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Discussion

Is tree planting an effective strategy for climate change mitigation?

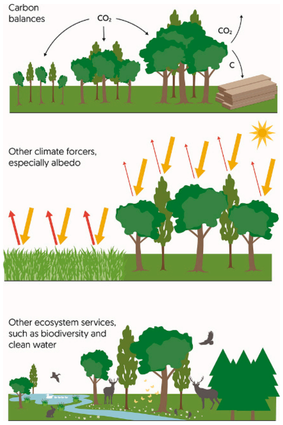
Miko U.F. Kirschbaum [a,*], Annette L. Cowie [b], Josep Peñuelas [c,d], Pete Smith [e], Richard T. Conant [f], Rowan F. Sage [g], Miguel Brandão [h], M. Francesca Cotrufo [i], Yiqi Luo [j], Danielle A. Way [k,l,m], Sharon A. Robinson [n]

[a] *Manaaki Whenua - Landcare Research, Private Bag 11052, Palmerston North, New Zealand*
[b] *NSW Department of Primary Industries/University of New England, Armidale, Australia*
[c] *CSIC, Global Ecology Unit, CREAF-CSIC-UAB, Bellaterra, Barcelona, Catalonia, Spain*
[d] *CREAF, Cerdanyola del Vallès, Barcelona, Catalonia, Spain*
[e] *Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK*
[f] *Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, 80523, USA*
[g] *Department of Ecology and Evolutionary Biology, 25 Willcocks Street, Toronto, Ontario, M5S 3B2, Canada*
[h] *KTH Royal Institute of Technology, Department of Sustainable Development, Environmental Science and Engineering, Stockholm 100-44, Sweden*
[i] *Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA*
[j] *School of Integrative Plant Science, Cornell University, Ithaca, NY, USA*
[k] *Division of Plant Sciences, Research School of Biology, The Australian National University, Canberra, ACT 2601, Australia*
[l] *Department of Biology, The University of Western Ontario, London, Ontario, Canada*
[m] *Nicholas School of the Environment, Duke University, Durham, NC 27708, USA*
[n] *Securing Antarctica's Environmental Future & Centre for Sustainable Ecosystem Solutions, School of Earth, Atmospheric and Life Sciences, University of Wollongong, Australia*

HIGHLIGHTS

- Forests play an important role in the global carbon cycle. Forests store more carbon than alternative vegetation, and wood products and any fossil-fuel substitution widen that role.
- Forests also have important direct radiative effects, with forests generally absorbing more solar radiation than bare ground or other plant covers.
- Forests also have important non-climate effects by positively or negatively affecting ecosystem services such as water balances, conservation of biodiversity and others.
- Here, we try to give a balanced assessment of the many positive and negative environmental contribution of forests to ensure that new forests are planted in ways that maximise their beneficial contributions.

GRAPHICAL ABSTRACT



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* Corresponding author at: Manaaki Whenua - Landcare Research, Private Bag 11052, Palmerston North 4442, New Zealand.
E-mail address: KirschbaumM@LandcareResearch.co.nz (M.U.F. Kirschbaum).

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ABSTRACT

The world's forests store large amounts of carbon (C), and growing forests can reduce atmospheric CO_2 by storing C in their biomass. This has provided the impetus for world-wide tree planting initiatives to offset fossil-fuel emissions. However, forests interact with their environment in complex and multifaceted ways that must be considered for a balanced assessment of the value of planting trees.

First, one needs to consider the potential reversibility of C sequestration in trees through either harvesting or tree death from natural factors. If carbon storage is only temporary, future temperatures will actually be higher than without tree plantings, but cumulative warming will be reduced, contributing both positively and negatively to future climate-change impacts. Alternatively, forests could be used for bioenergy or wood products to replace fossil-fuel use which would obviate the need to consider the possible reversibility of any benefits.

Forests also affect the Earth's energy balance through either absorbing or reflecting incoming solar radiation. As forests generally absorb more incoming radiation than bare ground or grasslands, this constitutes an important warming effect that substantially reduces the benefit of C storage, especially in snow-covered regions. Forests also affect other local ecosystem services, such as conserving biodiversity, modifying water and nutrient cycles, and preventing erosion that could be either beneficial or harmful depending on specific circumstances.

Considering all these factors, tree plantings may be beneficial or detrimental for mitigating climate-change impacts, but the range of possibilities makes generalisations difficult. Their net benefit depends on many factors that differ between specific circumstances. One can, therefore, neither uncritically endorse tree planting everywhere, nor condemn it as counter-productive. Our aim is to provide key information to enable appropriate assessments to be made under specific circumstances. We conclude our discussion by providing a step-by-step guide for assessing the merit of tree plantings under specific circumstances.

1. Introduction

The atmospheric CO_2 concentration has increased from its pre-industrial concentration of about 280 μmol mol^{-1} to over 415 μmol mol^{-1} by 2022 (Fig. 1a), with a continuous upward trajectory and ongoing and further accelerating annual increases (Fig. 1b). This ongoing increase in atmospheric CO_2 concentration, together with increases in other greenhouse gases (GHGs), is raising global average temperatures (Fig. 1c). If these ongoing emissions cannot be halted, temperature will continue to increase over the 21st century (Fig. 1d).

These current and expected future climatic changes have generated an urgent need to adopt measures to reduce atmospheric GHG concentrations. However, government policies to reduce emissions are difficult to implement and often unpopular. Nonetheless, many companies are now trying to reduce the GHG emissions for which they are directly responsible (Sanderson, 2023; Seddon et al., 2021). When they have done as much as is practicable, they are increasingly turning to voluntary CO_2 emission offsets to get to net-zero.[1] Planting trees can initiate real, tangible carbon (C) storage benefits (as 'mighty oaks from little acorns grow'), and preventing deforestation not only prevents C emissions to the atmosphere but can potentially deliver a host of other benefits (Smith et al., 2019a).

For very ambitious organisations, emission offsets are the *only* way to zero-out historical emissions. It is now very easy to support forest conservation or to plant new trees, and there are tree-based C offsets available for purchasing plane tickets, getting an automobile licensed, and buying T-shirts (e.g. Liu et al., 2021; Seddon et al., 2021). Drawing down CO_2 by planting trees is often advocated by governments and non-government organisation (e.g. https://www.nature.org/en-us/get-involved/how-to-help/plant-a-billion/) as it is a simpler and less controversial climate-change response strategy than many alternatives so that it can more easily elicit strong public support. Growing trees, or maximising carbon storage in the soil is, therefore, often described in terms of 'buying time' (e.g. Kirschbaum, 2003; Smith, 2012; Minasny et al., 2017) by offsetting current fossil-fuel emissions until newer technologies can be developed to provide true emission reductions through longer-term fossil-fuel savings.

