Title: Synergies and trade-offs between tree cover expansion efforts within and outside forests to achieve climate, biodiversity and human well-being outcomes

Running title: Trees inside and outside forests

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Abstract:

Increasing tree cover is hailed as a leading climate mitigation strategy, yet there is increasing evidence that there may be trade-offs between trees in different parts of the landscape. Existing science, policy, and practice on natural climate solutions (NCS) assumes that trees outside of forests, for example on farms, homesteads, or in urban areas, are synergistic with forest conservation: if people have more access to trees outside forests, the thinking goes, they will use fewer trees in the forest, leading to forest conservation. However, recent evidence shows that trees inside and outside forests often serve different purposes and produce different ecological, social or economic outcomes. As a result, in many contexts trees outside of forests do not necessarily substitute for trees inside of forests, and in some circumstances, an increase in trees outside of forests could even contribute to forest loss. In this perspective, we review the existing evidence on dynamics and trade-offs of trees inside and outside forests to describe pathways that lead to trade-offs and synergies and identify critical research gaps that, if addressed, can inform the implementation of ecosystem restoration and climate mitigation programs and policies. These diverse pathways are not widely recognized in science, policy, or practice, leading to potentially unproductive policy investments and leaving significant research gaps that we identify in this paper. Additionally, there is a risk that tree planting programs that are not cognizant of potential trade-offs may have negative repercussions for forest conservation, biodiversity, carbon storage, and rural livelihoods. Recognizing pathways that lead to negative outcomes, and identifying research gaps that could anticipate or prevent such negative outcomes will help scientists, policymakers and practitioners move forward with more effective NCS.

Keywords: afforestation, trees outside forests, forest, tree planting, forest restoration

Introduction

Increasing tree cover has been hailed as a leading climate mitigation strategy[1–3]. Propelled by global initiatives and targets, such as the United Nations (UN) Decade on Ecosystem Restoration[4] (2021-2030) and the Bonn Challenge[5], a plethora of tree planting efforts are currently underway, with the goal of remaking global landscapes to store more carbon, as well as to provide benefits such as protecting biodiversity and improving the livelihoods of rural people[6–10]. These tree planting programs often include planting both inside forests and outside of forests — on farms, in non-forested ecosystems (savannahs, wetlands, and rangelands), and along roadsides, for example[11].

A working assumption of most programs appears to be that trees in one part of the landscape can be substituted for trees in other parts of the landscape. Yet, there is accumulating evidence that trees inside and outside forests serve different purposes and produce different outcomes[12–14], raising the risk that increased planting of trees outside forests may have negative repercussions for trees inside forests across spatial and temporal scales, and vice versa. Given the unprecedented scale of current tree planting efforts[9,10,15,16], greater understanding is needed of the potential for trade-offs and synergies between trees planted for different purposes in different parts of the landscape. We review the existing evidence on dynamics and trade-offs of trees inside and outside forests to identify critical research gaps that, if addressed, can inform the implementation of ecosystem restoration and climate mitigation programs and policies.

Box 1:Terminology

Various Definitions of forests:

According to FAO, a forest is a land with tree cover of more than 10% in an area of a minimum of 0.5 hectares[17].

According to the International Union of Forest Research Organizations (IUFRO), a forest is a land parcel with a minimum of 10% tree crown cover. This land parcel must have formerly had tree cover and must be natural or artificially regenerated or afforested.[18]

Trees outside forests: *According to FAO, trees outside forests are trees on land not defined as forest and other wooded land. This may include agricultural land, including meadows and pasture, built-on land (including settlements and infrastructure), and barren land (including sand dunes and rocky outcroppings). It may also include trees on land that fulfils the requirements of forest and other wooded land except that: i) the area is less than 0.5 ha; ii) the trees are able to reach a height of at least 5 m at maturity in situ but where the stocking level is below 5 percent; iii) trees not able to reach a height of 5 m at maturity in situ where the stocking level is below 10 percent; iv) trees in shelterbelts and riparian buffers of less than 20 m width and 0.5 ha area.*[19]

Forest landscape restoration: *According to the International Union for Conservation of Nature (IUCN), Forest landscape restoration (FLR) is the ongoing process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes. FLR is more than just planting trees – it is restoring a whole landscape to meet present and future needs and to offer multiple benefits and land uses over time.*[17]

Reforestation: *According to FAO, reforestation is the re-establishment of forest through planting and/or deliberate seeding on land classified as forest.*[17]

Afforestation: *According to FAO, afforestation is the establishment of forest through planting and/or deliberate seeding on land that, until then, was under a different land use, implies a transformation of land use from non-forest to forest.*[17]

Ecological Restoration: *According to the Society for Ecological Restoration (SER), Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*[20].

