv*; (iv) forest management AND product*; (v) forest management AND ecosystem service* OR benefit*. Search strings were then combined to narrow the *spectrum* of search outcomes (i.e., records). Searching was based on the title, abstract, and keywords in the case of SCOPUS, and topic in the case of WOS. The review process followed the PRISMA workflow [29]. After removing the search duplicates (identification phase), records were screened based on title, abstract, and keywords, and non-accessible records were excluded (screening phase); only the selected records from the previous phase were then read, while non-pertinent records were excluded (eligibility phase) (Figure A1). The main reasons for exclusion were (i) an inconsistency with the scope of the review (dealing with other land uses or other economic sectors than forestry); (ii) contents only partially dealing with forest ecosystems; (iii) the lack of a clear explanation/assessment of the impact of forest management practice(s) on forest ecosystem services provision (either one forest management practice vs. many services, or more forest management practices vs. one service).

### 2.2. Assessment of the Potential Effects of Practices on Forest Management Goals

Based on the contents of the included records, I evaluated the potential effect of each considered forest management practice (Table 1) on the management goals, namely adaptation, mitigation, biodiversity conservation, wood production, and other benefits (e.g., freshwater supply, hydrological protection, tourism and recreation, non-timber forest products, and cultural values and esthetics) (Table 2).

For each included record, I assigned a specific weight to the potential effects of forest management practices (those included in each record) on adaptation, mitigation, biodiversity conservation, wood products, and other benefits: 0 for negligible or negative potential effect; 0.5 for moderate, positive potential effect; 1 for high, positive potential effect. Forest management effects are distance-dependent: the higher the effect, the shorter the distance from the maximum value (=1). I then attributed a confidence level to each correspondence between a management practice and a management goal, partly following the IPCC guidance on the consistent treatment of uncertainty in reports, i.e., authors' judgments about the validity of findings, as determined through evaluation of evidence and agreement ([34] p. 3). The confidence levels are classified as low confidence (L), medium confidence (M), high confidence (H), and very high confidence (VH), each representing a 25% step increase in the frequency of observations over the maximum number of observations.

**Table 1.** List of management practices included in this study.

| Harmonized Forest Management Practices (Adapted from [30]) | Additional Practices Included |
|---|---|
| Close-to-nature management | Close-to-nature silviculture, continuous-cover forestry, reduced thinning |
| Disturbance management | |
| Intensive even-aged management | Ordinary management, business-as-usual management |
| Multi-purpose management | Selective thinning, reduced impact logging |
| No management or passive management | |
| Potential vegetation/natural regeneration | Natural forest regrowth, assisted natural regeneration |
| Residue removal | |
| Short rotation | Reduced rotation length/period |
| Sustainable management of plantations | |

**Table 2.** Definitions of management goals considered in this study.

| Management Goal | Definition |
|---|---|
| Adaptation | In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to the expected climate and its effects [31]. |
| Mitigation | A human intervention to reduce emissions or enhance the sinks of greenhouse gasses [31]. For the purposes of this work, mitigation includes activities aimed at maintaining and/or increasing both the carbon sink and stock in forest pools. In most cases, only living forest biomass is considered. The mitigation potential from harvested wood products is not included. |
| Biodiversity conservation | The conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings and, in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties (in situ conservation) [32]. |
| Wood production/wood products | As part of the ecosystem services framework, the amount of wood obtained from harvesting [33]. In this study, there is no distinction between solid and energy use of wood. The mitigation potential deriving from substitution effects is not considered. |
| Other benefits | Other ecosystem services except wood [33]. |

For each included record, I assessed the spatial and temporal dependence and climate sensitivity of management practices, where available. Temporal dependence refers to the susceptibility of management outputs to time (e.g., higher mitigation potential via short-rotation forestry compared to prolonged rotation length). I specifically evaluated whether the following aspects were considered in the included records: the presence of simulations incorporating time scales, the breakdown of practices by rotation period/length, and the analysis of the effects of management practices at various time steps/periods. Spatial dependence refers to the susceptibility of management outputs to site/local characteristics (e.g., higher biodiversity values of tree species mixtures via sustainable management of plantations compared to intensive management of pure stands). I specifically evaluated whether the following aspects were considered in the included records: the presence of simulations incorporating site-specific characteristics, the distribution of practices in more than one location, and the analysis of the effects of management practices at multiple spatial scales. Climate sensitivity refers to the susceptibility of management outputs to climate-related effects, such as changes in temperature, precipitation and the frequency and severity of natural disturbances (e.g., higher adaptation via disturbance management compared to no management or passive management). I assigned a score of 0 and 1 for low and high dependence/sensitivity, respectively. Management susceptibility to driving forces is distance dependent: the higher the susceptibility, the shorter the distance from the maximum value (=1).

For each management practice, I then combined the forest management effects on goal cluster and their susceptibility to driving forces such as space/time and climate, through Equation (1):

$$combE_{i,n} = (w_n \cdot s)_i \quad (1)$$

where $combE_{i,n}$ is the average effect of the practice $i$ on the goal cluster $n$, including dependence and sensitivity; $w$ is the weight of the effect of the practice $i$ on the goal cluster $n$; and $s$ is the average score of the dependence and sensitivity of the practice $i$ to space, time, and climate. $combE_{i,n}$ is distance dependent: the higher the effect and the lower the susceptibility to external drivers, the shorter the distance from the maximum value (=1).

I finally obtained the *mapping* of the overall potential effects of forest management practices on management goals, incorporating their spatial and temporal dependencies, and climate sensitivity.

All assessments performed herein concern a linear, individual practice–goal relationship; they are subjective and based on my expertise and background. I did not deepen the assessment by considering synergies and/or adverse side-effects among forest management practices which might have resulted in trade-offs among multiple management goals. Such an evaluation would have required a quantitative meta-analysis and more advanced modeling approaches to obtain sufficiently robust results, which are beyond the scope of this study.