Organisations like Verra, and others have developed rules, accounting systems, and procedures intended to ensure the validity of C offsets (e.g., Verra, 2021). These rules aim to ensure that a verified quantity of CO_2 actually means that the specified quantity of CO_2 is taken out of the atmosphere and stored, in relevant pools, such as forest biomass C. However, verifying C gains by tree planting or forest protection has presented challenges in the real world (e.g. Nabuurs et al., 2022). For example, the C value of preserving a forest depends on whether protected forests would have actually been deforested without the protection of C credits. While it is difficult enough to measure actual C stocks, it is even more difficult to validate any counterfactuals (Bradford et al., 2019).

How can one prove that a forest would have been deforested without protective measures? Furthermore, how can one know that preserving a forest in one place does not lead to deforestation in another place? The pressure for deforestation will continue as long as the demand for wood or agricultural land remains. Similar problems apply to establishing new forests. If new trees are planted on an agricultural field, might that prompt expansion of agriculture and deforestation elsewhere to meet the existing demand for agricultural products (Schwarze et al., 2002)? Several current initiatives seek to raise confidence in C credits available for purchase and increase the credibility of offsetting claims, such as the Integrity Council for the Voluntary Carbon Market (https://icvcm.org) and the Voluntary Carbon Markets Integrity Initiative (https://vcmintegrity.org). Understanding how well measurement, reporting, and verification procedures address questions of additionality and leakage is essential for assessing the veracity of C offsets for forest preservation or tree planting (Schwarze et al., 2002).

Others have criticised these approaches (e.g. Holl and Brancalion, 2020; Fleischman et al., 2020; Heilmayr et al., 2020; Seddon et al., 2021) and claimed that tree planting may not 'buy time' but instead create a liability if even deeper cuts in future fossil-fuel emissions may be needed in future. For example, if limited funds for climate change mitigation are spent on tree-planting schemes, those funds could not be used for developing or installing cleaner and more energy-efficient appliances. Tree plantings also have other impacts that may be either positive or negative (e.g. Holl and Brancalion, 2020; Fleischman et al., 2020; Heilmayr et al., 2020; Di Sacco et al., 2021; Tölgyesi et al., 2021). Forests can affect the climate in ways other than through changing atmospheric CO_2, especially by changing surface albedo. Forests also have non-climate related impacts, such as ecological and socio-economic impacts, which may also be beneficial or harmful. And forests may

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[1] "Net zero" [GHG emissions] refers to the condition in which GHG emissions are counterbalanced by CO_2 removals achieved through actions such as tree planting.

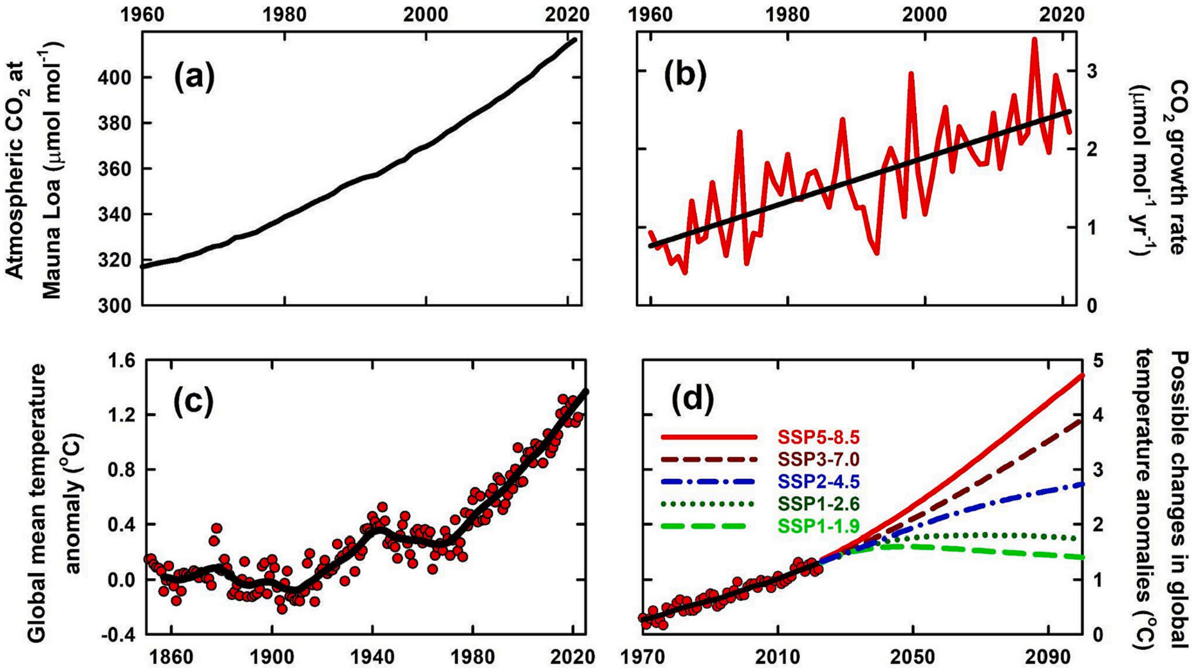

Fig. 1. Aspects of global change, showing: (a) changing CO$_2$ concentrations since 1960; (b) annual changes in CO$_2$ concentration; (c) observed global temperature anomalies since 1850; (d) projected temperature increases to 2100 under different future emission pathways, designated as 'shared socio-economic pathways' (SSPs). The CO$_2$ observations are from Mauna Loa (Keeling et al., 1976, with recent updates downloaded from https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt). Temperature anomalies since 1850 were obtained from the Climatic Research Unit at the University of East Anglia and the UK Met Office. Temperature anomalies are expressed relative to the average of the 1850–1900 period. Future temperature anomalies are based on five SSPs obtained from IPCC (2021). The numbers after each SSP approximate radiative forcing by 2100: for example, SSP5–8.5 refers to a scenario reaching radiative forcing of 8.5 W m^{-2} by 2100.

provide wood that can be used as wood products or biofuel that can replace fossil fuels. We elaborate on these factors in the text below.

