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MINI REVIEW

The Plant Ecology of Nature-Based Solutions

Unintended consequences of planting native and non-native trees in treeless ecosystems to mitigate climate change

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Abstract

1. Naturally treeless ecosystems are being replaced by native and non-native trees worldwide, often through deliberate afforestation using forestry tree species. By introducing species having novel traits, such as relatively rapid growth, many afforestation efforts also produce numerous changes in ecosystems, at the landscape scale.
2. Trees are considered critical for climate change mitigation; indeed, many current carbon sequestration strategies rely on trees. Planting trees or allowing trees to naturally colonize through range expansions can be seen as an ideal way to increase atmospheric carbon capture. For example, a snapshot approach may show that introducing trees into treeless ecosystems enhances aboveground accumulation of carbon, helping increase ecosystem carbon storage.
3. However, considering other impacts such as reductions in soil carbon or albedo and increased fire severity (through increases in fuel loads and connectivity) reduces the effectiveness of afforestation strategies for climate change amelioration. Additional negative impacts of afforestation are also likely, such as the reduction of native biodiversity and productivity, substantial water yield losses, and changes in nutrient cycles, which can exacerbate other global change drivers. Further, tree invasions originating from afforestation can exacerbate these negative impacts.
4. *Synthesis*. This review highlights that the positive and negative impacts of planting trees in naturally treeless ecosystems as a strategy to mitigate climate change are idiosyncratic, depending on the location where trees are introduced, the time period trees are allowed to grow, and risks of spread and impacts associated with specific tree species. Although planting trees can potentially be a tool to fight climate change, a greater consideration of their impacts is required to minimize the unexpected negative consequences of afforestation efforts.

KEYWORDS
afforestation, carbon certification, carbon sequestration, global change ecology, invasive woody plants, natural climate solution, plant-climate interactions

1 | INTRODUCTION

Climate change, driven largely by the increase in the concentration of greenhouse gases in the atmosphere, is one of the most important challenges facing humanity (IPCC, 2022) stimulating many alternative solutions to mitigate its progression (Griscom et al., 2017; Seddon et al., 2020; Smith et al., 2016). Unfortunately, current estimations indicate that atmospheric carbon enrichment will not lead to increased carbon sequestration at the ecosystem level (Jiang et al., 2020). Although reducing energy use and limiting the emission of greenhouse gases are widely thought to be the most effective solutions (Anderson et al., 2019; Baldocchi & Penuelas, 2019; Bond et al., 2019; Smith et al., 2016), this is not yet feasible in many countries or sectors of society. On the other hand, replacing naturally treeless ecosystems (i.e. ecosystems that in their natural form lack trees, such as grasslands, shrublands and wetlands) with tree plantations using species having high growth rates (hereafter afforestation) is increasingly promoted globally as a natural climate solution (i.e. nature based-solutions that apply specifically to climate change mitigation) (Bastin et al., 2019; Xu et al., 2023; https://www.bonnchallenge.org/) and carried out across the world through large scale schemes (Figure 1; Bond et al., 2019; Feng et al., 2016; Lewis et al., 2019). The goal of this natural climate solution is to fix more carbon in plant biomass and, therefore, remove carbon dioxide, the primary greenhouse gas emitted through human activities, from the atmosphere. Potential benefits of afforestation projects are increased carbon storage (i.e. carbon stock per unit of area), reduced soil erosion, growth of local economies, and provision of fibre and shelter for local communities (Holl & Brancalion, 2020). One of the main incentives for the adoption of this natural climate solution is the economic market of carbon credits which, through the adoption of certified standards (https://verra.org/programs/verified-carbon-standard/), can also make afforestation projects economically profitable. However, the long-term effectiveness of afforestation as a solution has been called into question both for overall ecosystem carbon storage and associated positive (co-benefits) or negative ('co-harm') effects in naturally treeless ecosystems (Table 1).