## 3. Main Findings

### *3.1. Review Outcomes*

This review finally focused on 33 scientific articles (61% research articles and 39% reviews) (see Table A1). Most of the research articles provided a more detailed and focused analysis of the contents compared to the review articles. The geographical scope is predominantly Europe (58% of the selected records), followed by global (18%), Northern America (12%), Central America (6%), Asia (3%), and Oceania (3%). Such a polarization of geographical representativeness could be expected, considering that the search databases used in the review (SCOPUS and WOS)—developed in the Western world—might have generated an underrepresentation of forests and forest management practices from developing countries in the global South. The same goes for the exclusion of gray literature or other document types (e.g., technical reports) that might have implicitly omitted information relevant to certain areas, e.g., Southern America, Africa, South-eastern Asia.

A deep analysis of the included records resulted in 84 observations of all management practices (e.g., about 2.5 management practices on average for each record). Close-to-nature management, intensive even-aged management and multi-purpose management are the most frequent practices (treated in almost 70% of records). This is quite obvious considering that these practices cover to some extent the whole range of frequency and intensity of interventions (from close-to-nature to multi-purpose to intensive management; from lower to higher human interaction), usually target alternative management goals and often involve trade-offs among management outcomes (e.g., biodiversity conservation vs. timber provision). These management alternatives are frequently used in scientific articles to show extremes in management-driven simulations [35].

I found information (quantitative or semi-quantitative) for spatial and temporal dependence and climate sensitivity in only 14, 11, and 13 records, respectively. Only eight records consider all the three aspects together. Such low numbers are explained by the fact that assessing the temporal and spatial dependence and climate sensitivity of management practices towards different goals is complex, as it requires robust long-term on-ground data and information, advanced modeling techniques, and simulation tools. In general, I found that in more than 65% of observations, forest management practices are highly dependent on space and time, and highly sensitive to climate. Intensive even-aged management is the practice most highly dependent on and sensitive to space and time, and climate, respectively (around 20% over all observations), followed by multi-purpose forest management (around 14% over all observations). No management or passive management is the least dependent and sensitive practice (around 9% over all observations). This is rather obvious, especially considering that the most impactful forest management practices are more susceptible to space, time, and climate, compared to no intervention. However, this of course depends on the intensity and frequency of human–forest interactions. The more intensively and more frequently a forest stand is disturbed (e.g., intensive even-aged management), the more uncertain are the potential effects of such interventions on management goals, i.e., in this case, timber production. For some examples of how forest management can face adaptability to space and time, and the unpredictability of climate change in Canada and Fennoscandia, and in Austria, please refer to [36,37], respectively.

### 3.2. Goal-Driven Management Framework

The overall potential effects of selected forest management practices on adaptation, mitigation, biodiversity conservation, wood production, and other benefits are outlined in the goal-driven management framework (GMF) (Figure 1).

