Should tree invasions be used in treeless ecosystems to mitigate climate change?

Martin A Nuñez1,2*, Kimberley T Davis3, Romina D Dimarco4, Duane A Peltzer5, Juan Paritsis6, Bruce D Maxwell7, and Aníbal Pauchard8,9

Intentionally allowing or promoting invasion by non-native trees into areas characterized by treeless vegetation could contribute to climate-change mitigation by increasing carbon (C) sequestration. In some areas of the world, incentives exist to retain invasive non-native trees in natural systems as a mechanism for increasing ecosystem C storage and reducing atmospheric carbon dioxide levels. Although this novel opportunity for C sequestration holds appeal, such an approach is problematic for several reasons: (1) invasive trees do not always increase net C sequestration due to greater occurrence of fire or reduced soil C; (2) lower albedo in invaded areas can increase absorption of solar radiation, thereby offsetting potential C sequestration; and (3) tree invasions often also have negative effects on biodiversity, economic opportunities, and water yield. Such drawbacks are sufficient to raise doubts about the widespread use of non-native tree invasions in treeless areas as a tool to ameliorate climate change.

In a nutshell:

- Non-native tree invasions can increase carbon (C) sequestration in some ecosystems; consequently, unmanaged incursions of introduced tree species are often considered a potential opportunity for climate-change mitigation.
- The overall effect of tree invasions on climate-change mitigation is poorly understood, but evidence suggests net negative effects in some instances.
- Tree invasions can alter fire regimes, soil C sequestration, and light absorption, all of which influence the impact invaders may have on climate regulation.
- Overall, the detrimental impacts of tree invasions on biodiversity, economic opportunities, and water yield may offset any positive effects on C sequestration.
- Managers or organizations considering using non-native trees for C sequestration should take into account the diverse problems associated with plant invasions.

1Grupo de Ecología de Invasiones, INIBIOMA, CONICET, Universidad Nacional del Comahue, San Carlos de Bariloche, Argentina; 2Department of Biology and Biochemistry, University of Houston, Houston, TX (nuñezm@gmail.com); 3Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT; 4Grupo de Ecología de Poblaciones de Insectos, IFAB (INTA-CONICET), San Carlos de Bariloche, Argentina; 5Manaaki Whenua Landcare Research, Lincoln, New Zealand; 6Laboratorio Ecotono, INIBIOMA, CONICET, Universidad Nacional del Comahue, San Carlos de Bariloche, Argentina; 7Land Resources and Environmental Sciences Department, Montana State University, Bozeman, MT; (continued on last page)
trees. Tree invasions into treeless ecosystems (e.g., grasslands, shrublands) are widespread (Rundel et al. 2014) but may not enhance C sequestration because of increased fire risk and reduced soil C. In addition, because the overall aim of C credits is to minimize global warming, woody species invasions may result in lower albedo, raising land surface temperatures. Here, we present and discuss the evidence suggesting that invasion of non-native tree species into treeless ecosystems is a less than ideal mechanism for C sequestration, and that it can have detrimental, unintended environmental impacts, even including promotion of positive climate-change feedbacks (Figure 1).

**Changes in fire regimes**

Aboveground biomass accumulation due to tree invasion increases fuel loads and alters fuel distribution, which in turn modifies fire regimes and enhances fire risk (e.g., Mandle et al. 2011; Souza-Alonso et al. 2017; Castro-Díez et al. 2019). For example, dense invasions of broad-leaved paperbark (*Melaleuca quinquenervia*) into Florida prairies and wetlands have caused a shift in fire regime from low to high intensity (Mandle et al. 2011). In fuel-limited systems like the Patagonian steppe of South America, woody invasions increase both fuel loading and connectivity, leading to increased fire intensity and severity (Taylor et al. 2017; Paritsis et al. 2018). In contrast, some invasive trees have traits that reduce fire spread in areas with frequent-fire regimes (e.g., Stevens and Beckage 2009). Plantations of non-native trees are typically managed to improve wood quality (e.g., by pruning lower branches), which can limit vertical fuel connectivity; however, tree invasions into grasslands or shrublands have lower crown base heights that connect surface vegetation to the canopy, thereby increasing the risk of crown fire (Paritsis et al. 2018). Fire season length and fire activity are widely projected to increase in many parts of the world due to climate warming (Jolly et al. 2015), making stands of invasive trees (particularly flammable species, such as *Pinus* and *Eucalyptus*) more likely to burn and release stored C back into the atmosphere (Panel 1 and Figure 2).
Non-native tree invasions and climate change