Considering all these diverse factors, should we consider tree planting as 'good' or 'bad' in terms of mitigating climate change? Or is it 'good' or 'bad' in terms of attendant non-climate changes that may also be regarded as important and maybe as even more important than the role of forests in mitigating climate change? Here, we discuss the main issues that need to be considered in the context of planting trees for climate-change mitigation. The issues are complex and cannot be covered exhaustively in a single journal article, but we have described what we consider to be the most important key issues and provided references for readers to find more comprehensive treatments of these issues in other publications.

2. Issues to consider

2.1. Forests globally – pools and fluxes

Between 1750 and 2019, fossil fuel emissions have added about 445 GtC to the atmosphere, with land-use change adding a further 240 GtC. Of that combined 685 GtC, the world's oceans have taken up about 170 GtC, and 285 GtC have accumulated in the atmosphere (Canadell et al., 2021b). The remaining 230 GtC, or about 30 % of C emitted from anthropogenic activities, have been sequestered in land ecosystems or through other mechanisms (Fig. 2a).

Over the more recent period from 2010 to 2019, land-use change has contributed only about 1.6 GtC yr^{-1}, thus a relatively smaller fraction of total anthropogenic CO$_2$ emissions than historically, while net emissions to the atmosphere are now dominated by fossil-fuel emissions, adding about 9.4 GtC yr^{-1} (Fig. 2b). The oceans take up an estimated 2.5 GtC yr^{-1} and the atmospheric C content is increasing by about 5.1 GtC yr^{-1} (Canadell et al., 2021b), while land ecosystems and fluxes into other pools (Kirschbaum et al., 2019) sequestered an average of 3.4 GtC yr^{-1}. Studies have partitioned the land C sequestration into vegetation and soil organic matter pools (Xu et al., 2021; O'Sullivan et al., 2022), and indicated that each is responsible for 40–60 % of the land C sink. Thus,

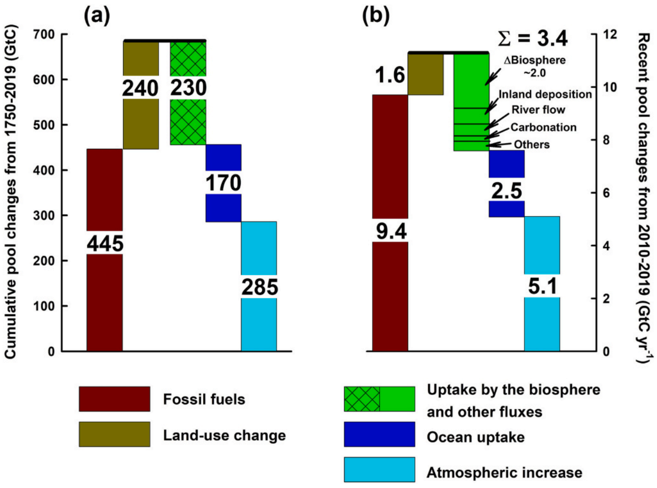

Fig. 2. Global anthropogenic CO$_2$ emissions and uptakes: (a) historically for the 1750–2019 period; (b) for recent average fluxes for the 2010–2019 period (b). Emissions are broken down into fossil-fuel based emissions, including cement production, and emissions resulting from land-use change. These emissions are balanced by ocean uptake, uptake by the biosphere and a range of other fluxes. The difference constitutes the increase of CO$_2$ in the atmosphere. Recent fluxes are sub-divided into actual biosphere-C increments, deposition in inland water reservoirs, C transfer to the oceans via river flow, cement carbonation and a range of other minor contributors. Figure redrawn from Friedlingstein et al. (2020), with updated numbers from Canadell et al. (2021b). The subdivision into biosphere and other fluxes follows Kirschbaum et al. (2019). We are not aware of a similar sub-division of historical fluxes.

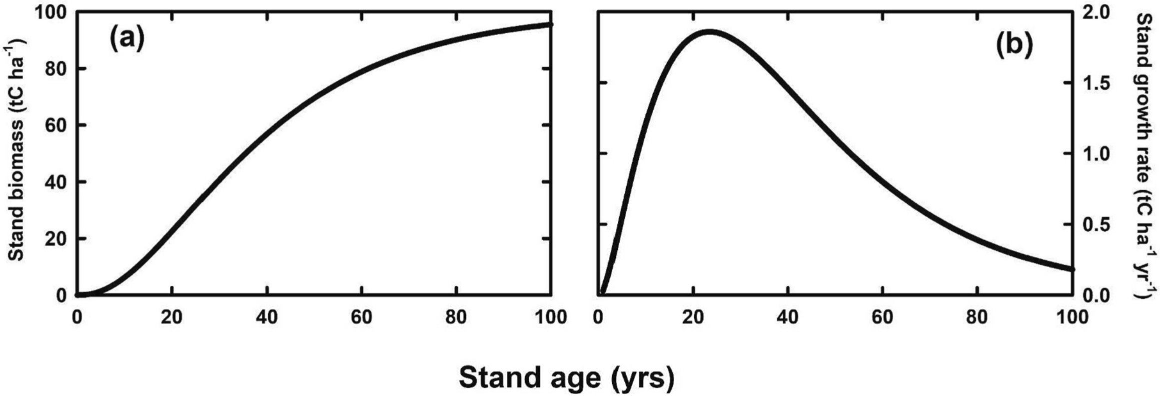

Fig. 3. Typical pattern of C stocks showing: (a) forest biomass over time; (b) the derived rate of stand growth (b). These curves show stylised relationships to illustrate the key features of forest growth. All forests follow this basic pattern, but there are large differences in maximum C storage, growth rates, and the timing and steepness of the growth peak (e.g., Yuan et al., 2012; Poorter et al., 2016; Gundersen et al., 2021).

forest biomass growth and subsequent C transfer to soil organic matter pools are currently playing an important role in the global C cycle and have the potential to contribute to climate change mitigation.

The biosphere has clearly played an important role in the past and is continuing to play an important role in current global C budgets, such that growing new forests or preserving and protecting existing forests could usefully augment existing C stocks. Forests can be managed to maximise C stocks by preserving existing forest cover, especially where forests have a high standing biomass, or by establishing new forests on currently non-forested land. However, there is a limit to the potential contribution that on-site C storage can make to global C cycles because the C stocks that can be stored on any area of land are finite (Fig. 3).