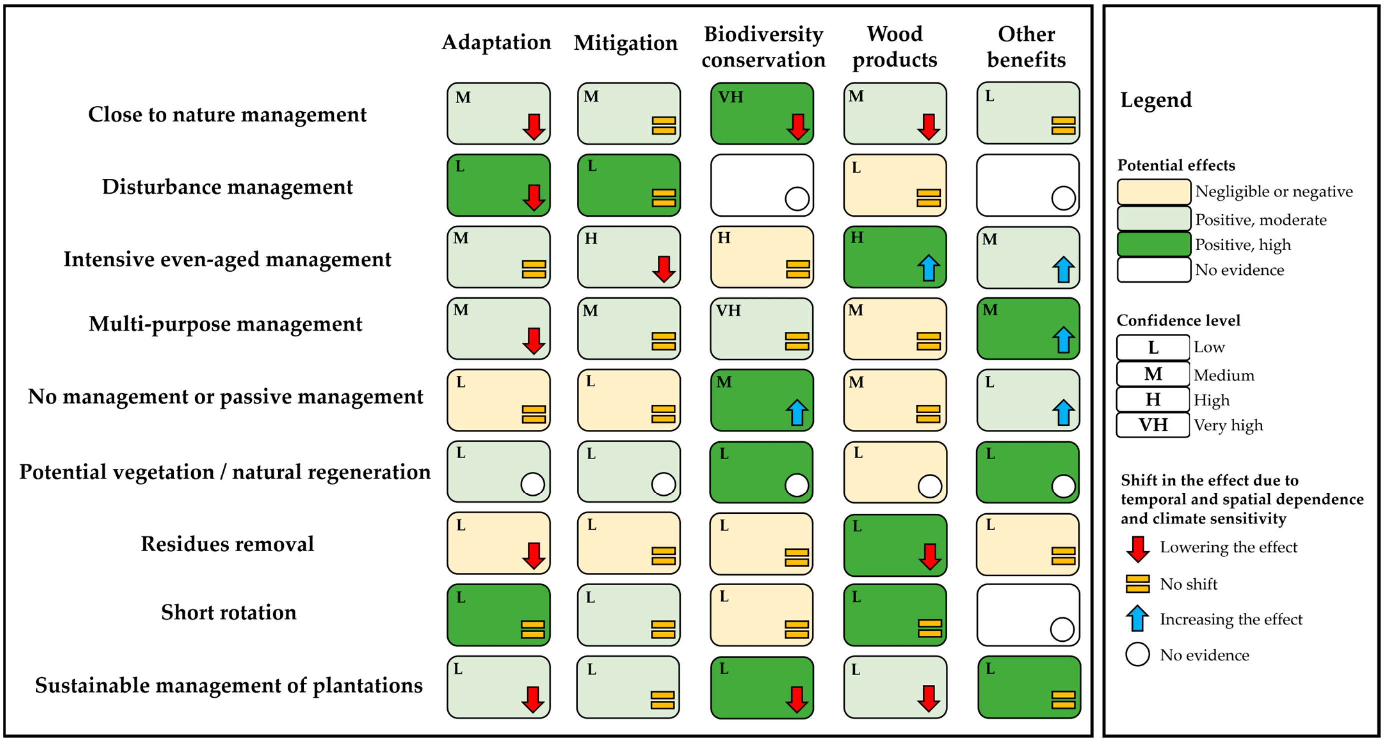


**Figure 1.** Goal-driven management framework (GMF) showing the potential effects of forest management practices (rows) on management goals (columns), the confidence levels attributed to each correspondence, and an evaluation of the shift (lowering, increasing, or none) of the management effects when temporal and spatial dependence, and climate sensitivity are considered.

Most practices have a **moderate, positive effect** associated with at least a medium confidence level: close-to-nature management on adaptation, mitigation, wood products (32 observations); intensive even-aged management on adaptation, mitigation, and other benefits (36 observations); and multi-purpose management on adaptation, mitigation, and biodiversity conservation (45 observations). Few practices have a **high, positive effect** associated with at least a medium confidence level: close-to-nature management on biodiversity conservation (18 observations); intensive even-aged management on wood products (11 observations); multi-purpose management on other benefits (seven observations); and no management or passive management on biodiversity conservation (six observations). In contrast, intensive even-aged management, multi-purpose management, and no management or passive management have **negligible or potentially negative**

**effects** on biodiversity conservation (19 observations) and wood products (12 and 6 observations), respectively.

The GMF provides rather clear findings. First, practices with a lower frequency and intensity of interventions (e.g., close-to-nature management, multi-purpose management) promote biodiversity and other benefits, while practices with a higher frequency and intensity of interventions (e.g., intensive even-aged management) have a potential positive impact on wood products. This is consistent with the available studies demonstrating that reducing the frequency and intensity of management interventions promotes species richness and structural complexity [38–40]. Second, almost all practices (except for short rotation) show the same overall effect (i.e., moderate, positive) on both adaptation and mitigation. This is because the evaluation of the effects of forest management on adaptation and mitigation is in most cases difficult to disentangle. To help trees adapt to changing climate and associated events (disturbances and drought), forest management needs to be tailored to site-specific circumstances and targeted to specific tree species or groups (resulting in homogenized results from this broad review). Moreover, uncertainty linked to the combined effects of climate, disturbances, and management on productivity, resilience, and stability, as well as on other ecosystem services, might result in biased simulations and assessments. Such uncertainties often trigger conservative estimates of management effects, as simulation models and approaches might face challenges when dealing with the unpredictability of the interactions between climate and ecosystem responses [41,42]. On the other hand, in the scrutinized records, mitigation is very often associated with maintaining the forest carbon stock (rather than the sink). This might imply that preserving the biomass stock on site is a positive effect of both close-to-nature management and intensive even-aged management, just to mention two extremes. Third, about half of the screened records show low uncertainty in the estimates because of the low number of observations, especially relating to potential vegetation/natural regeneration, residue removal, short rotation, and the sustainable management of plantations. This might have two causes: some practices are often considered within broader management categories, e.g., residue removal or short rotation under intensive even-aged management; and some practices, e.g., the sustainable management of plantations, are found in tropical and subtropical regions, while most records' geographical scope is narrowed to Europe. Nevertheless, the recent agreement at COP29 in Baku, Azerbaijan, on Article 6.4 of the Paris Agreement on crediting mechanisms within voluntary carbon markets can pave the way to further incentivize the implementation of sustainable forestry practices in developing countries.

The GMF also highlights a clear pattern concerning the susceptibility of the effects of practices to space, time, and climate. First, external drivers such as location/site characteristics, increased/reduced time windows, and changing climate variables lower the effects of the majority of the considered practices on adaptation. Close-to-nature management, disturbance management, and multi-purpose management usually embed interventions, e.g., single tree or group selection systems, promotion of certain (more adaptable) tree species, natural regeneration, small gaps opening, and other prevention measures (e.g., fuel breaks). The effectiveness of such management interventions on adaptation is therefore very difficult to predict as it heavily depends on specific site characteristics, the time elapsed while evaluating whether the management goals are met, and the uncertainty linked to the responses of forest stand development to variations in temperature and precipitation (see, e.g., [43,44]). Second, space, time, and climate likely increase the effect of three management practices on other benefit provision (intensive even-aged management, multi-purpose management, and no management or passive management), albeit with some differences. For instance, practices that are not effective in meeting specific goals under certain conditions (place-based, time-dependent, and climate sensitive), such as in the case of, e.g., intensive even-aged management for timber provision, can be less susceptible to ensuring other benefits, e.g., reduced risk associated with natural disturbances, water quality, and cultural attributes (see, e.g., [45]). Third, close-to-nature management and the sustainable management of plantations have lower effects on adaptation, biodiversity conservation, and wood products because of their increased spatial and temporal dependence, and climate sensitivity. This is because the effects of both management practices towards adaptation, conservation, and productivity particularly rely on the case-specific responses of forest stand development to management effects, especially in terms of tree establishment and survival (in the case of plantations), regeneration capacity, competition for light and nutrients, and maintenance of particular high-nature-value elements (see, e.g., [46–48]).

### 3.3. Extracted Forest Management Recommendations

Based on the GMF, I here provide a list of forest management recommendations that can help managers, planners, and other practitioners to better orient their decisions towards ensuring multiple goals (Table 3).