Treeless ecosystems have been historically underappreciated both in the context of biodiversity conservation and climate change mitigation, a tendency influenced by culturally driven beliefs that trees are inherently good for the environment (Cohen, 2004; Han, 2007; Kaine et al., 2023). For many, trees represent stability, longevity, and community (Djoudi et al., 2022), often playing a role in community building rituals—the planting of trees can even symbolize renewal and forward progress for both people and the environment (Elmendorf, 2008; Tidball, 2014). The practice of afforestation on large scales has historical ties to timber economics, with standardized measures of minimum percent cover (to maintain productive forests) dating back to the early 1800s (Davis & Robbins, 2018). Restoration initiatives today still reflect these standards despite decades of advances in ecology and land management that contest them (Bond et al., 2019; Davis & Robbins, 2018).

Even if some treeless ecosystems (e.g. grasslands, shrublands) were less diverse and captured less carbon than other ecosystems (e.g. forests), they are still highly valuable ecosystems whose unique biodiversity and ecosystem services could be jeopardized if replaced with trees (Veldman et al., 2015). Among these ecosystems, grasslands alone cover more than 40% of earth's land surface, store 34% of the terrestrial carbon stock (White et al., 2000), provide habitats for numerous plant and animal species, and deliver a wide range of ecosystem services (Bardgett et al., 2021). However, 49% of the area covered by grasslands has been degraded (Bardgett et al., 2021), with an average 8.5% reduction in soil carbon (Eze et al., 2018), a problem that could be exacerbated by their replacement with tree plantations. On the other hand, through management and biodiversity restoration, grasslands can also provide low cost and high carbon gain

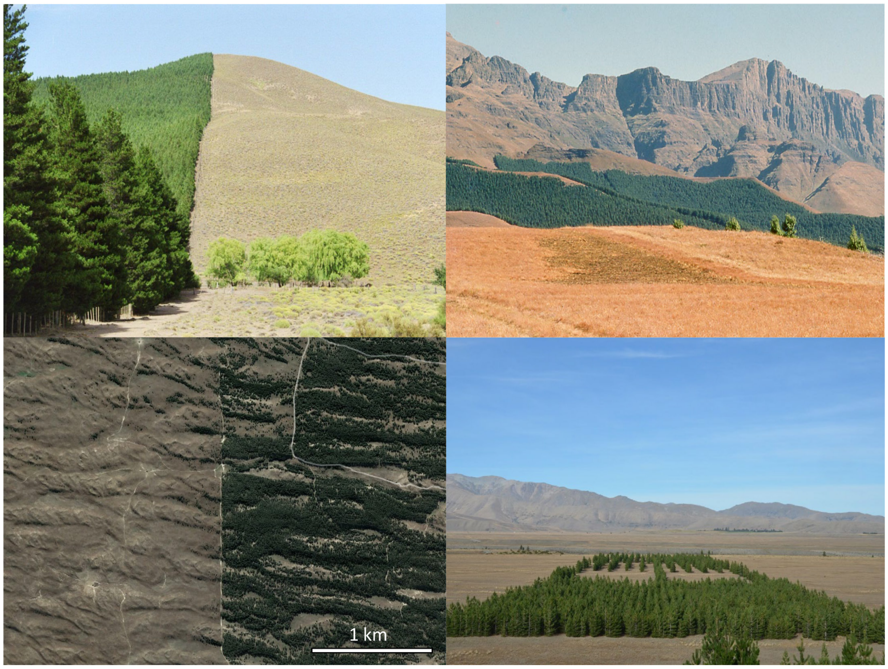

FIGURE 1 Upper left panel: Afforestation site where *Pinus contorta* was planted in a Patagonian semiarid steppe, near Junín de los Andes (Argentina). Photo: Mauro Sarasola. Upper right panel: Afforestation with *Pinus* spp. in a grassland of the Drakensberg (South Africa). Photo: Brian W. van Wilgen. Bottom left panel: Aerial image of afforestation site at Nebraska National Forest at Halsey (United States). Source: Google Earth. Trees were planted as part of an experimental forest in the 1930s through 50s (the original vegetation on these sites was semi arid C4 dominated grasslands). This is the largest afforestation in USA. Bottom right panel: Afforestation replacing grassland near Christchurch (New Zealand). Photo: Martin A. Nuñez.

TABLE 1 Afforestation impact [increase (+), decrease (−), no change (=)] on aboveground plant carbon, soil carbon, albedo, fire severity, biodiversity, local water yield and tree invasions.

