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PERSPECTIVE

For the sake of resilience and multifunctionality, let's diversify planted forests!

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Abstract
As of 2020, the world has an estimated 290 million ha of planted forests and this number is continuously increasing. Of these, 131 million ha are monospecific planted forests under intensive management. Although monospecific planted forests are important in providing timber, they harbor less biodiversity and are potentially more susceptible to disturbances than natural or diverse planted forests. Here, we point out the increasing scientific evidence for increased resilience and ecosystem service provision of functionally and species diverse planted forests (hereafter referred to as diverse planted forests) compared to monospecific ones. Furthermore, we propose five concrete steps to foster the adoption of diverse planted forests: (1) improve awareness of benefits and practical options of diverse planted forests among land-owners, managers, and investors; (2) incentivize tree species diversity in public funding of afforestation and programs to diversify current maladapted planted forests of low diversity; (3) develop new wood-based products that can be derived from many different tree species not yet in use; (4) invest in research to assess landscape benefits of diverse planted forests for functional connectivity and resilience to global-change threats; and (5) improve the evidence base on diverse planted forests, in particular in currently under-represented regions, where new options could be tested.

KEYWORDS
Biodiversity, climate change mitigation, ecosystem services, forest functioning, forest landscape restoration, plantations, resilience, sustainable forest management

1 | MAIN TEXT

Current forest management practices, including the establishment of planted forests, are important human-induced changes in terrestrial ecosystems. While planted forests have traditionally been established to optimize wood and fibre production, they are now being proposed (1) as a way to reduce harvesting pressure on natural forests (e.g., land sparing-sharing or functional zoning approaches) (Betts et al., 2021); (2) as a nature-based solution to mitigate climate change, restore degraded land, and maintain ecosystem functions and services (e.g., water supply and regulation, biodiversity, recreation) (Bauhus et al., 2010; Griscom et al., 2017); and (3) as a means to foster economic development in rural areas (Malkamäki et al., 2018). Hence the establishment of new forests including planted ones features prominently in important fields of international policy. Examples of such global initiatives are the 2011 Bonn Challenge and the 2014 New York Declaration on Forests, where 350 million ha of forest are to be restored globally by 2030; China's Grain-for-Green Program, the world's largest reforestation scheme; the 2019 pledge by the Canadian government to plant 2 billion trees in Canada by 2050, and the new 2019 EU Biodiversity Strategy, which aims to plant 3 billion trees in Europe by 2030. Owing to the important multiple objectives that these new planted forests should provide and the rapidly changing global environmental and social conditions, we argue that the establishment of functionally and species diverse planted forests that are multifunctional (i.e., simultaneously provide multiple ecosystem services) and more resilient (i.e., maintain ecosystem functioning under predicted future environmental change) should be prioritized. This, while ensuring that the principles of sustainable forestry are upheld (FAO, 2010).

2 | PLANTED FORESTS TODAY: A SHORT OVERVIEW

The FAO (2020) divides planted forests into two categories: (1) plantation forests, composed of one or two species, that are intensively managed for productive purposes; and (2) other planted forests, that consist of one or more tree species and are less intensively managed, typically for multiple purposes. In 2020, plantation forests, as defined by the FAO, comprised 45% of all planted forests (FAO, 2020). Often, these plantations are (1) composed of fast-growing tree species, (2) managed in relatively short production cycles, and (3) often requiring high inputs of fossil energy and agrochemicals to make full use of the site and species potential. In this paper, we use the term planted forests to refer to both plantations and other planted forests as defined by the FAO (2020). The "diverse planted forests" we propose comprise both mixed plantations with two tree species and other planted forests with two or more tree species. Of the estimated 294 million ha of planted forests worldwide in 2020, up from 170 million in 1990, China has by far the largest area with 84.7 million ha, followed by the United States (27.5), the Russian Federation (18.9), and Canada (18.2). For years, this interest in planted forests has resulted in planting mainly monospecific stands. Even today, initiatives such as the Bonn Challenge have been criticized for too heavily relying on monocultures (Lewis et al., 2019).