**Table 3.** Summary of forest management recommendations based on the GMF, by management practice and goal. The table includes some considerations of the dependence on and sensitivity of management practices to space, time, and climate, respectively (low, medium, and high).

| Management Practice | Management Goal | Recommendations | Temporal Dependence | Spatial Dependence | Climate Sensitivity |
|---|---|---|---|---|---|
| Close-to-nature management | Biodiversity conservation | • Optimize deadwood retention;<br>• Promote natural regeneration;<br>• Implement selective thinning and minimize other interventions;<br>• Set aside areas for conservation;<br>• Protect specific species on site;<br>• Preserve and restore soils. | **Low**<br>Effects of management on biodiversity conservation are seen over a long period. | **High**<br>Highly dependent on site: effects are linked to target species, habitats and biodiversity-rich areas. | **Medium**<br>Some species or communities might suffer from the effects of climate change, depending on the location. |
| Disturbance management | Adaptation | • Adjust tree species composition to more warm- and drought-tolerant species;<br>• Reduce competition through more frequent thinning;<br>• Promote structural and species diversity;<br>• Shorten rotation periods. | **High**<br>Effects of management might take time to result in a more resilient and adaptable stand configuration. | **Medium**<br>Effects are dependent on site characteristics (soil, topography), stand structure, and species composition. | **Low**<br>If implemented correctly, disturbance management should anticipate the negative effects of climate change. |
| Intensive even-aged management | Wood products | • Reduce rotation length;<br>• Increase frequency of thinning based on evolutionary stage;<br>• Promote high quality timber species;<br>• Homogenize stand's structure. | **High**<br>Requires regular cutting cycles to maintain productivity. | **High**<br>Applicable only in highly fertile, productive, and accessible zones. | **Medium**<br>Selected species might suffer in the medium to long term from drought and water stress. |

**Table 3.** *Cont.*

| Management Practice | Management Goal | Recommendations | Temporal Dependence | Spatial Dependence | Climate Sensitivity |
|---|---|---|---|---|---|
| Multi-purpose management | Other benefits | • Implement practices targeting management objectives that are consistent with local socio-economic contexts (communities' needs, economic profitability, accessibility, etc.);<br>• Distribute practices with different goals over larger areas rather than single forest management units (e.g., landscape level), including on considering ownership (public vs. private) and legal restrictions (e.g., protected areas);<br>• Implement practices tailored to stand and site characteristics, including considerations of soil productivity, connectivity and other ecosystem-based adaptations;<br>• Extract damaged trees. | **Medium**<br>Effects are dependent on the time at which the targeted good or service is available (e.g., short time for hydrological protection). | **High**<br>Effects are extremely sensitive to site characteristics. | **High**<br>Unpredictability of the effects due to uncertainty in climate-driven perturbations. |
| No management or passive management | Biodiversity conservation | • Gradual abandonment of management practices;<br>• Leaving stands to evolve naturally, completely untouched;<br>• In some cases, prefer low-intensity practices favoring different age classes, dead biomass, and large trees. | **Low**<br>Effects on biodiversity conservation unfold over a long period. | **High**<br>Highly dependent on specific locations (biodiversity-oriented stands). | **High**<br>Unpredictability of the effects due to the high vulnerability of biomass-dense, structurally diverse forests to climate change. |
| Sustainable management of plantations | Other benefits | • Plant tree species tailored to site conditions and adaptation capacities;<br>• Reduce impact of logging;<br>• Extend rotation length compared to short-rotation plantations;<br>• Alternate with other land uses (e.g., cropland). | **Medium**<br>Effects are dependent on the targeted goods or services (e.g., carbon sink vs. biodiversity conservation). | **Low**<br>Effects are not directly dependent on site characteristics. | **High**<br>Stability and growth of planted species highly dependent on climate change effects. |

The GMF only covers specific management practices, thus not including umbrella strategies in forestry that might have multiple management outcomes but for which precise recommendations are difficult to delineate. Some of the identified management practices in the GMF can be framed within such umbrella strategies (Table 4).

**Table 4.** Correspondence between management practices in the GMF and umbrella forest management strategies. Management practices utilized in the GMF are also reported by strategy.

| Strategy | Brief Description | Management Practice(s) in GMF [1] | Selected Source(s) |
|---|---|---|---|
| Adaptive forest management | Measures that adapt intact forest stands to a changing environment (e.g., climate change and forest use) | Disturbance management | [49,50] |
| Climate-smart forestry | Approach improving socio-ecological resilience through balancing a wide set of forest ecosystem services, including mitigation and adaptation measures | Multi-purpose management, disturbance management, and sustainable management of plantations | [51,52] |
| Continuous-cover forestry | Silvicultural approaches using management systems, e.g., single-stem and group selection and irregular shelterwood. Proforestation is part of this umbrella strategy | Close-to-nature forest management and passive or no management | [53] |
| Community-based forestry | Combination of collaborative management regimes (e.g., on lands that have communal tenure and require shared actions) and smallholder forestry, depending on access rights, participation in planning, or implementation and benefits sharing | Multi-purpose management, residue removal and sustainable management of plantations | [54] |

[1] Only practices with moderate to high positive effects (as in the GMF) are reported.

## 4. Discussion: Should-Have(s) in Forest Management

### *4.1. Considering the Trade-Offs Between Biodiversity and Other Benefits*

Mimicking natural disturbances and properly distributing them in time and space can be beneficial for a broader set of goods and services. This comes from the ecological basis of silviculture but requires forest managers to balance economic revenues with nature conservation. Depending on place-based historical socio-economic development, forest biomes around the globe are typically associated with standardized management regimes targeting one or more management goals (see, e.g., [55]), such as intensive even-aged management and conventional selective logging to maximize wood production in temperate and boreal, and tropical forests, respectively; and retention forestry, selection systems, and reduced impact logging to balance wood production with biodiversity conservation and other non-marketed goods and services in temperate and boreal, and tropical forests, respectively.