Variable	Afforestation impact	Reference
Aboveground carbon	+	Bastin et al., 2019; Lewis et al., 2019; Rohatyn et al., 2022; Roe et al., 2019; Xu et al., 2023
Soil carbon	−/=/+	Bárcena et al., 2014; Berthrong et al., 2009; Berthrong et al., 2012; Deng et al., 2016; Duarte-Guardia et al., 2020; Dube et al., 2009; Eclesia et al., 2012; Guo & Gifford, 2002; Hong et al., 2020; Laganière et al., 2010; Veldman et al., 2019
Albedo	−	Arora & Montenegro, 2011; Bright et al., 2015; Mykleby et al., 2017; Rohatyn et al., 2022; Rotenberg & Yakir, 2010; Li et al., 2015
Fire severity	+	Archibald et al., 2013; Lindenmayer et al., 2023; McWethy et al., 2018, Paritsis et al., 2018; Stevens & Bond, 2024; Veldman et al., 2019
Biodiversity	−	Allan et al., 1997; Armstrong et al., 1998; Andrés & Ojeda, 2002; Bremer & Farley, 2010; Lipsey & Hockey, 2010; Nerlekar & Veldman, 2020; Prangel et al., 2023; Veldman et al., 2015
Water yield	−	Alvarez-Garreton et al., 2019; Farley et al., 2005; Feng et al., 2016; Jackson et al., 2005; Jobbágy et al., 2013; Veldman et al., 2019; Wang et al., 2020
Invasion	+	Nuñez et al., 2017; Simberloff et al., 2010; Richardson et al., 1994; Shackleton et al., 2014

natural climate solutions (Bai & Cotrufo, 2022; Dass et al., 2018; Yang et al., 2019), with a potential net carbon sequestration of 0.35 Gt C/year at a global level (Griscom et al., 2017), which is comparable to the potential for carbon sequestration of afforestation in all suitable dryland regions (0.40 Gt C/year; Rohatyn et al., 2022).

Knowledge of plant ecology is key for the design of most natural climate solutions. In this regard, previous studies have focused on different aspects through which afforestation affects plant ecology to mitigate climate change. These include: the potential to increase carbon sequestration in plant biomass (Bastin et al., 2019; Lewis et al., 2019; Rohatyn et al., 2022; Veldman et al., 2019); the effect of introducing a new plant life form on other carbon pools, such as soil carbon (Berthrong et al., 2009; Deng et al., 2016; Hong et al., 2020); the net effect on climate warming mitigation (Arora & Montenegro, 2011; Rohatyn et al., 2022); the impact on plant and animal biodiversity (Andrés & Ojeda, 2002; Lipsey & Hockey, 2010; Nerlekar & Veldman, 2020; Prangel et al., 2023); the changes to fire severity (Lindenmayer et al., 2023; McWethy et al., 2018, Paritsis et al., 2018; Stevens & Bond, 2024); the alteration of water cycling (Farley et al., 2005; Feng et al., 2016; Jackson et al., 2005; Ricciardi et al., 2022); and the possibility of using tree invasions, originating from tree plantations, to mitigate climate change (Nuñez et al., 2021). Here, we integrate all these aspects to address the unintended negative impacts of afforestation at a global level, outline possible solutions to avoid these unintended consequences, and identify research opportunities for better understanding the long-term consequences of this natural climate solution.

2 | UNINTENDED CONSEQUENCES OF AFFORESTATION

2.1 | Limited mitigation potential

For the year 2021, the total anthropogenic emissions reached 10.20 Gt C/year, of which 3.00 Gt C/year were sequestered by the oceans and 2.90 Gt C/year were sequestered in land ecosystems (Friedlingstein et al., 2022). The remaining 4.30 Gt C/year will continue to be released into the atmosphere, increasing the concentration of greenhouse gases. Estimations from the potential area of treeless ecosystems that can be afforested, spanning from 350 to 448 million ha indicate, on average, a potential net increase in carbon sequestration of 0.83 Gt C/year (Table 2; Bastin et al., 2019; Lewis et al., 2019; Rohatyn et al., 2022; Veldman et al., 2019). According to these estimations, to mitigate anthropogenic emissions only through afforestation would require converting more than one-third of global grasslands into tree plantations. This carbon sequestration capacity can be even more limited if we consider how tree growth (Cabon et al., 2022) and survival (Brodribb et al., 2020) is restricted by droughts, which are expected to become more frequent and severe (Cook et al., 2020). On the other hand, the reforestation of areas previously covered by forests has the potential to produce a net increase in carbon sequestration of 1.82 Gt C/year, more than twice as much as the afforestation potential (Table 2; Bastin et al., 2019; Griscom et al., 2017; Kemppinen et al., 2020; Veldman et al., 2019). While afforestation is being widely promoted to mitigate climate change, the restoration of forests throughout the world is much more effective at increasing carbon sequestration.