Of all tree species being planted worldwide, native and non-native *Pinus* species remain dominant in most regions, while non-native *Eucalyptus* species are the most common in the tropics and subtropics (Figure 1). However, a substantial proportion of planted trees in some countries, including Canada, Finland, the United States, China, and India, are native tree species (*Picea, Pinus, Cunninghamia*, and *Tectona*). These tree species are widely used because of their fast initial growth rate and/or broad range of environmental conditions in which they grow well. Under favorable growing conditions, where threats from biotic and abiotic factors are low, monospecific planted forests, and particularly intensively managed plantations of non-native species, can be economically more profitable than diverse planted forests when value assessments are based only on wood production. However, these monospecific planted forests typically have less potential for providing ecosystem services other than timber or fibre and they often harbor lower associated biological diversity (Bauhus et al., 2010). They are also more susceptible to pests and diseases, saturation or collapse of wood product markets, and climate change when compared to diverse planted forests (Hildebrandt & Knoke, 2011; Jactel et al., 2021). The model of large-scale industrial, monospecific planted forests has also been questioned on social grounds since they can lead to an unequal distribution of forest resources and a loss of traditional goods and services used by communities (Fleischman et al., 2020; Malkamäki et al., 2018).

At the same time, planted forests are efficient sources of wood and can be a valued source of rural employment (Bauhus et al., 2010). In the context of a broader geographic and economic context, well-managed planted forests can contribute to sustainable development (FAO, 2010). New planting solutions are therefore needed to deliver the multiple ecosystem services and increased resilience to global changes at a scale that humankind demands from planted forests.

3 | THE MULTIPLE VALUES AND BENEFITS OF DIVERSE PLANTED FORESTS

We argue that diverse planted forests are one such solution. More and more examples of diverse planted forests now exist in many parts of the world. The advantages of a greater diversity of tree species with high functional diversity (i.e., range of functions that organisms perform in an ecosystem) in planted forests have been supported by an increasing number of scientific papers and field experiments. Recent meta-analyses, systematic reviews, and