Nevertheless, forest management has recently evolved towards incorporating multi-purpose and multi-objective approaches to promote the health, stability, and resilience of forest stands almost worldwide (in ordinarily managed forests, thus excluding deforested and degraded areas in the global South), to thus ensure a broader set of benefits, such as adaptation and mitigation, hydrological protection, tourism, and recreational opportunities, etc. (see, e.g., [56]). Close-to-nature and multi-purpose management fall within this category, especially in temperate and boreal forests. That is, when non-marketed benefits such as biodiversity (conservation of habitats and species) come into play, practices that are particularly oriented towards wood production might be limiting for a wider scope. Lower intensity and frequency are indeed associated with forest management systems promoting stand complexity and high naturalness levels [57]. For example, the authors of [55] demonstrate that close-to-nature forestry practices (e.g., selection and retention systems) are more beneficial for species richness in several regions compared to intensive practices.

Reducing harvest intensity and frequency and promoting species mixtures may strengthen forest stand resilience, improve carbon accumulation in living biomass and soil, foster the conservation of forest-dependent animal and plant species, and ultimately ensure that people will benefit from aspects such as water availability and purification, non-wood forest products, and cultural values [58]. However, harvest intensity and frequency have various effects depending on the forest biome and local conditions. For example, in tropical forests, harvest intensification (under a certain threshold: few large trees per hectare) stimulates the overall growth rates which are relevant for mitigation, but delays the full recovery of timber stocks within a felling cycle [59]. Maintaining tree cover (reducing the occurrence and size of canopy gaps) may prevent soil loss, degradation, and desertification, especially in tropical biomes (where the recovery capacity is limited) [60]. Evidence that continuous-cover forestry increases multi-functionality compared to ordinary approaches has also been shown for boreal forests [61]. Such practices in turn promote soil retention and reduce the risks associated with floods and landslides affecting people in the neighborhood [62]. The retention approach within the framework of ecologically sustainable forest management—which has a large potential for implementation worldwide (85% of total forest cover)—might help to maintain structures (such as large living or dead trees, cavity trees, and logs) and organisms (e.g., particular plant species), as well as preserve small intact forests [63].

Benefits derived from climate mitigation vary depending on harvest intensity. For example, intensively managed stands show faster carbon accumulation in above-ground biomass but slower in soils (e.g., temperate forests, [64]). When harvest intensity and frequency reduce progressively over time, forests accumulate large quantities of biomass and likely become more susceptible to disturbances such as wind throws and wildfires (e.g., temperate forests, [65]), which can happen, for example, in old-growth forests. These stands are carbon dense (in living and dead biomass, and in soil) but show high density-dependent mortality due to competition [66]. On the other hand, old forests with large trees as well as primary and untouched forests host invaluable habitats and species for global biodiversity (e.g., tropical forests, [67] and other forest biomes [68]). In contrast, less frequent and intense harvesting operations can lower the short- and medium-term economic revenues from forests, as well as inducing a smaller contribution to mitigation via biomass growth and carbon accumulation in wood products. Balancing economic values from timber extraction with biodiversity conservation would indeed require the optimization of forest management practices extending over larger areas, even including set-aside hotspots for specific purposes (e.g., landscape functional zoning [69]). For instance, climate-smart forestry and continuous-cover forestry might provide effective strategies for reducing trade-offs among alternative services (e.g., temperate forests [70] and tropical forests [71]).

In the case of no management or passive management, other human activities might interact with forest stands and cause deviation from reaching the envisaged management goals. For example, tourism and recreational activities in natural reserves might trigger a local redistribution of certain forest-dependent animal species, thus lowering the biodiversity conservation effects.

### *4.2. Reflecting Time and Space Variability*

Forest management outcomes depend on stand development and on the associated uncertainty in the medium to long run. For example, future expectations for certain levels of timber production might not be fulfilled because of the impact of a windstorm or wildfire. Similarly, the maintenance of high biodiversity levels might reduce because of sudden changes in nutrient or water availabilities. Forest management should therefore consider the future trade-offs in temporal stability of outcomes resulting from the implementation of a given practice. Forest managers and planners might use decision support systems to simulate the future evolution of forest ecosystem services based on management alternatives [58], or more advanced tools such as dynamic simulation models to account for the effects of climate or environmental parameters on forest stand development over time [72]. Life cycle assessment can also be used to evaluate the environmental impact of certain forest management practices on the whole value chain [73].

The biodiversity–productivity relationship strengthens with time (e.g., in subtropical forests [74]). However, reducing the rotation period and increasing the frequency of thinning (i.e., adaptive forest management) might simultaneously promote timber production and carbon sequestration but limit biodiversity and water runoff (e.g., in temperate forests [75]). Continuous-cover forestry enhances multi-functionality in the long term (e.g., boreal forests [76]).

In terms of climate mitigation, there are opposite responses of forest ecosystems to management. For example, afforestation programs and short-rotation forestry might promote net carbon accumulation in the short term, i.e., the sink in living biomass and the carbon inflow to wood products (e.g., in subtropical forests [77]), while less intensive practices might progressively increase carbon stocks in biomass and soil through aging [78]. Shorter harvesting periods are associated with a greater adaptation capacity to external disturbances (e.g., storms), lower species diversity, and less carbon accumulation, especially in soils (e.g., boreal forests [79]).

The correlation between the short-term economic benefits and increased frequency and intensity of timber extraction triggers a controversial debate. The net present value is generally maximized when a forest reaches commercial maturity (ordinary rotation cycle and harvest intensity) with adverse side effects on other important services (e.g., Mediterranean forests [80]). However, if the rotation cycle is too short (as in the case of short-rotation plantations), the net income is lower than for ordinary rotation lengths, mainly because of smaller tree sizes at harvesting time (e.g., boreal forests [79]).