Reductions in soil C

Although increased aboveground C storage following woody species invasion is well documented, much less is known about belowground storage. This is surprising because soil C storage is the primary component of global C sequestration, with two- to threefold more C stored in soils than in terrestrial vegetation (Houghton 2007). A meta-analysis across invasive species and ecosystems revealed that soil C can increase slightly following invasion (Liao et al. 2008), but recent experimental evidence suggests that non-native species reduce soil C through interactions with herbivores and soil biota (Waller et al. 2020). Other studies focused on woody species suggest that soil C can either increase or decline after invasions (Jackson et al. 2002) due to changes in rooting depth, associated soil biota, or lower C inputs from resident species. For instance, co-invasion of ectomycorrhizal tree species, which are globally important invaders (eg all Pinaceae and Eucalyptus, and species in the Salicaceae and Acacia), and their symbionts can increase rates of nutrient cycling and oxidation of C pools compared to native mycorrhizal forms, thereby reducing soil C in comparison to native vegetation (Farley et al. 2004; Dickie et al. 2014).

C accumulation in soils is driven by numerous and complex processes that are both directly and indirectly influenced by invasive trees (Sapsford et al. 2020) through, for example, differences in biomass allocation or accretion of the invader itself, longevity of the non-native species, or alteration of litter quality and quantity to the soil subsystem and therefore C and nutrient cycling (eg Castro-Díez et al. 2014). The relatively rapid increase in aboveground biomass of invaders (Liao et al. 2008) commonly exerts important indirect effects on ecosystem C by altering the composition, diversity, and function of resident vegetation (Wardle and Peltzer 2017; Davis et al. 2019). Overall, the assumption that tree invasions will promote soil C levels may not be true in all cases, underscoring the need for more comprehensive species- and system-specific information.

Reduction in albedo

Increased forest cover in the temperate and cold regions of the world can produce a net warming of the atmosphere even under scenarios of C accumulation due to altered surface albedo (Arora and Montenegro 2011; Davies-Barnard et al. 2014; Kreidenweis et al. 2016). Changes in albedo are fundamental to understanding the net effect of tree invasions on global warming, especially in treeless areas. Because of the vast extents of the planet’s terrestrial surface that could potentially be occupied by non-native tree species, changes in albedo could undermine the overall goal of using invasive woody species as a tool to mitigate climate change. To illustrate, we observed a 20% reduction in albedo in a native steppe in Chile within ~10 years of pine invasion (Figure 3); if unmanaged, it is likely that the invaded area will eventually attain albedo levels similar to those of nearby plantations (or possibly even lower, given the higher tree density in invaded versus managed stands). Other studies have reported even greater differences; for instance, evergreen plantations and grasslands were characterized by albedos of 0.12 and 0.19, respectively (that is, 88% and 81% of the sunlight received by these landcover types would be absorbed) (Schaeffer et al. 2006). It was beyond the scope of this article to calculate temperature increases that could result from such invasions, but these findings illustrate that changes in albedo of this magnitude could contribute to shifts in global temperature if they occur over large spatial scales, possibly producing a net rise in temperature even under a scenario of high C accumulation (Davies-Barnard et al. 2014; Kreidenweis et al. 2016). Although albedo can be affected by complex factors (eg cloud cover), a change in albedo of
Impacts of tree species invasion beyond climate-change mitigation