The cost-effectiveness and the opportunity for large scale deployment have made increasing tree cover a popular natural climate solution (NCS) (Figure 1)[21]. Governmental efforts to meet their nationally determined contributions include some of the largest global tree planting initiatives[22]. For example, India's Green India Mission attempted to increase green cover by 5 million hectares by 2025 largely through tree planting initiatives[23], or Brazil's Green Growth Program that will plant 24 million trees by 2050[24]. Approximately 65% of tree planting organizations were established in the last 25 years, showing the quick rise in popularity of tree planting as an NCS[25] (Figure 2). Moreover, >50% of these organizations focus on planting new trees outside forests through activities such as agroforestry[15], which has contributed to 17% ± 3% or 6 million hectares in the increase in tree cover in the moist tropical regions from 1982 to 2015[12]. It is estimated that trees outside forest systems such as agroforestry, support approximately 900 million people, especially in the tropics[26], with significant direct material and economic benefits to people[27,28]. By contrast, only 20% of the tree planting organizations focus on established low-cost reforestation techniques such as natural regeneration of trees in previously forested lands[25], even though recent estimates have found that natural regeneration constituted 56% ± 3% of the tree cover increase in the moist tropics[12].

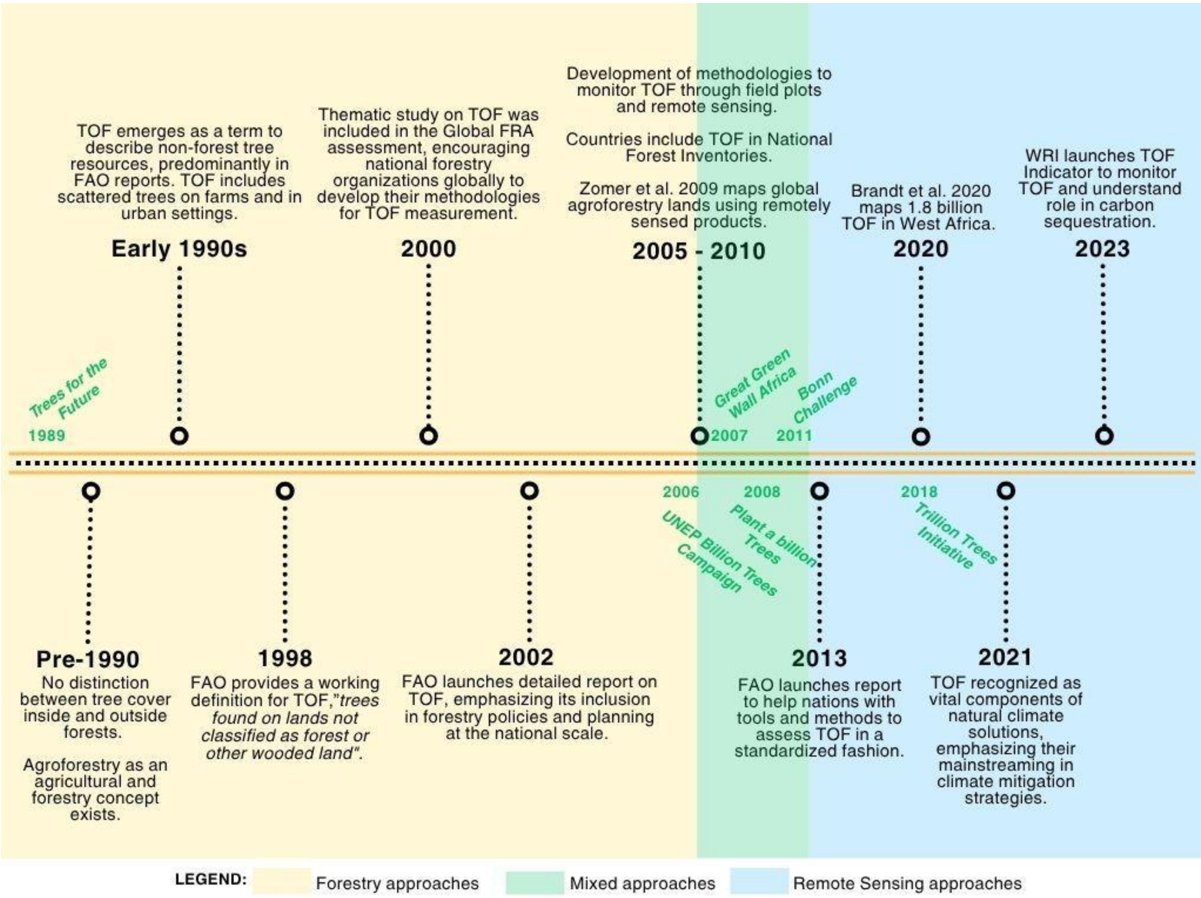


Figure 1: A timeline of the evolution of the concept of 'trees outside forests' and its measurement according to global organizations such as the United Nations Food and Agriculture Organization (FAO). Text in green indicates the year of major global tree-planting programs around the world. The colours represent the approaches or methods predominantly relied on to quantify the trees outside forests in a location. Yellows represent mainly forestry approaches of field-based measurements to create inventories of trees outside forests. Mixed approaches refer to the combination of field-based inventories and early days of remote sensing based tree cover classification and blue refers to primarily remote sensing

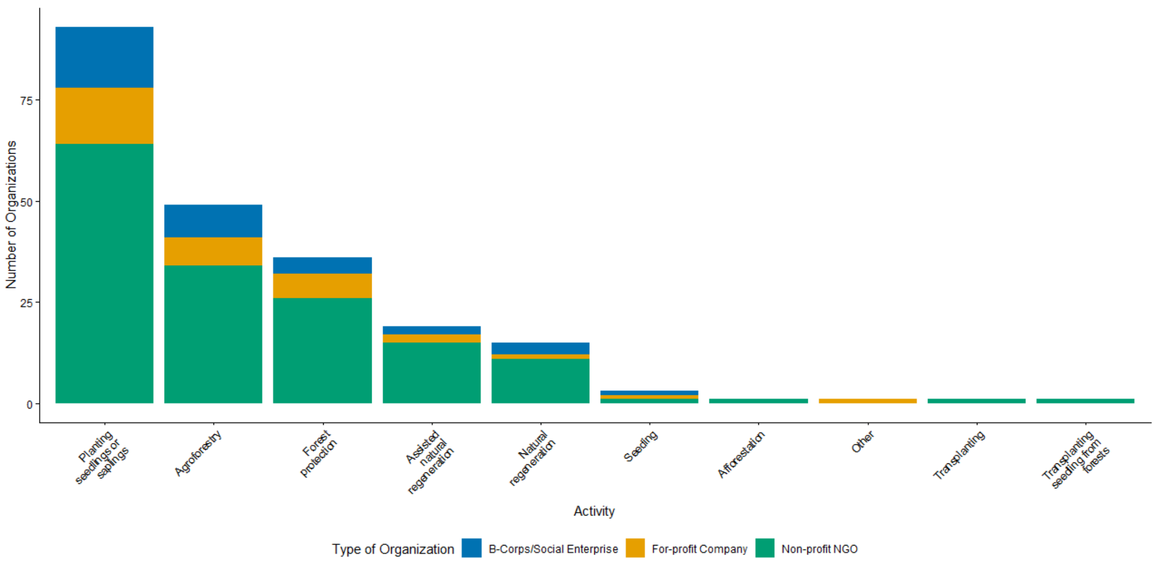
based quantifications of trees outside forests. TOF refers to trees outside forests; FRA refers to forest resources assessment; WRI refers to World Resources Institute. Studies referenced in the figure are [26,29].

Relationship between tree cover inside and outside forests:

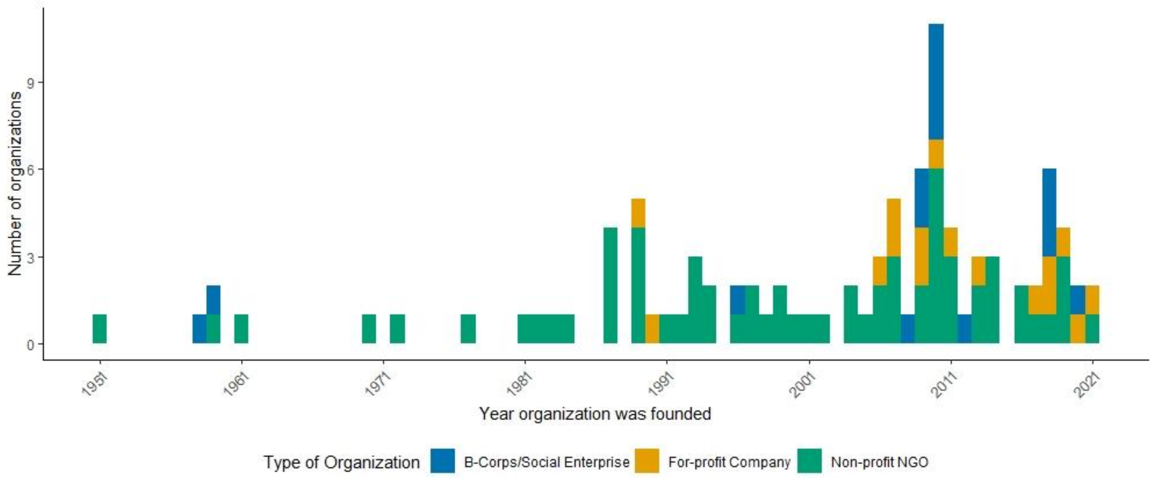
Assumptions driving tree planting efforts

In theory, the right trees (for example, native species) in the right places (for example, the appropriate ecosystem for those species) can provide a range of climatic, ecological, economic and social benefits for people[30–32]. However, in practice, trees are often thought to be good regardless of their position on the landscape or their role, in part because of their perceived potential as carbon sinks, with co-benefits [2,28,33]. Fulfilling climate and land restoration targets by increasing tree cover, mainly outside existing forest areas, is complex[8,34]. Many tree planting programs assume incorporating trees on farms and planting trees outside forests will reduce tree harvests and resource use from existing forest areas, potentially reducing deforestation and degradation and their associated carbon emissions[35–38]. However, trees inside and outside of forests may not be substitutes for each other, because they may provide distinct ecosystem services and be subject to different anthropogenic and environmental pressures, among other possible reasons[13,39]. Furthermore, the climate, biodiversity, and human wellbeing benefits that trees could provide, depend on the land use or ecosystem that they are replacing[40,41]. For example, grasslands and open natural ecosystems that cover approximately two thirds of the world have, for centuries, been classified as 'wastelands' or ecosystems less valuable than forests[42,43]. This misclassification has led to countless tree planting programs in countries like India, Brazil, and Madagascar to convert grasslands to 'forests' or plantations, impacting endemic flora and fauna[44–46]. Ambitious goals of planting as many as a trillion trees[15] assume that landscapes lack cultural, social, or environmental thresholds for tree cover, meaning more trees planted would result in increased tree cover both locally and globally[31,47]. This, in turn, assumes that tree planting activities are both additional (i.e. that adding seedlings or saplings leads to the growth of trees in places where they were not already growing) and do not lead to leakage (i.e. that planting trees in one place does not lead to loss of trees or forest cover somewhere else)[2,35,36,38]. These assumptions have not been widely tested, raising concerns for the future of existing and newly planted tree cover inside and outside forests. We argue that there is an urgent need for research that examines the dynamics of forest cover and trees outside forests[48] as there are potential social and environmental trade-offs between different trees in different places[12,13].

(a)



(b)



(c)