Forest management outcomes are to some extent susceptible to space. The effects are twofold. On the one hand, management practices are adapted to local conditions for a better level of efficiency. On the other hand, the resulting ecosystem services are distributed depending on local (site) environmental characteristics. Management strategies usually seek to promote certain stand attributes with the aim of maximizing the largest set of benefits possible. In some cases, low intensity and no management are associated with tree species richness and evenness, vertical heterogeneity, and large tree sizes, thus promoting high carbon stocks and structural diversity (e.g., in boreal forests [81]). In other cases, objective forestry combined with some interventions might be beneficial for trees hosting microhabitats for forest-dependent species (e.g., Mediterranean mountain forests [82]). Other benefits, such as wood and non-wood products, higher adaptation capacity to external disturbances, and the availability of some soil nutrients, are correlated with tree canopy cover and shrub richness in managed stands (e.g., boreal forests [81]).

In the tropics, the management of climate change mitigation should be distributed in a way that specific species have enough space for growing and soils are protected from potential impacts via harvesting operations [83]. Topography, soil fertility, and microclimate conditions are of the utmost importance for maximizing management goals. For example, in [84], the authors found that maintaining thinning in planted forests might reduce the competition for light and water and favor the recruitment of new species in the understory, hence improving above-ground carbon sequestration and stand biodiversity, especially in uplands and humid areas. Trade-offs are therefore amplified in dry conditions.

### *4.3. Incorporating Climate Sensitivity*

Climate change triggers small-to-large-scale variations in forest ecosystem responses to management. Changes in temperature and precipitation have direct implications for forest ecosystem processes, for example, species and habitat composition and distribution, stand productivity and regeneration capacity, water and nutrient flows, and health and resilience [85]. Climate change also has indirect implications, both negative, e.g., increasing the stand vulnerability to the severity and frequency of natural disturbances, and to drought [86,87], and positive, e.g., favoring net growth through $CO_2$ fertilization under certain conditions [88,89].

The combination of aridity with clearcut, small-patch, or seed-tree retention results in lower carbon stocks (both above and below ground) and reduced biodiversity indexes compared with unmanaged stands (e.g., boreal forests [90]). Under warmer conditions, continuous-cover forestry or no management might increase the tree species mixture via facilitating broadleaves in pure coniferous stands (e.g., boreal forests [79]).

When the unpredictability of climate change comes into play, forest management should move towards putting adaptation and resilience into practice. For instance, forest management shows the potential of contrasting the negative effects of climate, especially those deriving from natural disturbances. Increasing the thinning regime and adopting disturbance management options (e.g., prescribed burning) might speed up tree growth and the survival of remaining individuals in the short term, thus improving the short-term resistance to drought or reducing the risks associated with fire and windstorms. However, in stands vulnerable to fire or drought, the harvest intensity and frequency should be reduced to avoid long-term negative consequences for carbon sequestration, biodiversity and nutrient cycling (e.g., Mediterranean forests [91]). Temperature rises and changes in precipitation patterns might modify stand development over time, thus increasing the unpredictability of the effects of certain practices on reaching a given management goal in the near future. For example, some practices that are relevant for adaptation (e.g., disturbance management, short rotation) might be partly unsuccessful under warmer and drier conditions because of a reduction in tree growth, a change in tree species composition and/or a re-assemblage of existing species, an increase in stress, and a vulnerability to water and nutrient scarcity and pathogens. A solution would be to implement adaptive management strategies to modify the intensity and frequency of interventions at shorter time intervals than planned to prevent potentially negative, abrupt climate change effects (e.g., prolonging the rotation cycle).

The relationship between climate change and forest management for mitigation is to some extent controversial. On the one hand, changes in temperature and precipitation, as well as in the atmospheric $CO_2$ concentration, likely increase net growth and alter species distribution over the mid- to long term, in turn modifying the way certain management practices are implemented (e.g., thinning frequency and intensity and the extent of clearcutting). On the other hand, climate change might exacerbate the combined effects of harvest and natural disturbances in the short term. These aspects require a more comprehensive management approach, which simultaneously takes into account the mitigation potential (e.g., increasing net growth and ensuring the substitution effects of forest products; [92]) and adaptation capacity of forest ecosystems [49].

Climate change hampers biodiversity conservation, especially at the global extremes, such as in tropical and boreal forests [93,94]. A potential solution is to enlarge areas set-aside from timber extraction to provide buffer zones for forest-related species against climate change (e.g., in boreal forests [95]). This is also demonstrated in tropical forests, where forest landscape restoration (an ensemble of practices, e.g., planting, tending, reduced impact logging) show trade-offs between timber production and net carbon accumulation on one side, and non-timber forest products and biodiversity conservation on the other side [96]. The sustainable management of plantations towards, for example, improving tree species mixtures leads to lower risks associated with natural disturbances than in monocultures [97].

## 5. Limitations, Remaining Challenges, and Concluding Remarks

The proposed GMF provides an overview of the potential implications of alternative management practices for broad groups of services and conveys these via so-called "should-have(s)" that help to improve decision-making processes in forest management and planning towards ensuring multiple goals. To summarize, (i) management practices that mimic natural dynamics (e.g., close-to-nature management) are more beneficial for a broader set of non-marketed services, such as biodiversity conservation, but trade-offs arise depending on the intensity and frequency of interventions; (ii) management practices that are oriented towards a more comprehensive set of forest ecosystem goods and services (e.g., multi-purpose management) are less time- and space-dependent than practices targeting a single or few services at one time (e.g., intensive even-aged management); and (iii) management practices need to consider the potential side-effects of changing environmental conditions on the future evolution of forests to reduce their susceptibility to climate change.