Conversion of naturally treeless ecosystems to tree plantations may not increase total carbon sequestration in many cases (Lewis et al., 2019; Veldman et al., 2019) because the main carbon pool in these ecosystems, soil carbon (Farley et al., 2004; Jones & Donnelly, 2004; Tang et al., 2018), may be substantially reduced through afforestation (Duarte-Guardia et al., 2020; Guo & Gifford, 2002; Li et al., 2023). The loss of soil carbon caused by afforestation can completely offset the increment in carbon sequestration in tree biomass (Friggens et al., 2020; Veldman et al., 2019). The current methodology (United Nations, 2013) followed by certification standards assumes that afforestation increases soil carbon in the long term (i.e. tens of years) for most sites, so the measurement of changes in soil carbon are optional. Just recently (by the end of 2023), one of this certification standards was updated to require the measurement of changes in soil carbon only if soils are heavily disturbed during the plantation of trees (https://verra.org/programs/

Natural climate solution	Carbon sequestration potential (Gt C/year) for 400 M ha	Reference
Afforestation	2.96	Bastin et al. (2019)
	0.01	Lewis et al. (2019)
	0.00	Veldman et al. (2019)
	0.36	Rohatyn et al. (2022)
Reforestation	2.90	Bastin et al. (2019)
	1.63	Griscom et al. (2017)
	1.12	Veldman et al. (2019)
	1.63	Kemppinen et al. (2020)

Note: More detail on these estimations can be found in Table S1.

TABLE 2 Estimations of carbon sequestration potential (Gt C/year) for afforestation (planting trees in previously treeless ecosystems) or reforestation (planting trees in areas previously covered by forests) for an area of 400 M ha, based on different literature sources.

verified-carbon-standard/). However, many variables influence the impact of afforestation on soil carbon.

Although it is not yet clear how to predict where afforestation will increase soil carbon and where it will reduce it, there is accumulating evidence on some key variables influencing this process. Annual precipitation is one of the main factors that modulates the impact of afforestation on soil carbon. Sites with higher precipitation (humid sites) show soil carbon loss (Berthrong et al., 2012; Eclesia et al., 2012; Guo & Gifford, 2002) while sites with lower precipitation (drier sites) gain soil carbon (Berthrong et al., 2012; Eclesia et al., 2012) or have no net change (Guo & Gifford, 2002). Time since afforestation is another key variable, with soil carbon increasing as trees in the plantation grow (Bárcena et al., 2014; Berthrong et al., 2012; Duarte-Guardia et al., 2020; Eclesia et al., 2012), highlighting the need for long growth periods before clearcutting (harvest) or a switch to 'carbon farming' where the intention is not to harvest. Tree species identity also makes a substantial difference on the change in soil carbon, with conifers either reducing soil carbon (Berthrong et al., 2009; Guo & Gifford, 2002) or having no effect (Bárcena et al., 2014) and broadleaf species either increasing soil carbon (Laganière et al., 2010) or having no effect (Guo & Gifford, 2002). The soil carbon level before afforestation is also important, with a negative relationship between initial soil carbon and soil carbon after afforestation (i.e. sites with higher initial soil carbon tend to lose carbon because of afforestation) (Deng et al., 2016; Hong et al., 2020). Further, the soil depth considered can influence the overall impact of afforestation on soil carbon, with greater impacts of afforestation in superficial layers (Bárcena et al., 2014; Dube et al., 2009). Therefore, it is key to consider the ecological context when designing afforestation projects (Holl & Brancalion, 2020), since the interaction between these variables can cause unexpected effects in soil carbon with potential carbon losses. Future research could address the interaction between the main variables that affect the impact of afforestation on soil carbon.