The total amount of C stored in a forest at any given time determines its role in preventing or contributing to climate change. Young forests grow rapidly and absorb C at higher rates than old forests, but older forests generally have larger C stocks. A forest's effectiveness in preventing climate change is determined by its C stocks rather than the rate of C uptake, as the C stored in the forest would otherwise be in the atmosphere. Any C stored in wood products or used to substitute for fossil fuels contributes to this overall benefit (see below for more details).

Fig. 3a shows the C stocks in the standing biomass of a typical forest over time, and Fig. 3b shows the annual growth rate of C stocks. A young forest stores little C, but it may grow rapidly and accrue more C. Eventually, growth and C uptake of any stand ceases as a forest approaches its maximum size. While a mature forest may no longer be growing, the C in the forest is kept out of the atmosphere. This is the valuable contribution to climate-change mitigation of a forest.

In practice, this growth pattern is often disrupted by natural factors or forest management. Natural disturbances can include fire, wind damage or pests and diseases (Kurz and Apps, 1999; Thom and Seidl, 2016; Watt et al., 2019). When a forest is harvested and timber is removed, its on-site C storage is greatly reduced. However, coarse roots and surface litter can continue to retain substantial amounts of stored C until these components decompose and return C to the atmosphere. Different natural disturbances lead to varying patterns. Fires, for example, often results in the release of most above-ground biomass, while other disturbance factors typically remove less C immediately but damage or kill trees, thereby preventing further growth and biomass accumulation. Existing biomass can remain on site until it decomposes.

2.2. *The global mitigation potential of tree planting*

Trees accumulate C at different rates, depending on climate zones, soil properties, species and management. For example, in warmer climates, trees tend to grow faster than in colder regions (Ryan, 2010; Baldocchi and Penuelas, 2019), and most broadleaved species (e.g., oak) grow more slowly than many coniferous species (e.g., Sitka spruce or radiata pine; Hamilton and Christie, 1971; CABI, 2013). Planted trees can also become established more quickly than trees that regenerate naturally (Ackzell, 1993). The growth rate of forests, however, is not the only consideration for C sequestration, and if natural forests remain undisturbed, they can ultimately store more C than plantation forests due to their more complex stand structure and because managed forests are typically harvested before they would reach their maximum size (Cook-Patton et al., 2020; Waring et al., 2020). The maximum storage capacity of trees also varies across the world, with moist temperate forests capable of the highest C storage, followed by tropical forests. Boreal forests typically store the least C (e.g., Keith et al., 2009; Cook-Patton et al., 2020).

When new forests are established on treeless land, the C stored in biomass and soil organic C (SOC) will typically increase (e.g. Yang et al., 2011), thus drawing down atmospheric CO_2. While growing or regrowing a forest will increase the standing C in biomass, there can sometimes be SOC losses (e.g., Matthews et al., 2020; Paul et al., 2002; Zhou et al., 2022), which can offset biomass C gains. Plantations established on peatlands present a special case, and more C can be lost from peat when peatland is drained for tree planting than can be sequestered in the above-ground biomass of planted trees (Friggens et al., 2020; Mayer et al., 2020). Additionally, forests' SOC is typically less protected by mineral association than SOC in agricultural and grassland systems and may become more vulnerable to warming (Lugato et al., 2021). The net C balance of tree plantings can sometimes even be negative on soil types with high SOC levels (Matthews et al., 2020).

Bastin et al. (2019) estimated the biophysical potential for tree growth across the world and concluded that 900 million additional hectares of forest could be planted on land that would be capable of supporting forests and is not already covered by forests or used for other essential services such as agricultural land or human settlements. An additional 900 million hectares would represent a $>$ 25 % increase in global forested area. These forests could sequester an additional 205 GtC (= 750 $GtCO_2e$) at maturity. However, others have criticised these estimates as being too optimistic, especially by suggesting that trees could be planted in areas where forests do not naturally occur (Veldman et al., 2019).

The IPCC Special Report on Climate Change and Land reviewed the relevant literature, and reported a range of estimates of carbon sequestration from reforestation and forest restoration of 1.5–10.1 $GtCO_2eq$ yr^{-1} (Smith et al., 2019a). The IPCC AR6 report gave a mitigation potential for the restoration of forests, peatlands, coastal wetlands, savannas and grasslands of 3.9–13.1 $GtCO_2eq$ yr^{-1} (calculated up to a marginal abatement cost of 100 US\$ tCO_2e^{-1}) but only about 0.65 $GtCO_2eq$ yr^{-1} have actually been delivered over the 2010–2019 period (Nabuurs et al., 2022). Other global estimates have explicitly separated reforestation (planting trees on former forest land) from afforestation (planting trees on land not formerly supporting forest) – with reforestation providing a much greater aggregate C sequestration potential of 3 $GtCO_2$ yr^{-1} (for a marginal abatement cost up to 100 US\$ tCO_2e^{-1}). Reforestation was also shown to have greater co-benefits for biodiversity, air, water and the soil (Griscom et al., 2017; Smith et al., 2022).

However, C in tree biomass is inherently vulnerable to loss (e.g., Hermoso et al., 2021). This is seen most dramatically through forest fires (e.g. Dass et al., 2018) that are becoming more prevalent and severe (e.g., Canadell et al., 2021a; Descals et al., 2022). Less dramatic, but just as devastating, can be C losses after tree death from drought, pests or diseases (e.g., Kurz et al., 2008b), with the mountain pine beetles in northern North America being a widely studied example with huge implications for forest C storage (e.g., Kurz et al., 2008a).

Future global change may make even wider tracts of forest vulnerable to these kinds of disturbances, with associated losses of stored C. New forests, especially if they are planted in areas with unsuitable current or future climatic conditions, may be particularly vulnerable to extreme events (droughts, fires and floods) and, thus, to C loss with such events becoming more prevalent in a warming climate. If any beneficial C storage in new forests is vulnerable to unintended loss in future, this vulnerability needs to be factored into the assessed benefit of any planting efforts (e.g. Dass et al., 2018).

2.3. CO_2 feedbacks through the global carbon cycle

From an atmospheric point of view, sequestering C in trees and retaining it in storage beyond the end of any assessment horizon is equivalent to avoiding fossil-fuel CO_2 emissions. However, if C is sequestered only temporarily before trees are cut (or die inadvertently through fires, drought, pests or diseases), and the stored C is released again, it is more complex to assess the climate-change mitigation benefit of that temporary storage.