However, implementing the GMF presents some limitations. First, the GMF does not incorporate the effects of combining various management practices at wider scales, e.g., the landscape. Several tests have thus far demonstrated that forest landscape restoration is successful in ensuring high biodiversity levels [98], climate change mitigation [99], and adaptation [49] from tropical to boreal regions. In addition, large forest areas can be managed in a way in which various parcels/portions have different management goals, e.g., set-aside areas for biodiversity conservation vs. areas for maximizing timber extraction (e.g., integrated forest management at the landscape scale). Implementing different practices within the same stand is possible but likely to be more complicated, and generally leads to less suitable outcomes. Furthermore, the GMF does not explicitly incorporate the potential, abrupt effects of climate change on forest functions and services over time and space, in addition to those considered with the management practices themselves. The environmental effects of variations in temperature and precipitation are difficult to frame, because of their dynamism (medium- vs. long-term effects) and the complexity linked to temporal and spatial peculiarity (scale, frequency, and intensity of climate). Finally, the GMF does not depict the side effects on management practices as originating from changes in social, economic, and political dimensions. Local needs and social conflicts might result in the modification of management regimes. For example, investments for building consortia and/or stakeholder associations can smooth such conflicts and promote the diversification of forest management practice implementation to ensure a larger portfolio of forest goods and services at the local scale, as well as the economic profitability of the whole forest-value chain. Market fluctuations at both the local and global scale also interact with the way forests are managed, especially in the short term. For example, national and global demands for harvested wood or other products might generate an increase in the intensity and frequency of interventions at the local scale with adverse side-effects on some management goals, e.g., biodiversity conservation, hydrological protection, and adaptation. Policy and governance decisions also play a crucial role in ensuring that forest management is implemented effectively towards maximizing the benefits from forests. In some cases, management intensity and frequency might change because of local restrictions (e.g., overlap with Protected Areas).

To overcome such limitations, I provide the following suggestions: First, the **monitoring of activities** should be improved to obtain a clear picture of forests over time. This potentially supports the more effective planning and implementation of interventions targeting specific management goals at various scales. Data should not be limited to biophysical or economic aspects but should also concern the needs, perceptions, and desires of local communities and relevant stakeholders (e.g., administrators, enterprises). Such information can be obtained by effective stakeholder engagement strategies, such as bilateral meetings, structured interviews and local surveys, and co-design and co-planning activities. Second, forest managers and planners might consider **implementing modeling tools** to simulate the evolution of forests and associated benefits over time and across space depending on management practices. That would be relevant to prevent and adapt to unintended external effects, such as those from climate change. Models should be selected depending on the biophysical context, economic resources, and background of the experts using them. Models can use currently available forest-related datasets to ensure the monitoring, reproducibility, and validation of modeling outcomes (e.g., FAOSTAT). Moreover, future studies can focus on quantitative meta-analyses of the existing literature to deepen the understanding of management practice–management goal relationships. Third, there should be more consideration of **policy trajectories** (e.g., sustainable development goals, nature conservation, and climate targets) in practical forest management to include management goals that are sometimes overlooked from a production-oriented perspective. Such consideration might also start from the bottom, and then move to higher levels of forest governance. In Europe, both the EU Forest Strategy to 2030 and the EU Biodiversity Strategy to 2030 aim to enhance protection, resilience, and adaptation in managed forests and forest habitats. Such strategies have triggered a series of EU policies enhancing the role of forests, forest management, and the forestry sector in climate change mitigation and biodiversity conservation (e.g., Deforestation-Free Product Regulation, LULUCF Regulation, Nature Restoration Law). In Africa, the recent Sustainable Forest Management Framework 2020–2030 commissioned by the African Forest Forum points to several priorities: enhancing the sustainable production, processing, and trading of forest products and ecosystem services; improving capacity building and knowledge management; strengthening the political and institutional frameworks of member states and regional economic communities; reducing deforestation and forest degradation, and restoring forest landscapes; further developing partnerships and resource mobilization. In Southeast Asia, several national forest policies are oriented towards improving sustainable forest management and increasing the role of local communities for the conservation, protection, and restoration of forests (e.g., the Community-based Forest Management Strategy in the Philippines and the Forestry Sector Development Strategy in Vietnam).

Future studies should perform deeper analyses of the impacts of socio-economic drivers (e.g., ownership structure and property rights) and legal restrictions (e.g., protected areas and protection sites) on the effectiveness of forest management strategies towards ensuring multiple goals. Conversely, future studies might further explore the contribution of forest management practices to social and economic sustainability, beyond the currently predominantly assessed environmental aspects. To this end, I present the concept of **sustainable operating spaces** for forests, forest management, the forest value chain, and forest governance as a conceptual framework to keep track of the progress made in forest management practices towards reaching sustainable development targets. This can be achieved, for example, by assessing the distance of impact and response indicators of forest management alternatives from the targets of environmental, social, and economic sustainability (see, e.g., the indicators of the UN Sustainable Development Goals and Targets), i.e., the further the distance, the less the overall sustainability of a given management practice.

In conclusion, forest managers should be always aware of their responsibility to manage a public, renewable resource (i.e., a forest) which is potentially able to (re-)generate multiple benefits to people. This awareness can only be translated into practice if the entire concept of sustainability is at stake.