2.2 | Potential net warming effect

Even if afforestation projects do increase total carbon sequestration, they can still contribute to global warming through other mechanisms. Trees absorb more solar energy than snow, bare soil or other life forms (such as grasses) because they reflect less solar radiation (reduced albedo). As a result, the areas where trees have replaced (previously) treeless ecosystems absorb more heat, producing warming effects that may offset their cooling effect via increased carbon sequestration (Arora & Montenegro, 2011; Bright et al., 2015). In some cases, this land use change can increase soil temperatures (Kropp et al., 2020). This trade-off between albedo and carbon sequestration due to afforestation produces a net warming effect (because the reduction in albedo offsets the increase in carbon sequestration) at high latitudes and high elevations (Li et al., 2015; Mykleby et al., 2017; Rohatyn et al., 2022) and in semi-arid regions for decades before it turns into a cooling effect (when the increase in carbon sequestration compensates the reduction in albedo) (Rotenberg & Yakir, 2010). Furthermore, the eventual cooling effect that afforestation could create is slight (Rohatyn et al., 2022), reducing the global temperature only 0.45°C by 2100 if afforestation was carried out across the total area actually covered by crops (2020 million ha), which is a highly unlikely scenario (Arora & Montenegro, 2011). Considering the limited effect of tree planting to cool down the atmosphere, it would require replacing all treeless ecosystems throughout the world to mitigate climate change (Arora & Montenegro, 2011; Baldocchi & Penuelas, 2019; Bastin et al., 2019; Bond et al., 2019), with negative consequences that far exceed their potential benefits (Holl & Brancalion, 2020; Jackson et al., 2005; Veldman et al., 2015). Smart forestry aims to avoid afforestation in locations where this results in net warming, reducing the afforested area and increasing its climate change mitigation effectiveness (Rohatyn et al., 2022).

2.3 | Fundamental alteration of fire regimes, water balance and nutrient cycling

Fire intensity increases with afforestation in deserts and xeric shrublands, and in temperate and tropical grasslands (Veldman et al., 2019) and some common plantation species, such as *Eucalyptus globulus*, have traits that make them especially flammable (Guerrero et al., 2022). Studies from multiple countries have documented large, high severity wildfires in fast growing and densely stocked tree plantations

(Lindenmayer et al., 2023). In the context of climate change, fire risk is expected to increase in many areas of the world (Bowman et al., 2020; Jolly et al., 2015; Kitzberger et al., 2022), making fire suppression highly unachievable (Bowman et al., 2020). Tree plantations may not only exacerbate this tendency (McWethy et al., 2018; Paritsis et al., 2018) but, if burned would also release large portions of the carbon previously sequestered (Stevens & Bond, 2024; Veldman et al., 2019), seriously calling into question the effectiveness of afforestation as a strategy to mitigate climate change, while also threatening human well-being in wildland-urban interface areas. On the other hand, grasslands store most of their carbon belowground (Farley et al., 2004; Jones & Donnelly, 2004; Tang et al., 2018), a carbon sink which is better protected from fire (Dass et al., 2018).

Afforestation also changes the hydrological cycle, mainly because an increase in carbon assimilation requires an increase in evapotranspiration (Law et al., 2002) and, as a result, water yields decrease at the local scale (Alvarez-Garreton et al., 2019; Farley et al., 2005; Jobbágy et al., 2013; Wang et al., 2020), increasing soil salinization and acidification (Jackson et al., 2005). These water yield losses increase with plantation age and when plantations are composed of broadleaf species (Farley et al., 2005). At wetter sites the absolute water losses are greater, but in drier sites the proportional losses are larger (Farley et al., 2005). These negative consequences on the hydrological cycle are especially relevant for areas where water is scarce and further reductions in its availability will create shortages for local populations (Bond et al., 2019; Feng et al., 2016; Wang et al., 2020). On the other hand, the increase in evapotranspiration due to afforestation can contribute to rain in neighbouring areas through a redistribution of water at the regional scale and increased albedo through the formation of clouds (Ellison et al., 2017; Hoek van Dijke et al., 2022). Further, nutrient cycles are also greatly modified by the conversion of treeless ecosystems into tree plantations by reducing litter decomposition (Araujo & Austin, 2015).