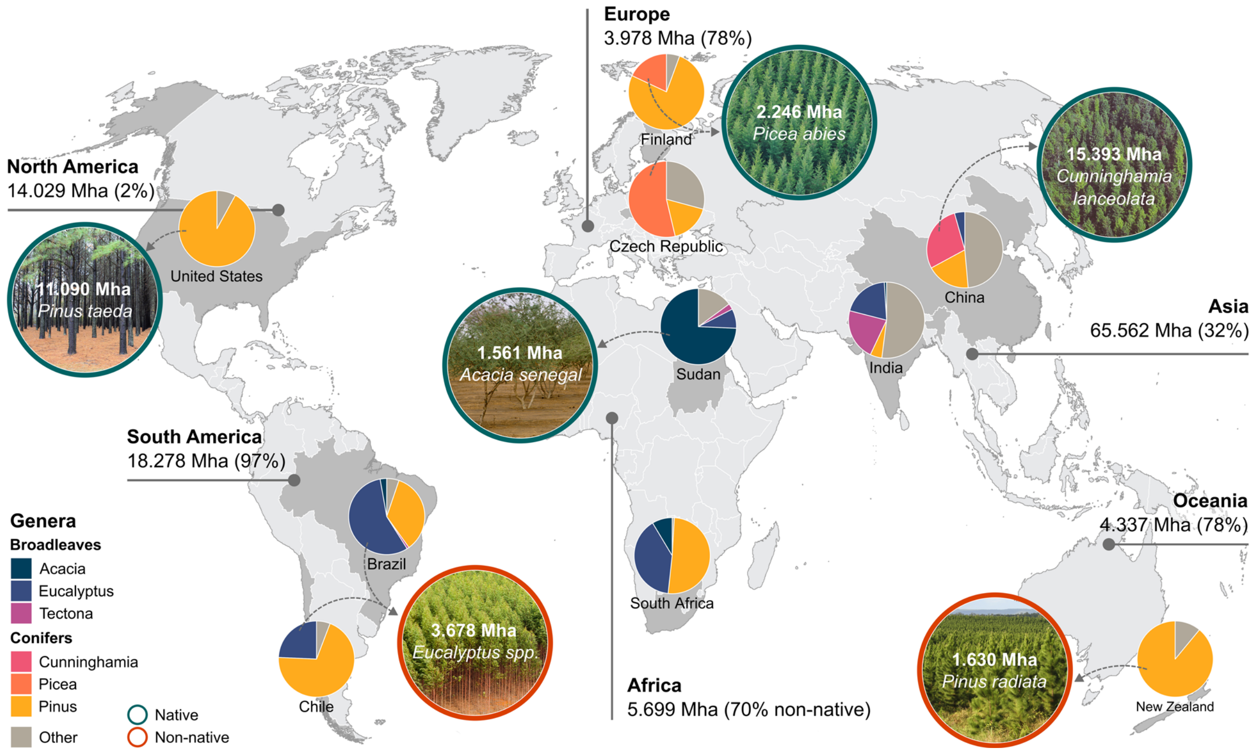

FIGURE 1 Plantation areas and the proportions composed of non-native tree species (in parenthesis) for all continents (excluding Antarctica) and reported areas for different tree species within the selected countries. For clarity, less abundant genera have been grouped under "Other" (lower than 10%). For data and photograph sources, see Supporting Information

syntheses have pointed out that diverse planted forests (1) are often similarly or more productive in terms of biomass (Forrester & Bauhus, 2016; Huang et al., 2018) but not necessarily in terms of harvested products (Puettmann et al., 2016), (2) are typically less susceptible to biotic and abiotic disturbances such as pest outbreaks and extreme weather events (Bauhus et al., 2017; Jactel et al., 2021), (3) harbor greater biodiversity (Ampoorter et al., 2020), (4) provide a higher level of other ecosystem functions and services than wood (Schuldt et al., 2018), and (5) may be more socially accepted than monospecific ones (Williams, 2014) (Figure 2). Nevertheless, a large percentage of planted forests are established and maintained as monospecific stands (FAO, 2020). There is therefore a gap between strong scientific evidence and increasing societal support for the multiple benefits and reduced risks of diverse planted forests, and the continuing dominance of monospecific planted forests on the other hand. Here we suggest some potential reasons for the differences between evidence that can be found in the literature and the practice of planted forest establishment and management. We also suggest some starting points to bridge the gap between findings in the scientific literature and the practice of forestry.

4 | NEW POLICIES AND GUIDELINES FOR DIVERSE PLANTED FORESTS

Although reasons for this lack of diversification of planted forests across the world are context-specific, we see four main impediments: (1) it is less complex operationally to cultivate, manage, and harvest monospecific stands; (2) there are existing markets for standardized timber commodities from a few well-established tree species; (3) the public goods (ecosystem services) produced by more diverse planted forests are not easily marketable by private for-profit companies in the current markets; and (4) the tendency of forest owners to do what they see other big and successful forest owners do. Concerning impediment #1, it is relatively easy to co-plant additional tree species with similar planting stock and growth rates, allowing for similar harvesting intervals, but it is likely that this will require different species-specific tending programs and may provide different products. Alternatively, it is also possible to intersperse tree species with different growth rates within adjacent strips or patches to facilitate coexistence and later harvesting; this technique can also provide new revenue streams outside the normal management cycle of monospecific planted forests (Paquette & Messier, 2010).