Tree species invasions into treeless areas may have multiple ecosystem-scale effects, many of which – such as altering C sequestration – can be pervasive (Panel 2 and Figure 4). First, these invasions often lower the abundance and diversity of native species (Pyšek et al. 2012; Davis et al. 2019) and induce shifts in soil biotic communities and nutrient cycling (Le Maitre et al. 2011; Castro-Díez et al. 2019), resulting in fundamental and persistent changes to ecosystems. Second, greater aboveground C sequestration is associated with increased water use and consequently lower water yield in catchments. Global studies show afforestation of grasslands or shrublands reduces streamflow and runoff by 40–75% (Farley et al. 2005; Jackson et al. 2005), which can restrict water availability to urban areas (Pejchar and Mooney 2009) and exacerbate problems of surface and groundwater availability in dry regions (Le Maitre et al. 1996, 2000). In addition, decreased soil organic matter beneath invasive pines can reduce soil water retention relative to native grasslands (Farley et al. 2004). Greater water use can also interact with other factors, for example, by increasing fire risk. Third, woody species invasions can have severe negative social and economic impacts across diverse sectors, such as plantation forestry, tourism, and sheep and cattle ranching (Ledgard 2001; Le Maitre et al. 2011; van Wilgen and Richardson 2012; Castro-Díez et al. 2019). Heavily invaded areas cannot be used for other activities without the removal of trees, which is often unaffordable for landowners (Nuñez et al. 2017). For example, at sites in New Zealand, the cost of removing invasive pines ranges from NZ$1–50 per hectare for sparse invasions to more than NZ$2500 per hectare for dense invasions, and management is often repeated within a site before a different land use is feasible. Other major economic impacts include the reduction of surface streamflow, ecosystem-scale effects, many of which – such as altering C

![Figure 3](image-url). Total shortwave albedo (mean ± standard deviation) obtained from Landsat 7 products for the Coyhaique area, Chile, for a Patagonian steppe, a dense but recent (~10-year-old) lodgepole pine (*P. contorta*) invasion in the steppe, and a lodgepole pine plantation in an adjacent area. Albedo was calculated based on 20 points for each vegetation type using equations described in Liang (2001).

0.01 at a global scale would have a warming effect equal to that generated by a doubling of the current amount of carbon dioxide in the atmosphere (Wielicki et al. 2005).

### Panel 2. A practical example of the potential conflicts and concerns of using tree invasions for C sequestration in New Zealand

Species of Pinaceae underpin the plantation forestry industry in New Zealand but are also widely naturalized biological invaders. For example, wood exports from pines comprise ~99% of total log volume exports and are the fourth largest industry nationally (NZMPI 2019). On the other hand, at least 14 species of Pinaceae are considered to constitute a serious weed problem on ~1.8 million ha (Froude 2011; Hulme 2020). As a consequence, government agencies, land managers, and communities currently spend in excess of NZ$15 million annually on management. Overall, there are nontrivial costs and benefits of non-native pines in New Zealand that have generated much debate over their management, both as a resource and as invaders. One of these issues is whether invasive pines should be retained in some areas for C sequestration. There is active debate on the pros and cons of using invasive trees for C sequestration. This debate spills over directly into C sequestration policy through New Zealand’s Emissions Trading Scheme (ETS; www.mfe.govt.nz/ets), which is intended to promote more environmentally sustainable management by C emitters paying for C credits from entities that remove greenhouse gases. At present, New Zealand is the only country so far to include plantation forests as full participants in an ETS (Evison 2017). A large number of plantations that were established in the 1980s through afforestation incentives are now due for harvest, and this has created an urgent need to replace forests that can rapidly sequester C to meet international climate obligations, such as the 2015 Paris Agreement. Post-1989 forests registered in the ETS can be liable for deforestation by removing invasive trees; likewise, pre-1990 forests require a “tree weed” exemption if subject to the ETS. The 1989/1990 cutoff in managing forests for C sequestration means that, in some instances, there are ~30 years of potential invasion that either can be partially claimed under ETS or require exemption to allow for weed management. Although tree invasions can be considered under some circumstances to provide benefits for C sequestration, the trade-offs involved with ongoing invasion and negative impacts mean that retaining invasive trees is not generally considered acceptable practice over the long term (Edwards et al. 2020). However, invasive trees are retained in some long-invaded or remote areas where management is considered intractable or unaffordable, but these are not included in the ETS. Ultimately, this example highlights that the interplay between management of biological invaders, policy, and practice underpins decisions for when and where tree invaders are removed or retained (Hulme 2020).
for instance after the introduction of acacias in South Africa, which resulted in losses equivalent to over US$200 million and exacerbated social conflicts in the region (De Wit et al. 2001; Shackleton et al. 2018). Tree invasions can also alter landscapes and their aesthetics, driving shifts in intrinsic, tourism-based, and recreational values (Castro-Díez et al. 2019). Collectively, these impacts and the shifts they produce (eg in fire regimes or water cycles) suggest that tree invasions can cause major environmental and social problems (Kull et al. 2018). How the total economic costs or benefits of biological invaders can be quantified adequately across their multiple effects on environmental, social, and economic factors remains unresolved (Bartkowski et al. 2015).