2.4 | Negative impacts on native biodiversity

Native plant and animal communities are also threatened by the replacement of treeless ecosystems by tree plantations, which drastically modifies native habitats (Araujo & Austin, 2015; Lipsey & Hockey, 2010) and reduces native biodiversity (Veldman et al., 2015). Afforestation reduces grassland plant species richness (Prangel et al., 2023) and Mediterranean heathland shrub species richness and cover, affecting especially short-lived and endemic species (Andrés & Ojeda, 2002). Afforestation of heathlands also reduces the diversity and abundance of flowers and pollinators (Pérez-Gómez et al., 2024). Grassland and shrubland plant richness and diversity loss due to afforestation is higher when exotic trees are planted (Bremer & Farley, 2010). In the case of old growth grasslands, the restoration of herbaceous plant diversity, lost through land use changes including afforestation, requires at least a hundred years (Nerlekar & Veldman, 2020). Grassland and shrubland plant and animal species have become threatened or even extinct due to afforestation (Armstrong et al., 1998). Grassland bird diversity is negatively correlated with the extent of afforestation, which reduced the diversity of both endemic and threatened bird species (Allan et al., 1997), particularly affecting grassland specialists (Lipsey & Hockey, 2010).

Afforestation can also reduce the ecosystem services provided by the ecosystems which are replaced by trees. A recent study found a reduction in grassland pollination, provisioning of forage, wild food and medicinal herbs, as well as recreation and aesthetic value, due to afforestation (Prangel et al., 2023). Further, this land-use change causes a reduction of the area covered by grasslands and shrublands, the main forage source for extensive livestock grazing in many regions (Veldman et al., 2015, 2019). When afforestation is carried out planting non-native *Pinus* species (one of the most widely planted tree genera across the world), it also favours the invasion of non-native invasive animals (red deer and wild boar; Lantschner et al., 2013), which produce multiple negative impacts in native ecosystems, such as the alteration of soil functioning and biodiversity (Barrios-Garcia et al., 2023), alteration of plant composition and structure (Barrios-Garcia et al., 2014), and facilitation of the invasion of non-native trees (Nuñez et al., 2013). Finally, the harvest of tree plantations causes a massive disturbance that not only releases to the atmosphere a big part of the sequestered carbon (Achat et al., 2015; Peng et al., 2023) but can also further reduce native biodiversity (Chaudhary et al., 2016).

2.5 | Tree invasions exacerbate negative impacts of afforestation

Afforestation frequently causes tree invasions (Nuñez et al., 2017; Richardson et al., 1994; Shackleton et al., 2014; Simberloff et al., 2010), which produce impacts that are similar in some respects (Le Maitre et al., 2011; Nuñez et al., 2021; Rundel et al., 2014; Shackleton et al., 2014). However, tree plantations and invasions differ in key aspects. For instance, tree invasions are not circumscribed to a planted area, but affect an ever-increasing area as seeds are dispersed (Rundel et al., 2014), threatening native systems across entire landscapes surrounding tree plantations, including protected areas and (previously) well-conserved ecosystems (e.g. McConnachie et al., 2015; Peña et al., 2008). Another key difference is that tree invasions cover a broad range of tree densities, which tend to increase with time (Nuñez et al., 2017), as opposed to a standard density range for tree plantations. This wide variation in tree densities causes a broad variation in their impacts, a relationship described by density-impact curves, where generally higher densities cause larger impacts (Bradley et al., 2019; Yokomizo et al., 2009). Therefore, the impacts of tree invasions should be assessed in relation to the population density of the invader (Moyano et al., 2023; Paritsis et al., 2018; Taylor et al., 2016). As with the time since afforestation, the time since invasion also plays a key role on the impacts produced (Kumschick et al., 2015). However, unlike tree plantations, tree invasions are not composed of even-aged stands but include a distribution of ages from seedlings to adults (similar to a native forest), which is difficult to characterize (Milani et al., 2020; Nuñez & Paritsis, 2018). Further, in the case of tree invasions, time since invasion interacts with invasion density in a way that their respective effects are difficult to disentangle (Milani et al., 2020; Nuñez & Paritsis, 2018). Because of these complexities, the effect of tree invasions on ecosystem carbon storage becomes highly context dependent (see also Sapsford et al., 2020).