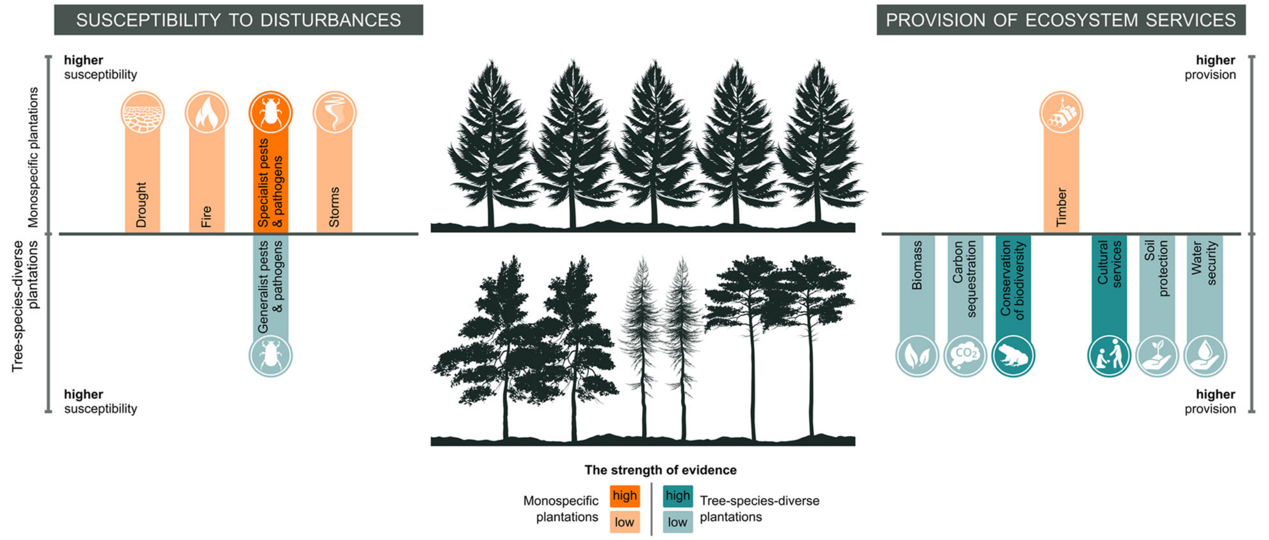

FIGURE 2 Visual summary of the comparative (1) susceptibility to some main forest disturbances (left) and (2) provision of key ecosystem services (right) between monospecific (top) and tree-species-diverse plantations (bottom). Bars are individual disturbances/services and the direction of the bars (top vs. bottom) indicates higher susceptibility to the disturbances and higher potential to provide the service between these two types of plantations. The different color intensities of the vertical bars represent the strength of evidence supporting each conclusion as evaluated by the authors (high or low certainty). For selected references, see Supporting Information

However, the knowledge base for optimal combinations of commercially attractive diverse planted forests, under current and future environmental conditions, still needs to be developed and operationalized at a scale useful for commercial forestry in many parts of the world. To address impediment #2, research is needed to develop alternative products from less well-established tree species, and subsidies may be necessary to encourage the establishment of tree species with little current use. As for impediments #3 and #4, the increasing uncertainty due to climate change, exotic pests and diseases, and rapidly changing market and customer preferences for different wood products provides a very strong incentive for the diversification of planted forests. For example, the recent large-scale level of tree mortality in many monospecific planted forests across most of Europe, a consequence of the unusually severe and long drought in 2018 and 2019 followed by attacks from various pests and diseases (Schuldt et al., 2020), provides a dramatic case in point. With the increasing climatic, biotic, and economic uncertainties associated with growing trees over decades, the time has come to ensure planted forests contain more tree species with a greater functional diversity for the sake of both resilience and multifunctionality.

All forest management involves trade-offs, which is particularly the case for production of timber and other ecological services from planted forests (Bauhus et al., 2010). New policies and guidance are needed to convince or encourage private forest owners, investors, governments, and foresters alike of the added benefits and feasibility of diverse planted forests. Moreover, investment in research and development is critical to minimize those trade-offs. Here we propose a series of concrete ideas to foster the adoption of more resilient, multifunctional, and productive diverse planted forests worldwide:

1. More practical guidelines are needed to develop diverse planted forests that are easy to manage to overcome impediment #1. These guidelines should be based on the best current scientific knowledge regarding multifunctionality, resilience, and productivity. For example, Baeten et al. (2019) proposed tree species compositions that could maximize both multifunctionality and productivity of forests in Europe. Brancalion and Holl (2020) also recommend that the types and number of tree species to be used in planted forests should vary according to the goals of landowners, managers, and investors. Similarly, Meli et al. (2014) suggested combining ecological, social, and technical criteria to select tree species that are the most appropriate for restoration purposes in tropical planted forests of southeastern Mexico. Different tree species with different growth rates, shade tolerances, and production cycles could also be planted in strips and patches so that partial harvesting could be implemented in diverse planted forests instead of clearcutting, as is being experimented in Eastern Canada (Paquette & Messier, 2013). Nevertheless, some basic rules are likely to apply in all regions, such as mixing tree species with higher complementarity in light exploitation to maximize productivity and

increase structural heterogeneity to foster multifunctionality.