Fig. 4 presents some illustrative simulations of the effect of 1 tC sequestered in 2020 with possible subsequent reversal. These simulations show the consequences of the release of that C in later years for radiative forcing, temperature and cumulative warming (Fig. 4).

When C is taken out of the atmosphere (in 2020), it reduces the atmospheric CO_2 concentration, thus reducing the driving force for CO_2 uptake by the oceans. Consequently, the oceans will absorb less C from the atmosphere than they would have without the C sink. Because of the reduced ocean uptake, the reduction of atmospheric CO_2 continuously diminishes from the initial draw-down at the time of C removal (Joos et al., 2013), with an effect on radiative forcing (Fig. 4b). If the initial C sequestration is reversed in later years, it leads to higher atmospheric CO_2 concentrations and, consequently, to higher radiative forcing than if C had not temporarily been removed from the atmosphere (Korhonen et al., 2002). These effects on radiative forcing are not proportional to the effects on atmospheric CO_2 because radiative forcing per unit of CO_2 (radiative efficiency) diminishes over time in line with increasing background CO_2 concentrations (Reisinger et al., 2011).

Changes in radiative forcing lead to corresponding changes in global temperatures, with ultimate temperatures actually being increased slightly through temporary C storage (Korhonen et al., 2002; Kirschbaum, 2003, 2006). This counter-intuitive outcome means that temporary storage and subsequent re-release of C will lead to slightly elevated future temperatures (Fig. 4c). Climate-change impacts can also be quantified through calculating cumulative warming (Fig. 4d). In contrast to future temperatures, cumulative warming will be reduced by temporary C storage even if the storage is subsequently reversed. The extent of this beneficial reduction increases with the length of time over which C is kept out of the atmosphere.

On balance then, is temporary C storage useful as a mitigation strategy? If one assesses climate-change impacts in line with global warming potentials (i.e., through summing radiative forcing), then even temporary C storage would be assessed as usefully reducing climate-

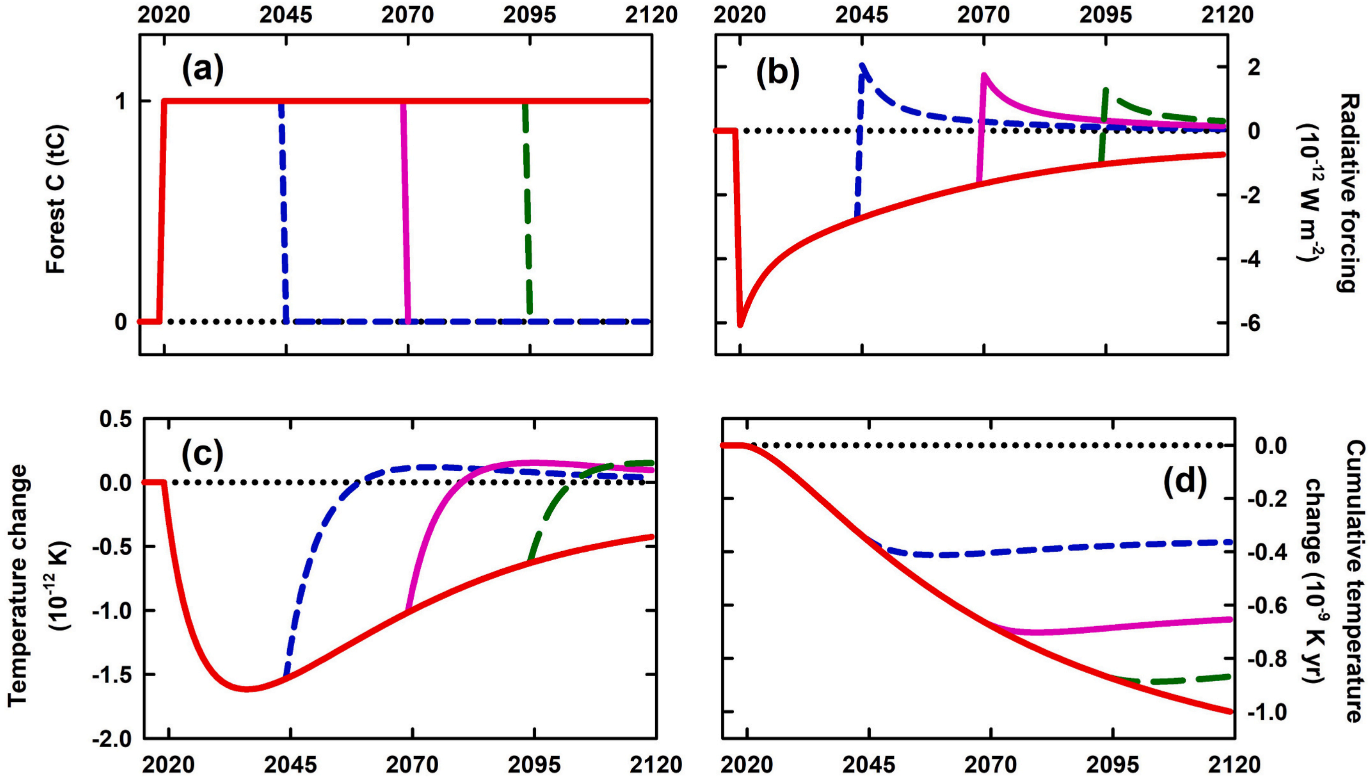

Fig. 4. The consequences of sequestering 1 tC in 2020 and releasing stored C after 25 (blue lines), 50 (magenta lines) or 75 years (green lines), or retaining it for >100 years (red lines). Shown are: (a) the initial perturbation; (b) effects on radiative forcing; (c) temperature changes; (d) cumulative warming. These simulations are based on the detailed calculation routine described by Kirschbaum (2017) and used SSP5 (see Fig. 1d) as background condition.

change impacts (essentially integrating the curves shown in Fig. 4b). Alternatively, one may aim to minimise future temperature increases, as stipulated in the Paris Agreement (UNFCCC, 2015). This can be assessed through the application of Global Temperature change Potentials (GTPs; Shine et al., 2005). Temporary C storage would make it harder to reach that goal as temporary storage would not reduce, but even increase maximum future temperature increases (Fig. 4c).