As is the case with afforestation, tree invasions into treeless ecosystems will have highly variable effects on carbon sequestration and overall effect on climate change. While the impact of tree invasion on carbon sequestration has rarely been evaluated, one study shows that (similar to the effect of afforestation) tree invasions in grasslands increase plant biomass carbon sequestration across a gradient of precipitation but reduce soil carbon in sites with higher precipitation, to the extent of completely offsetting increases in plant biomass carbon (Jackson et al., 2002). As with afforestation, invasive trees reduce surface albedo of invaded grasslands (Nuñez et al., 2021), but this effect will be highly influenced by invasion density, and possibly by the variables that affect the impact of afforestation on albedo, such as precipitation, elevation and latitude (Li et al., 2015; Mykleby et al., 2017; Rohatyn et al., 2022; Rotenberg & Yakir, 2010), although further research is needed to confirm this. Tree invasion also increases fuel loads and fuel connectivity, potentially increasing fire intensity (Paritsis et al., 2018; Souza-Alonso et al., 2017; Taylor et al., 2017), which may release to the atmosphere large portions of the fixed carbon, undoing their positive effect on climate change mitigation (as is the case with afforestation). In fact, high density tree invasions produce a larger increase in fire hazard than tree plantations (Paritsis et al., 2018), and an increase in fire frequency can exacerbate the spread of invasive trees (Franzese & Raffaele, 2017; Souza-Alonso et al., 2017). Tree invasions into treeless ecosystems also contribute to other drivers of global change, for example, reducing grasslands and shrublands diversity (Davis et al., 2019; Franzese et al., 2017; Pyšek et al., 2012; Taylor et al., 2016), and productivity (Ferraina et al., 2021; Morford et al., 2022; Moyano et al., 2023), altering nutrient cycles and soil biotic communities (Castro-Díez et al., 2019; Dickie et al., 2014, 2022; Le Maitre et al., 2011; Sapsford et al., 2022), and reducing local water yield (de Wit et al., 2001; Le Maitre et al., 2000).

Woody plant invasions are also a potential threat to human health (Loss et al., 2022). Several important disease vectors, including mosquitoes and ticks, have wildlife hosts that are often associated with habitats dominated by trees and shrubs (Allan et al., 2010; Horncastle et al., 2005; Ostfeld et al., 2018), and some evidence points to woody plant invasions into (previously) treeless ecosystems as the impetus for elevated vector-borne disease infection in humans (Noden, Cote, et al., 2021; Noden & Dubie, 2017; Noden, Tanner, et al., 2021). Increasing woody plant invasions can concentrate populations of reservoir hosts (e.g. deer, birds and rodents) seeking nesting sites and refuge from predators (Maichak et al., 2022; Negasa et al., 2014), proliferating the abundance of mosquitoes and ticks. Such increases in vectors could potentially enhance disease risk for the humans living in the region (Adalsteinsson et al., 2018; Noden, Cote, et al., 2021; Noden, Tanner, et al., 2021). Less work has been conducted in this research area, so it remains unknown when and where woody plants invasions can elevate vector-borne disease risk in humans. However, given that mosquitoes and ticks vector harmful diseases like West Nile, Malaria and Lyme disease (Anderson & Magnarelli, 2008; Campbell et al., 2002; LaDeau et al., 2007; Rothman et al., 2021), it is crucial to understand how tree invasions affect vector-borne disease risk before promoting them with the goal of climate change mitigation.