Whether or not non-native tree species are used in these mixtures should depend on their ecological functions, the services they provide, their suitability to future climatic conditions and their potential harm to the environment. Nativeness or non-nativeness as such is not an indication of the ecological effects a species may have or its evolutionary fitness (Davis et al., 2011). Yet, one should probably prefer native species when they are equal to or better than non-native species for the purpose intended. Finally, some forms of variable retention or partial harvesting, as currently practiced in some semi-natural forests (e.g., Gustafsson et al., 2020) and previously suggested for planted forests (e.g., Norton, 1998), could be implemented in these diverse planted forests to foster biodiversity conservation. Diverse planted forests, in particular with patchwise mixing patterns, would be more amenable to these alternative practices since different species often have different production cycles and some species may be more suitable for retention and associated risks from exposure such as wind-throw and desiccation (e.g., Bauhus et al., 2017).

2. Public funding is needed to support forest ecosystem restoration and tree establishment (e.g., for carbon sequestration projects), particularly those on long production cycles, to be conditional on strategies to make planted forests diverse and thus provide more ecosystem services and resilience at stand and landscape scales. Such support for diverse planted forests should not come at the expense of non-forest ecosystems such as native grasslands and savannas, nor should they have a negative effect on the atmospheric energy budget (i.e., through a reduction in albedo) or the water cycle. In addition, in some regions with well-established large-scale monospecific planted forests, special efforts and incentive programs may facilitate both key wood industry and forest landowners to diversify species composition and structure to overcome impediments #3 and #4. Such incentive programs have been successful in central and northern Europe to encourage the planting of native deciduous species in pure conifer plantations (e.g., Felton et al., 2016).
3. Changes in demand from the timber market would encourage the establishment of diverse planted forests. Currently, a limited number of commodity tree genera provide most of the industrial roundwood from planted forests. Yet, a growing number of architects and foresters are asking that the wood being used in construction should adapt to the forest and not the other way around (Ibañez et al., 2019; Oliver et al., 2014). Recognizing that innovation opens new markets, we challenge the industry to *diversify* and develop competitive new wood-based products that facilitate a high-value end-use for a wide range of tree species, for example, more hardwoods being used in construction.
4. More research is required to evaluate at what scale, and where in the landscape, diverse planted forests should be established to increase functional connectivity of the forest landscape to maximize resilience to global-change threats. Recent studies from agricultural landscapes suggest that landscape diversity is as important as crop diversity at the farm scale in maintaining key ecosystem services (Hass et al., 2018). Similar studies in planted forests landscapes should evaluate the advantages and disadvantages of an increased heterogeneity of monospecific planted forests arranged as spatially distinct areas of monospecific stands (chessboard type spatial arrangement) compared to homogeneous diverse planted forests (intermingled mixtures at the stand scale). These mono- or multispecific stands within planted forest landscapes could be strategically positioned, for example, along drainage lines or to connect patches of remnant forests, and could act as seed sources for natural regeneration of the surrounding area with better-adapted tree species in case of large-scale tree mortality (Messier et al., 2019).
5. Finally, we invite researchers and practitioners from all over the world to report on well-established diverse planted forests and to establish new ones at experimental or operational scales. These experiments are needed to test harvesting technology as well as other novel ideas, such as the effect of spatial arrangements of tree species or sequential planting of different tree species. Both these old and new diverse planted forests could be registered within TreeDivNet (https://treedivnet.ugent.be/) as a new global research initiative to quantify the ecological and social role of diverse planted forests to maximize their usefulness. More data and the dissemination of already existing information on such diverse planted forests are needed worldwide.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

CM and JB conceived the original idea and wrote the first draft of the manuscript with support from RSS. RSS prepared the figures with input from all co-authors. All authors critically reviewed and approved the final version for submission.

ETHICS STATEMENT

There was no primary data collection undertaken for this manuscript prompting an ethics review process.

DATA ACCESSIBILITY STATEMENT

No primary data was collected for this manuscript. Data used to create Figure 1 are available in the public domain; full details of these data sources are given in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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