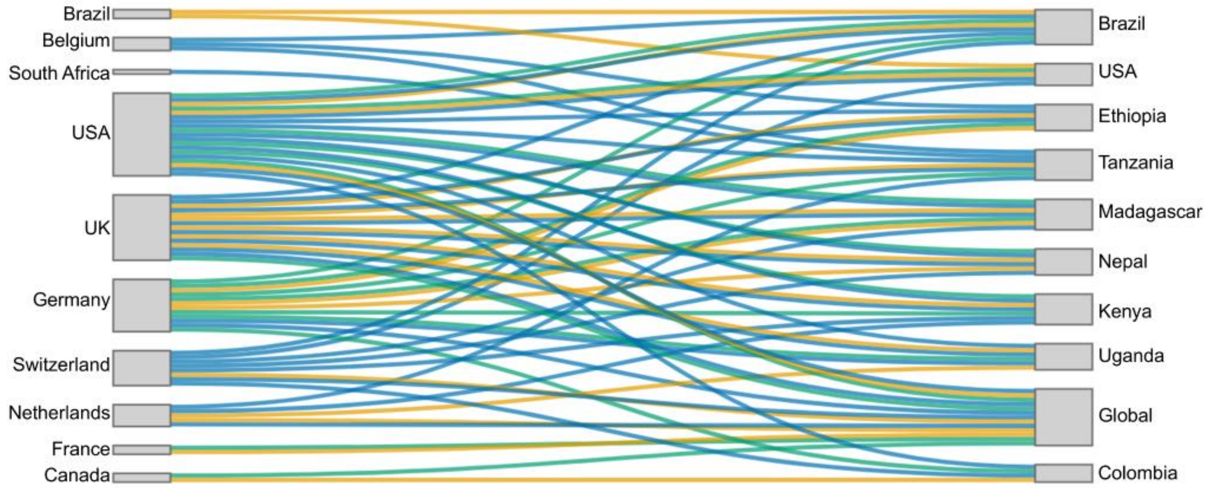


Figure 2: (a) Bar plot of the strategy of tree planting used by different types of organizations. (b) Bar plot of the year in which the tree planting organizations were registered or founded. (c) Sankey plot of the top 10 countries with the highest number of tree planting organizations registered and the countries where they carry out tree planting activities. For (a), (b) and (c), the colours represent the type of organization. Data sourced from Schubert et al. 2024[25].

Dynamism of tree cover inside and outside forests

Historically, without long-term and high resolution remotely sensed data, the relationship between trees outside and inside forests could not be studied at the spatio-temporal scales required to understand the contextual factors that determine whether their relationship is **synergistic** (as most tree planting organizations assume) or **antagonistic** (the reality in some cases). Below we outline scenarios that describe synergism and antagonism at a local scale, but these interactions could exist at different spatial and temporal scales. The advent of high resolution satellite imagery and fine spatial and temporal resolution of socio-economic data can allow us to quantify the dynamic relationship between trees inside and outside forests and examine socio-environmental trade-offs associated with different relationships at different spatial scales. For example, most recent global evidence (2000 to 2012) shows that tree plantations, which are classified as trees outside forests, have replaced 9.2% of protected forests and natural ecosystems, indicating that in certain cases trees outside forests may directly replace natural forest cover[48]. Previously, without the ability to distinguish tree cover types, an increase in tree cover after a period of loss would be considered a 'forest transition'[49]. However, with distinctions in tree cover, we can better identify the drivers of the transition pathways (for example, adoption of agroforestry or plantations) and their potential outcomes[50].

The dynamics between trees outside forests and trees inside forests could be viewed with the same lens as the dynamics between two distinct land covers; for example, similar to the dynamics of agriculture and forest cover, which are often viewed as competing land uses[51–53]. If there is a commercial value to trees outside forests, especially cash tree crops such as palm oil, coffee, cacao, or timber species, there would be an incentive to reduce forest cover to increase trees outside forests systems[40,54,55]. Furthermore, plantations or 'forest plantations' for timber production and non timber products can provide substantial economic and material benefits[56], while on the other hand, increasing trees outside forests could result in a change in attitudes toward the environment and thus there are cases when both trees outside forests and forest cover can increase simultaneously[54].

Case studies from the last few decades shed light on outcomes of varied trees outside forests- trees inside forests relationships. Figure 3 provides a hypothetical change in different tree cover types over time, both inside and outside forests. Each scenario marked in Figure 3 represents a unique relationship, of which there can be several.