When would it be justified to use tree invasions as a climate-change mitigation effort?

Although leaving woody species invasions unmanaged to act as C sinks has several disadvantages, this approach may be a viable option for species that have a net positive effect on C sequestration over the long term but only minor adverse impacts on biodiversity and ecosystem services. Some non-native woody species are more invasive than others, which can be explained by their characteristics. For example, lodgepole pine (Pinus contorta) is highly invasive in the Southern Hemisphere due in part to its relatively small seed size and early age of reproduction (Richardson and Rejmánek 2004), making removal of this species essential regardless of its value to C sequestration because it can quickly spread into areas where it is unwanted; in addition, large-scale removal is costly and can produce negative soil legacy effects (Nuñez et al. 2017; Dickie et al. 2014). Similarly, invasions by some Acacia spp have negative ecological or economic impacts (Souza-Alonso et al. 2017) that far exceed the benefits of their C sequestration, such as reductions in water availability for crops and urban areas (De Wit et al. 2001). In contrast, other types of conifers (eg cypress [Cupressus spp]) do not readily spread in some areas (Richardson and Rejmánek 2004), and therefore may be preferable to more invasive species.

Retaining invasive tree species may also be considered if populations can be contained or managed within specific sites. Some woody species only become invasive in specific environments (eg degraded pastures) and may be passive bystanders as opposed to active drivers of ecological change (MacDougall and Turkington 2005); spread of these species may be more easily controlled, making them better suited for C sequestration purposes. At present, however, few management options exist for the efficient removal of invasive woody species, and containment requires ongoing management of buffers and surveillance to confirm effectiveness (Panetta 2012). Furthermore, removal of woody non-natives will not necessarily restore the ecosystem to its previous state (Sapsford et al. 2020) but instead may induce shifts toward different community compositions and ecosystem processes, and in some cases additional invasions by other non-native species (Nuñez et al. 2017). Overall, the management costs of retaining invasive tree species can be considerable, and these costs must be balanced against the benefits for climate mitigation or other services. Yet invasions should still be used with caution and continuously monitored given the ongoing and long-term potential for non-native species to both invade and, in some cases, fundamentally alter ecosystems (eg Strayer et al. 2006; Hulme 2020).

Are there more sustainable alternatives to using invasions?

Native species that spread into new ecosystems can also be used for C sequestration (Simberloff et al. 2011). Expansion of native tree species is a widespread phenomenon and may have fewer negative consequences for the environment than non-native invasive species given their coevolutionary history with the invaded community. However, invasion of native species into adjacent areas (that is, woody encroachment) can also result in loss of biodiversity (Jackson et al. 2002; Taylor et al. 2016b), shifts in fire regime (Ratajczak et al. 2014), and possibly lower C sequestration. Evaluation of leaving native invaders uncontrolled to serve as C sinks must therefore also take ecosystem impacts into account.