3 | THE WAY FORWARD AND POSSIBLE SOLUTIONS

While planting trees can potentially help mitigate climate change, afforestation should not be considered as the ultimate solution, but rather be integrated into a strategy including multiple approaches. Moreover, the potential for afforestation should not diminish efforts to reduce deforestation and forest degradation globally (Holl & Brancalion, 2020; Lewis et al., 2019; Mo et al., 2023). In fact, conservation and restoration of degraded forests should be prioritized over afforestation projects (Brancalion & Holl, 2020) since they have a much larger potential for carbon sequestration (Griscom et al., 2017; Lewis et al., 2019), especially tropical forests (Koch et al., 2021). In this regard, accurate mapping of different ecosystems through an understanding of landscape history is key to avoid misinterpretations of what areas constitute degraded forests that should be restored by replanting trees (Gillson et al., 2023; Parr et al., 2024; Veldman et al., 2015). Many afforestation efforts are dominated by non-native species, and this creates multiple potential risks and complex trade-offs among land use for different purposes involving carbon, biodiversity and economic activities. When considering afforestation projects and where to carry them out, we need to balance multiple ecological goals and seek to increase carbon storage without compromising other key aspects of native ecosystems, such as biodiversity, nutrient and hydrological cycles and fire regimes (Brancalion & Holl, 2020; Holl & Brancalion, 2020; Lindenmayer et al., 2012). A key tool for this purpose is risk analyses that assess potential risks to ecosystems, trade-offs between ecosystem services gained and lost, and uncertainties in ecosystem processes (Lindenmayer et al., 2012). Tree plantations should be avoided in vulnerable environments where the introduction of trees is likely to produce very negative impacts (Brundu et al., 2020; Veldman et al., 2015). In this line, the new Chilean Climate Change Law excludes monospecific tree plantations as a natural climate solution because their benefits are outweighed by the decline they produce in ecosystem services (Gómez-González et al., 2023). Considering both current and future climatic conditions is critical to ensure that the new tree plantations prosper under future climates (e.g. Shephard & Maggard, 2023).

More knowledge in plant ecology is needed to better understand the effects of introducing trees into naturally treeless areas, as well as the interactions between these effects and the key role of context when recommending afforestation for different scenarios. The high variability in the impact of afforestation on soil carbon and albedo creates the necessity to explicitly consider both effects in all cases, to avoid groundless assumptions of carbon storage and climate cooling effects. We propose that future carbon certification standards for afforestation projects demand the measurement of soil carbon throughout the whole soil depth (to comprehensively assess soil carbon sinks) and of surface albedo (to evaluate the net warming or cooling effect). Likewise, fire risk should be explicitly considered across spatial scales when planning where and which tree species to plant (Leverkus et al., 2022; Lindenmayer et al., 2023; Stevens & Bond, 2024). Possible practices to reduce fire hazard are avoiding fire-prone/flammable tree species, managing fuels to make afforestation less flammable (e.g. pruning lower branches; Paritsis et al., 2018) and regularly updating fire management plans (Lindenmayer et al., 2023). Further, tree plantations should be kept for longer periods to maximize carbon sequestration and then harvested for longer-lived products (Griscom et al., 2017; Houghton & Nassikas, 2018).

In cases where tree invasions are not successfully prevented, their spread should be controlled. The numerous negative impacts of tree invasions originating from afforestation bring the need to actively manage them. Therefore, certification standards should also require that plantation owners become responsible for the management of potential tree invasions. One possibility to reduce tree invasions is the use of forestry species that are not invasive (Rejmánek & Richardson, 1996, 2013). Highly invasive non-native tree species which tend to cause a wide range of negative impacts, from biodiversity reduction to increases in fire hazard and water consumption, should be avoided. Future research should study the impact of tree invasions on carbon sequestration of treeless ecosystems and overall cooling effects across a wide range of contexts (tree density, precipitation, altitude, latitude) (Sapsford et al., 2020), so that invasions are not favoured by the unfounded assumption that they help mitigate climate change. Even if the overall effect of tree invasions increases carbon sequestration this positive impact must be counterbalanced with the potential negative impacts these invasions generate (Nuñez et al., 2021). We hope this review will stimulate new research on natural climate solutions and offer a guide to future updates in certification standards for afforestation projects.

AUTHOR CONTRIBUTIONS

Jaime Moyano and Martin A. Nuñez designed the structure of the review and led the writing of the manuscript. All authors contributed with ideas and with the writing of all drafts. All authors gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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

Table S1: Estimation of annual mitigation potential for 400 M ha of afforestation or reforestation, according to different sources.

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