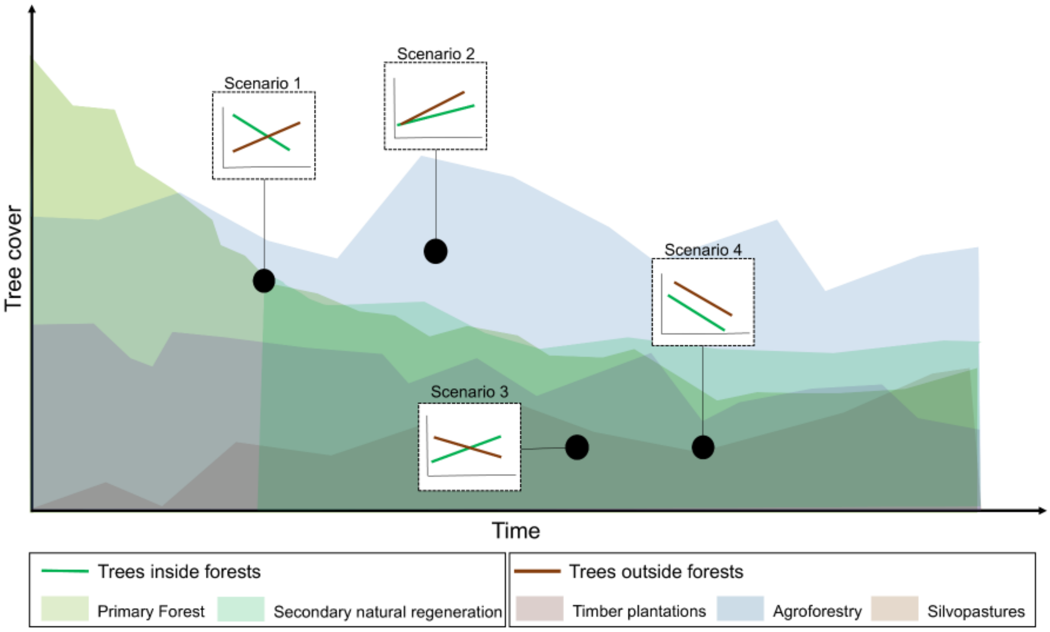


Figure 3: Scenarios of relationships between trees inside forests (primary forest, secondary natural regeneration) and outside forests (timber plantations, agroforests, silvopastures). The scenarios represent simplified synergistic trends (scenarios 2 and 4), antagonistic trends (scenarios 1 and 3).

Antagonism (Scenario 1 and 3)

In these scenarios, increasing trees outside forests leads to decreases in trees inside forests and vice versa. Recent evidence from China shows that trees outside forests, predominantly commercial plantations, often replace native vegetation or forests, leading to an increase in trees outside forests with an accompanying decrease in trees inside forests. China's National Forest Protection Program and the Green-For-Grain Program began in the late 1990s, spending approximately $19 and $47 billion respectively, until the early to mid 2010s[57]. An examination of tree cover change from 2000 to 2015 in China's Sichuan Province revealed incentives to convert croplands to monoculture tree plantations (~ 50% of converted croplands) by clearing existing regenerating forests on farmlands. Due to a large emphasis on active tree planting, a mere 1.5% of the cropland loss was associated with native forest increase through natural regeneration[57]. Ultimately, a gross tree cover gain of 32% in the region hid a ~7% loss of native forest[57], implying potential trade-offs between forest conservation and active restoration.

Another afforestation subsidy, the Decree Law 701, in Chile, has been shown to negatively impact biodiversity due to the creation of plantations in biodiverse forests[58]. In Chile's Valdivia region, where 53% of new plantations were created through the conversion of temperate rainforest, shows that often trees outside forests in the form of pulp or timber plantations are established by replacing native forest cover[59]. Mexico's *Sembrando Vida*[60], a national restoration and tree planting program displays a similar antagonistic relationship. For example, because of the program there has been a significant reduction in funding to national parks, which may have affected their ability to protect and monitor existing forest and non-forest ecosystems[61]. Additionally, although national reports suggest that 720 million trees have been planted as part of the program[60], evidence suggests that the program may have encouraged the deforestation of 72,000 hectares of forest land across the country[62], with a portion of it being caused by state-authorized burning[63].

We argue that tree cover changes in Scenario 1 can lead to contradicting outcomes for carbon sequestration. On the one hand, plantations are considered efficient means of sequestering carbon[64]. On the other hand, plantations are known to have substantial negative effects on biodiversity[65,66]. Emerging evidence shows that monoculture or species poor plantations may not be stable avenues to capture carbon in comparison to species rich forests or polycultures and may not be valuable to meet climate mitigation or biodiversity conservation goals[67,68]. Moreover, the carbon accumulation from planting trees outside forests may still be less than the carbon lost from deforesting, resulting in a net loss of carbon. Furthermore, trees outside forests could lead to an additional or alternative income for people[17,36], with material benefits, such as wood and wood fibre, but with limited biodiversity conservation value[66,70]. Plantations, especially proposed and incentivized by top-down government schemes, are often associated with negative outcomes for people's interactions and social relationships[27,71,72].