Native and non-native tree species in planted forests with clear commercial value and defined management plans may...
be a viable option for use as C sinks. Commercial value may derive from firewood, timber, or a non-wood forest product used in the food, chemical, or pharmaceutical industries (Rodrigues-Corrêa et al. 2012; Hulme 2020). In these cases, it is important to assess how invasive the commercial tree species is, given that it could escape into areas where it cannot be harvested commercially (Nuñez et al. 2012). Management plans of plantations should thus consider the control of all individuals that spread beyond the original plantation stands (eg through inclusion into Forest Stewardship Council standards).

Restoration of areas previously occupied by trees has been promoted as a key tool to increase C sequestration at a global scale (Griscom et al. 2017; Bastin et al. 2019). This alternative is ideal if the species included in the restoration were present historically (ie native). Large amounts of C can be stored through forest restoration, and this should be a priority given the combined benefit of C sequestration and the restoration of natural ecosystems.

How can management decisions be improved?

Economic and technical resources for controlling invasive species are often limited. In these instances, a detailed analysis of C sequestration and other impacts – taking into account soil C, fire activity, albedo, biodiversity, and water use – should be considered before the decision whether to retain an invasive species is made. Although invasions may provide net C accumulation, there are still no effective management options available, as with pine invasions in different parts of the world (Nuñez et al. 2017). In these scenarios, available methods for evaluating impacts (eg economic impact classification of alien taxa [EICAT], socioeconomic impact classification of alien taxa [SEICAT]; Bacher et al. 2018) should be used to produce objective impact assessments, which can then be used to determine the costs and benefits of different management options.

In cases where effective management options are available, net C sequestration and positive impacts on mitigating climate warming should be determined; these positive effects of C sequestration must be considered along with negative effects, such as impacts on local economies or biodiversity, when deciding whether the affected area should be prioritized for management. For example, funds available for climate-change mitigation can be allocated toward removal of invasive species that promote climate warming due to a reduction in long-term C sequestration or in albedo. As an example, several areas in New Zealand that are managed for pine invasions under a national wilding conifer control program are now being considered for subsequent afforestation under a different national initiative, the One Billion Trees Programme (Te Uru Rākau 2018), which uses both native trees and non-native tree species with low risk of invasion. Such an approach both reduces the current and future risks of tree invasion and supports a shift toward afforestation for climate mitigation.

When contemplating whether to remove or retain invasive trees it will be crucial to apply objective decision-making tools. The decisions might be similar to those made when considering managed relocation (or assisted migration), for which multicriteria decision frameworks have been developed (eg Richardson et al. 2009). In this regard, there are important scientific, regulatory, and ethical challenges that must be taken into account (see Schwartz et al. 2012). Experimental evidence concerning impacts and C accumulation is frequently lacking, yet such information is fundamental for decision making and adaptive management under global change scenarios.

Conclusions

Determining whether an invasive species can and should be retained as a C sink to help mitigate climate change involves consideration of aspects beyond its aboveground C storage capacity. Many factors play a role in decision making concerning the use of invasive woody species as climate-change ameliorators. Climate change and biological invasions are complex problems requiring solutions that incorporate scientific, economic, and social considerations. The objective of this review was to show that woody species invasions are rarely effective or desirable in mitigating climate change because their effects on C sequestration are not always positive, and they can have a range of detrimental impacts on ecosystems.

Acknowledgements

We thank P. Kardol and C. Iversen for helpful comments on early versions of the manuscript. MAN was supported by PICT 2016-1412 and PICT 2018 329; DAP was supported by the Winning Against Wildings research program funded by the New Zealand Ministry of Business Innovation and Employment; AP was funded by CONICYT PIA AFB170008; and MAN and AP were funded by NERC NE/S011641/1.

References


8Laboratorio de Invasiones Biológicas, Facultad de Ciencias Forestales, Universidad de Concepción, Concepción, Chile; 9Institute of Ecology and Biodiversity, Santiago, Chile