A more comprehensive assessment would be provided through the application of Climate Change Impact Potentials (CCIPs) that integrate the assessed climate-change impacts quantified through direct temperature changes (Fig. 4c), cumulative warming (Fig. 4d) and the rate of warming as well (Kirschbaum, 2014). This would result in assessed climate-change mitigation benefits for temporary as well as permanent C storage in trees. The assessment of any climate-change benefits, therefore, depends strongly on the choice of assessment methods. The same on-the-ground action can be assessed as either beneficial or detrimental to climate-change mitigation based solely on the choice of assessment method (Brandão et al., 2019). It still remains an urgent task for the global research and policy community to resolve this dilemma and enable less ambiguous assessments of the usefulness of possible mitigation options to be made.

2.4. *Forests for wood products and bioenergy*

Up until the Industrial Revolution, wood was the main source of energy used by human societies. Over the past 200 years, fossil fuels have become increasingly dominant as the supply of energy (e.g., Smil, 2010). With growing concern about climate change, the world is showing increasing interest in replacing fossil energy, like coal, oil and natural gas, with alternative energy sources (IEA, 2022). This has led to a renewed interest in greater use of woody biomass for heat and electricity generation.

Tree plantings can include plantations managed for wood production. The C sequestered in sustainably managed plantations can be retained for many decades in harvested wood products, including in engineered structural timber products in mid-rise buildings (Himes and Busby, 2020; Mishra et al., 2022). Sustainability here refers to forest management that ensures that the long-term productive potential of these plantations is sustained. Global modelling suggests that C sequestered through the expansion of plantations and substitution of wood for steel and concrete could deliver mitigation benefits of up to 900 $MtCO_2e$ yr^{-1} if 50 % of new urban buildings were made from engineered timber (Mishra et al., 2022). C is even retained in decommissioned wood products that are deposited in landfills (Ximenes et al., 2015). Alternatively, wood products could be buried in specially constructed wood vaults to ensure long-term C storage (Zeng and Hausmann, 2002). While average C stocks per hectare are typically lower in plantations than in mature forests, the mitigation benefits of production forests can accumulate with each harvest as new products are added to the global pool of wood products and their subsequent waste-stream stocks in landfills. Alternatively, some residues from harvesting and wood processing can be used for renewable energy generation to substitute for fossil fuels (e.g. Whittaker et al., 2011; Siarudin et al., 2023).

However, despite its renewable nature, the use of tree bioenergy as a strategy for climate change mitigation has been controversial and under close scrutiny over the past two decades. In Europe, concerns have arisen due to increased imports of US forest biomass into the EU (e.g. Junginger et al., 2008; Moiseyev et al., 2011; Lamers et al., 2015). While some studies have heralded forest bioenergy as an effective climate mitigation strategy (e.g., Gustavsson et al., 2017; Petersson et al., 2022), others have demonstrated that it is counterproductive, and that greater climate-change mitigation could be achieved if wood were kept in forests instead of being harvested for energy generation (e.g., Soimakallio et al., 2022). These studies suggested that the displacement of alternative products by wood products, like bioenergy, contributed less to climate-change mitigation than maintaining the C stocks of standing forests and maintaining their ongoing sink capacity.

Cowie et al. (2021) addressed these divergent findings by emphasising the need for system-level perspectives when studying the effects of climate-change policy measures. Studies need to consider the effects on forest C stocks, including C in residues and the soil, and on the energy and building sectors, as well as on agricultural land use. Climate effects of forest-based bioenergy depend on factors such as the alternative fates of the biomass, the substituted energy sources, and rates of forest regrowth. Studies that have applied a systems approach have generally found that forests managed for production of long-lived timber products, where residues are used for energy production, can provide greater long-term climate-change mitigation benefits than forests that are not harvested (e.g., Nabuurs et al., 2007; Ximenes et al., 2012; Smyth et al., 2020; Forster et al., 2021).

Assessing the merits of forest-based bioenergy as a strategy for climate-change mitigation is further complicated by the use of different assessment methods. Brandão et al. (2019) demonstrated that a scenario of converting a forest to a bioenergy plantation could be assessed as being either better or worse than using an equivalent amount of fossil fuels, depending entirely on the GHG metric used for the analysis. A scientific consensus on metrics for assessing the climate benefits of temporary C storage has not yet been achieved (e.g., Marland and Marland, 1992; Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008; Brandão et al., 2013, 2019; Parisa et al., 2022). This is a fundamental problem for rational policy making: while there is no consensus on appropriate metrics for quantifying climate-change impacts, it remains impossible to objectively determine optimal mitigation pathways.

Bioenergy is an important part of most scenarios that limit warming to <2 °C, particularly through Bioenergy with Carbon Capture and Storage (BECCS), which can deliver CO_2 removals (Nabuurs et al., 2022). The mitigation potential of BECCS is estimated at 0.5–11 $GtCO_2e$ yr^{-1}, which would require establishment of large areas of woody biomass crops, a form of forestation[2] that would need to be carefully managed to avoid risks to food security and biodiversity (Babiker et al., 2022). Woody biomass could also be converted to products such as biochar, bio-based chemicals and plastics, or building materials. This form of CO_2 capture and use in various products is described as Bioenergy with Carbon Capture and Utilisation (BECCU) and is now gaining increasing attention (Koytsoumpa et al., 2021).

2.5. *Climatic effects beyond modifying CO_2*

With careful planning and implementation, forestation can provide local climatic benefits in addition to C uptake. Potential benefits include shade, local evaporative cooling, and possibly even increasing precipitation (Syktus and McAlpine, 2016; Yosef et al., 2018; Stavi, 2019). However, at the global scale, forestation can also have adverse consequences. The best-understood secondary effect is a change in the reflectance of shortwave radiation (albedo). Forests typically absorb more radiation (lower albedo) than most other types of land cover and thus increase net radiation absorption that contributes to global warming (Bonan, 2008; Davin and de Noblet-Ducoudre, 2010). The albedo effect can be quantitatively important and therefore needs to be included in any assessment of the overall climate-change mitigation benefit of forestation (Bright et al., 2015; Favero et al., 2018).