Synergism (Scenario 2 and 4)

In these scenarios, trees inside and outside forests increase or decrease together. For example, in Scenario 2, trees inside forests increase at the same time that trees outside forests increase. In

Southern Ethiopia, an increase of trees inside forests and trees outside forests over 14 years (1999 - 2013) took place due to the addition of trees, woodlots, and crops around homesteads[73], following two decades of deforestation. Since the 1970s, local people have used an exotic species, *Eucalyptus,* to increase tree cover around their homes to diversify their incomes through the sale of timber[73]. Moreover, this case study implies that trees outside forests alleviated pressure on existing forest, allowing tree cover to recover within forests.

In Southeast Asia, Teo *et al.* 2025[54] found that increasing agroforestry practices around areas of deforestation led to a reduction in the amount of deforestation over a six year period from 2015 to 2023. This study suggests that agroforestry (or, more broadly, trees outside forests) can coexist with forest fragments in mosaic landscapes that are often found in Asia. These decreases in deforestation are similar to observations of declining deforestation in parts of Latin America[74–76]. In Latin America decreases in deforestation as a result of agroforestry were not sustained, indicating that longer time frames may be needed to understand the relationships between trees inside and outside of forests. Many of the agroforestry tree species used commonly in Southeast Asia, including fast-growing timber species, such as *Acacia* or *Eucalyptus*, and tree crops, such as rubber and oil palm[54] are not native to that region and/or are managed with very high intensity. This may imply trade-offs for carbon and/or biodiversity benefits, as these trees may not provide good habitat for native species and/or be harvested quickly and thus provide limited long-term carbon storage[65,66].

An increase in trees outside forests and trees inside forests (Scenario 2) could result in more stable carbon capture than in Scenario 1, high biodiversity conservation value and possibly more positive outcomes for local livelihoods[27,69,77]. There can be considerable variability in the carbon capture based on the tree species composition[68], and thus diverse native trees outside forests can greatly enhance the carbon value of a landscape. For example, agroforests support higher avian biodiversity than monocultures of commercial crops, such as rubber and oil palm[78,79]. However, the addition of trees- even a minimum of six different species, especially to oil palm plantations can significantly enhance biodiversity and ecosystem functioning in these plantations[80].

Chile is an ideal case study for Scenario 4. A remote sensing study by Altamirano and coauthors measuring tree cover changes between 2000 and 2016 found an overall loss in tree cover, both trees outside forests and trees inside forests[81]. Over the duration of the study, although there was overall tree cover loss, 51% of tree plantation pixels (predominantly exotic species such as *Eucalyptus*[82]) were eventually replanted[81]. The other half of the plantation pixels returned to bare ground or shrubs and grasses. However, it is likely that over time these pixels too will be replanted. About 50% of the trees inside forest pixels also turned to bare ground and shrublands at the end of the time period studied, indicating clearing of forests for either plantations, agriculture, or natural regeneration. In the case of Scenario 4, it is possible that the relationship between trees inside and outside forests is not causal, and may be driven by commercial or industrial pressures or even misguided natural resource policies as noted in the case of Chile. Here, we assume that trees would be used regardless of where they are, inside or outside forests.

We predict that a decrease in both trees inside forests and trees outside forests in favour of other land covers such as agriculture and built up areas could lead to a decrease in carbon sequestration and biodiversity conservation value. However, with different land covers, there could be positive outcomes for people's livelihoods and social relations. For example, people may switch from forestry to agriculture, which could bring more income and improve their well-being.

Future directions to study tree cover changes and inform tree planting projects

This paper lays out widespread scenarios of relationships between trees inside and outside forests. Understanding the prevalence of different scenarios, their drivers as well as the nature of social-ecological interactions and outcomes within these scenarios are the key to improving efforts to increase tree cover and mitigating any negative effects of these efforts on people and biodiversity. In other words, the crucial question for those who wish to use trees to restore or promote tree-dominated ecosystems or improve human well-being using trees is: when are there synergies between trees inside and outside of forests? Identifying factors that contribute to synergistic scenarios, such as Scenario 2, and the timelines on which they occur will better enable policymakers, tree planting NGOs, and local communities to design programs that achieve their desired outcomes. On the other hand, it is equally important to understand the unintended consequences of well-meaning policies, programs and subsidies, as case studies from Mexico[62,63], Chile[58] and India[83] have shown. The most important gap in our understanding, however, is causality, which can be addressed through more rigorous experimental research and cutting-edge causal inference methods.

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