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## Appendix A

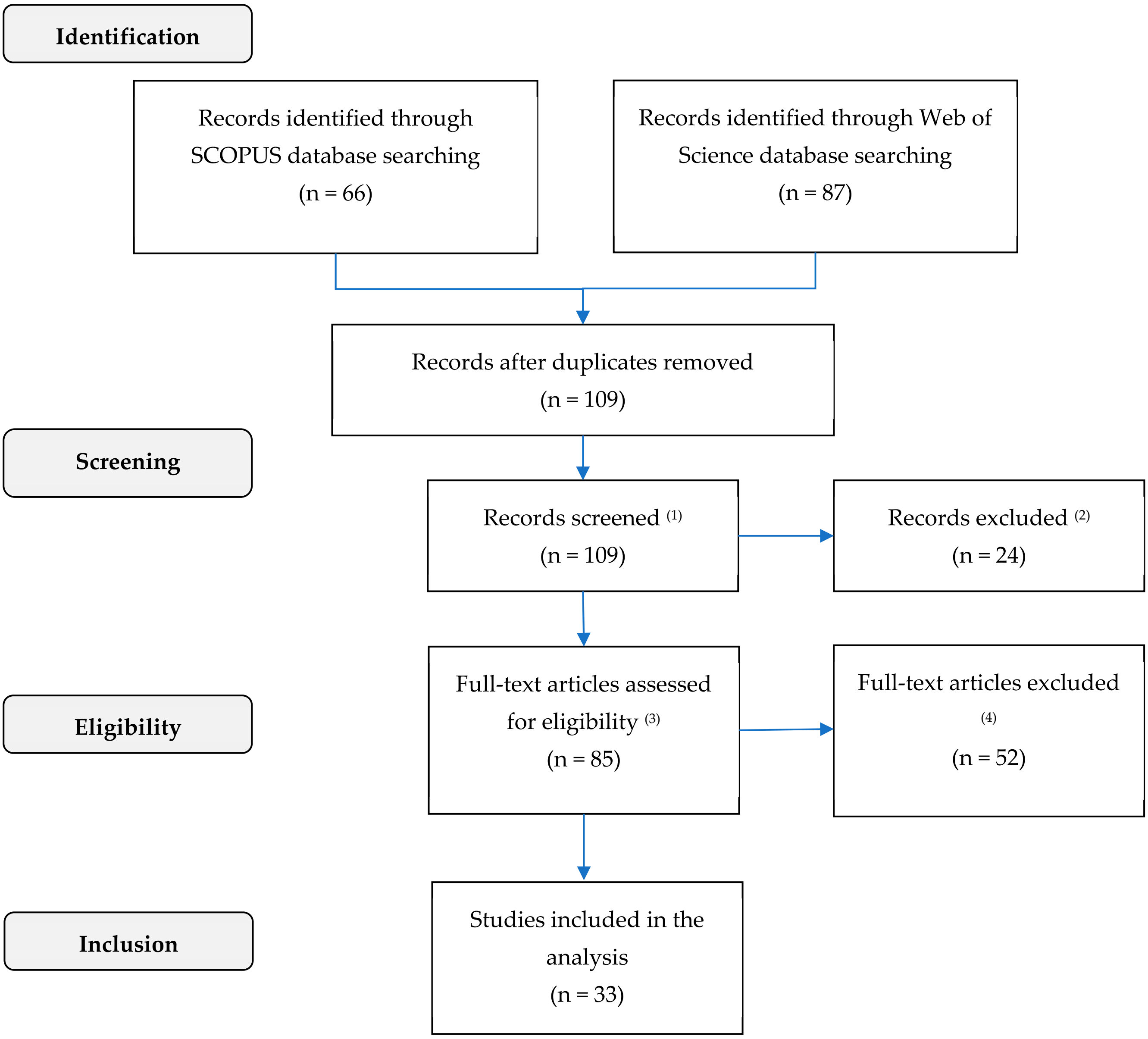


**Figure A1.** Main phases of the review process (based on PRISMA chart; [29]). (1) Screening performed on title, abstract, and keywords; (2) not in English/not accessible/not found/conference abstract/book introduction/editorial; (3) full-text reading; (4) no estimate of the correlation between forest management practice(s) and management goal(s).

**Table A1.** List of reviewed records, by lead author in alphabetical order.

| Lead Author | Year | Type | Geographical Scope | Source |
|---|---|---|---|---|
| Bachelet | 2018 | Research | US | [100] |
| Blattert | 2024 | Research | Switzerland, Slovenia | [101] |
| Butler | 2013 | Research | Australia | [102] |
| Calama | 2021 | Research | Spain | [103] |
| Carr | 2020 | Research | UK | [104] |
| Ciccarese | 2012 | Review | Global | [105] |
| Felton | 2016 | Review | Sweden | [106] |
| Felton | 2020 | Review | Sweden | [107] |
| Felton | 2024 | Review | Sweden | [108] |
| Fouqueray | 2020 | Review | France/Germany | [109] |
| Gregor | 2022 | Research | Europe | [110] |
| Guignabert | 2024 | Research | Belgium, Canada | [111] |
| Hof | 2017 | Research | Canada | [112] |
| Joyce | 2018 | Review | US | [113] |
| Lagergren | 2017 | Research | Sweden | [79] |
| Lundholm | 2020 | Research | Ireland | [45] |
| Mathys | 2021 | Research | Switzerland | [114] |
| McKinley | 2011 | Review | US | [115] |
| Mozgeris | 2019 | Research | Lithuania | [116] |
| Pawson | 2013 | Review | Global | [117] |
| Petersson | 2022 | Research | Sweden | [118] |
| Pichancourt | 2014 | Review | Global | [84] |
| Pinnschmidt | 2023 | Research | Costa Rica | [119] |
| Potterf | 2024 | Research | Finland | [120] |
| Ranius | 2018 | Review | Global | [121] |
| Rousseau | 2013 | Research | Nicaragua | [122] |
| Schwaiger | 2019 | Research | Germany | [123] |
| Seidl | 2018 | Research | Austria | [124] |
| Silva | 2019 | Review | Global | [125] |
| Smith | 2021 | Review | Bangladesh | [126] |
| Tarasewicz | 2021 | Research | Sweden | [127] |
| Toraño Caicoya | 2018 | Research | Germany | [128] |
| Weber | 2011 | Review | Global | [83] |

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