The albedo effect can be particularly strong when snow covers the ground which greatly amplifies the albedo difference between forests and other vegetation (Betts, 2000). In cold and snow-covered regions, tree growth and C storage may also be small so that albedo-induced warming may then be greater than the cooling effect from increased C

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[2] The term forestation covers both afforestation (planting trees on previously unforested land) and reforestation (planting trees on land that had previously been forested).

storage. Forestation in snow covered boreal regions, therefore, can have an overall warming effect, whereas in tropical and temperate regions without snow cover, the albedo effect is less important, and forestation is more likely to have a net cooling effect (Betts, 2000; Bala et al., 2007; Jackson et al., 2008; Davin and de Noblet-Ducoudre, 2010; Kirschbaum et al., 2011; Cherubini et al., 2012). For example, Kirschbaum et al. (2011) estimated that in a temperate *Pinus radiata* forest in New Zealand, averaged over a whole rotation, the albedo-induced warming would offset 17–24 % of the cooling effect of C storage.

In some dryland regions, the albedo-related warming from forestation may also outweigh the cooling effect of C sequestration with the change from a light and highly reflective land surface to darker tree canopies that absorb more radiation (Rotenberg and Yakir, 2010). Using high-resolution spatial analysis of global drylands, Rohatyn et al. (2022) identified 448 Mha of global drylands as suitable for forestation. However, while this land could sequester ~32.3 GtC by 2100, two thirds of that C gain would be negated by the associated albedo-related warming.

Other effects of forests are more complex. Forests create more surface roughness, which warms the atmosphere through convection of more sensible heat from the surface to the atmosphere (Baldocchi and Ma, 2013; Lee et al., 2011; Rotenberg and Yakir, 2010). Forests typically also lose more water through evapotranspiration than grass swards (van Dijk and Keenan, 2007). Both these effects can generate local cooling but are matched by warming elsewhere in the atmosphere so that effects on the overall energy balance of the Earth as a whole are small, but these increased fluxes of water vapour and sensible heat into the atmosphere alter atmospheric circulation patterns and cloud formation in the atmosphere (e.g., Findell et al., 2007).

Many tree species emit volatile organic compounds such as isoprene and other terpenes into the air (Peñuelas and Staudt, 2010). These chemicals can form atmospheric aerosols with complex climate effects. However, given their relatively low emissions and short atmospheric lifetimes, their overall net climate effects tend to be small compared with C uptake and albedo changes (Peñuelas and Staudt, 2010).

Many forests experience periodic fires on decadal to centennial timescales (e.g., Randerson et al., 2005), with corresponding climate impacts. Wildfires may release much of the carbon that has been sequestered over many previous years and can damage or completely destroy forests, thus preventing further CO_2 uptake. Wildfires can also emit methane, nitrous oxide, aerosols, ozone precursors and substances like black C (Liu et al., 2017). Fires also change surface albedo. Immediately after fires, the ground is often blackened by char, leading to high radiation absorption (Randerson et al., 2006). As vegetation starts to regrow, lighter-coloured patches of grasses and shrubs develop first. As these vegetation types reflect more solar radiation, they can have an initial cooling effect until the vegetation thickens and darkens again and absorbs more radiation (Randerson et al., 2006).

2.6. Non-climatic effects of planting trees

Tree planting has a range of non-climate effects (or ecosystem services), with a range of co-benefits or trade-offs, depending on the mix of trees planted, where they are planted, on which soil type, and how they are established and managed. Some of these non-climatic effects are positive, such as enhancing biodiversity (e.g. Chazdon, 2008; Watson et al., 2018; Di Sacco et al., 2021; Seddon et al., 2021), reducing erosion, forming windbreaks and animal shelter, providing aesthetic benefits, or producing economic products (e.g. Leakey, 2014; Monckton and Mendham, 2022). Planting trees near buildings can help to cool homes through shading and evapotranspiration, and forests can help sustain water quality (van Dijk and Keenan, 2007). Forests can enhance the control of soil-erosion and sustain biodiversity, with natural forests being more effective than managed plantations (Watson et al., 2018; Hua et al., 2022). Landscapes of natural vegetation also deliver positive health and social benefits through recreation and opportunities for spiritual enrichment (Bach Pagès et al., 2020).

Effects of forestation can also be negative, such as reducing soil water contents (van Dyke and Keenan; Filoso et al., 2017; Tölgyesi et al., 2020, 2023) and depleting groundwater reserves (Jackson et al., 2005). Land use for growing forests also competes with food production and reduces native species habitat, and, as forests usually employ fewer workers than agricultural activities, they tend to weaken rural economies (Smith et al., 2019b) and can cause other socio-economic conflicts (Seddon et al., 2021). In drier regions, forests can also increase the probability of wildfires, especially if fire-prone eucalypts and conifers are grown (e.g. Cruz et al., 2018; Fernández-Guisuraga et al., 2023).

Ecological benefits of tree planting will depend on the vegetation grown in a planted forest (e.g. Chazdon, 2008; Di Sacco et al., 2021; Tölgyesi et al., 2021). Planting indigenous forest species to replace agricultural fields can enhance ecological values by improving regional biodiversity and ecosystem integrity. In contrast, establishing commercial tree species in place of natural grasslands or other unique vegetation can reduce biodiversity and ecological values (Parr et al., 2014).

It is important to also consider the effect of tree planting on global change drivers other than climate change. Global change can affect ecosystems through alteration of land cover, disruption of water and nutrient cycles, invasions by exotic species, overexploitation of natural species, and direct effects of atmospheric CO_2 enrichment (Vitousek, 1994; Sage, 2020). Collectively, these other drivers represent threats to biodiversity that are as large, or larger, than climate change (Sala et al., 2000). Attempts to mitigate climate change through tree plantings need to also consider effects on these other global change drivers to ensure that planting schemes provide benefits across all ecosystem services.

If plantations are specifically designed to develop high ecological integrity and species diversity, they can offset loss of natural habitats elsewhere and help preserve regional biodiversity (Chazdon, 2008; Hua et al., 2022). They could also provide climate refugia and corridors for species migration in a changing climate, while enabling robust metapopulation dynamics, which will buffer against species loss (e.g. Donald and Evans, 2006; Keppel et al., 2012). In contrast, single-species forestry plantations, especially of exotic species that are managed to maximise C gain and wood production, could reduce natural habitat, contribute to habitat fragmentation and accelerate species loss. Natural grasslands for example, have been extensively converted to croplands, pastures, agroforestry and production forestry such that much of the remaining natural grasslands are now threatened (Bond and Parr, 2010). Because of their perceived low commercial and ecological value relative to forests (Tölgyesi et al., 2021), low-productivity grasslands are prime targets for afforestation, thereby contributing to further grassland loss (Parr et al., 2014).

Tree plantations should, therefore, be evaluated in terms of their overall impacts on ecosystem services that consider the whole suite of global change drivers. If they are effectively designed and managed, forest plots can provide a range of beneficial ecosystem services and mitigate not just climate change but other aspects of global change as well (Chazdon, 2008; Ciccarese et al., 2012; Di Sacco et al., 2021; Hua et al., 2022). This could magnify the benefits of tree-planting initiatives (Chazdon and Brancalion, 2019). By contrast, poorly designed and managed plantations may provide only marginal climate-change-mitigation benefits while aggravating the overall global-change impact on human and natural ecosystems (Bastin et al., 2019; Hua et al., 2022).

3. Conclusions

Forests across the world store a large amount of C, and increasing the forest area through targeted tree plantings will transfer C from the atmosphere to the biomass of trees. The resultant reduction in atmospheric CO_2 is then assumed to contribute to mitigating climate change. This simple logic has provided the impetus for a range of tree-planting initiatives by governments, companies, and individuals with the aim of offsetting damages caused by fossil-fuel emissions. However, new tree plantings have other impacts that also need to be considered in deriving a balanced assessment of the potential role and value of planting trees.

First, one needs to consider the potential non-permanence of C storage in forests. Fossil-fuel savings are essentially irreversible, but any C sequestered in trees can be released again in future years. This can occur either as part of a normal management cycle of commercial forests or inadvertently if wildfires, droughts or pests kill established stands of trees. Any such reversal of C storage can increase future temperatures compared to those that would occur without tree plantings (Fig. 4c). However, the benefits of temporary C storage would be retained in cumulative warming and would not be lost (Fig, 4d).

Sophisticated approaches need to be employed to assess whether temporary C storage increases or decreases overall climate change impacts. Use of different metrics can result in different assessed benefits, and the fundamental question of the quantification of climate-change impacts needs urgent resolution by the international science and policy community. Currently, there is no universally agreed methodology that is theoretically sound to quantify climate-change impacts resulting from changing greenhouse gas emissions. Without an appropriate methodology for quantifying impacts, it is not possible to objectively quantify the mitigation benefit of tree plantings. On the other hand, if forests are utilised to provide an ongoing stream of bioenergy or wood products to replace fossil-fuel based building materials, the C benefit can be equated with that of the replaced fossil fuel, which simplifies accounting and avoids the need to address issues of reversibility of benefits.

Newly planted forests affect the Earth's energy budget not only indirectly through the C cycle but also directly through the absorption or reflection of incoming solar radiation. As forests are generally darker and absorb more incoming radiation than most other land-cover types, this translates into an important warming effect of forests. This effect is particularly strong in snow-covered regions, where the warming effect of greater radiation absorption can fully negate the cooling effect of storing C. In regions without extensive snow cover, the albedo effect is less strong but can still negate a sizeable proportion of the C-storage benefit of tree plantings. This paradoxical and counter-intuitive effect means that locally, forests can have an important cooling effect that adds to the benefit of growing trees, while globally, forestation could contribute to global warming.

In addition to their role in climate change, planted forests have other effects on local ecosystem services, such as modifying water and nutrient cycles, preventing erosion and conserving biodiversity. These other effects are diverse and may be positive or negative, depending on the type and age of forests, their surroundings, and the nature of the alternative vegetation that may be grown on any specific site. This makes it difficult to provide generalisations of the net effect of tree planting on overall ecosystem services.

We therefore return to the questions we started with: considering all these factors, is tree planting good or bad? It clearly depends: many factors need to be considered that can add to, or detract, from the C storage benefit of tree plantings. And the importance of these factors depends on the details of the associated conditions. So, the question can only be answered in the specific circumstance of each newly proposed tree planting scheme.

We, therefore, suggest an approach for assessing the merits of each proposed tree-planting project (Sampson et al., 2000; Brown et al., 2000):

1) Determine the anticipated C-storage profile of the project over the assessment horizon (typically set at 100 years) compared to the C-storage profile of any alternative land use. This analysis should encompass projected forest-growth rates under the influence of specific soil, climatic and management factors. That analysis needs to also include any thinning and harvesting events and assess potential effects or vulnerabilities resulting from climate change.
2) Quantify off-site net fossil-fuel use in the C-storage profile. That can be either detrimental, such as fossil-fuel use for site preparation, fertiliser application or harvesting and wood processing, or beneficial if there is fossil-fuel substitution through wood products or bioenergy. Leakage is important, though, and the inclusion of off-site effects is only warranted if that can be associated with the establishment of a tree-planting scheme.
3) Extend the analysis by adding non-CO_2 radiative forcing, especially from albedo changes, but also from other greenhouse gases if there are any related net emissions.
4) Calculate overall radiative forcing from these drivers and resultant global temperature changes. An appropriate metric for quantifying climate-change impacts needs to be chosen, which could be GWP, GTP, CCIP (see Section 2.3), or some other metric. Use that metric to calculate the net climate-change mitigation effect of the planned project.
5) Combine the calculated net mitigation effect with an assessment of effects on other ecosystem services. If a project leads to changes in both net climate-change impacts and non-climate ecosystem services that are either both desirable or both undesirable, they would mutually reinforce each other. If their desirability conflicts, the effects need to be quantified, and a decision must be made on which is more important.

While such an analysis would result in the calculation of only vaguely defined 'mitigation units', it would allow comparison between different mitigation options as long as the same analysis protocol is applied.

We try to highlight that tree planting is neither universally good nor universally bad, and to provide some background information to enable appropriate decisions to be made in specific circumstances. Climate change is a critical issue facing the world both now and into the future. It is, therefore, important for the world to adopt and apply a dispassionate and objective assessment of the benefits and trade-offs of tree plantings in all specific circumstances to mitigate climate change most effectively and prevent adverse outcomes as much as possible.

CRediT authorship contribution statement

MUF Kirschbaum: Conceptualisation, Writing, Project Administration;
AL Cowie: Conceptualisation, Writing;
J Peñuelas: Conceptualisation, Writing;
P Smith: Conceptualisation, Writing;
RT Conant: Conceptualisation, Writing;
RF Sage: Conceptualisation, Writing;
M Brandão: Conceptualisation, Writing;
MF Cotrufo: Conceptualisation, Writing;
Y Luo: Conceptualisation, Writing;
DA Way: Conceptualisation, Writing;
SA Robinson: Conceptualisation, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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