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Valuing the functionality of tropical ecosystems beyond carbon

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Land-based carbon sequestration projects, such as tree planting, are a prominent strategy to offset carbon emissions. However, we risk reducing natural ecosystems to one metric – carbon. Emphasis on restoring ecosystems to balance ecosystem services, biodiversity conservation, and carbon sequestration is a more appropriate strategy to protect their functioning.

Trees to promote net zero?

The escalating threat of climate change has spurred global commitments to achieve net zero emissions by the middle of this century [1]. To reach a balance between reducing emission sources and enhancing greenhouse gas sinks, land-based carbon sequestration is viewed as an important strategy to offset emissions, most prominently via nature-based solutions [2]. This, together with the commodification of carbon and the substantial growth of the voluntary carbon market, has resulted in a boom in the number of commercial tree plantation projects across tropical ecosystems with significant financial flows from private and public sectors towards carbon offsetting projects [3]. In practice, these offsetting projects most commonly take the form of increasing aboveground carbon, via woody biomass.

Typically, the tropics, dominated by forests and grassy ecosystems, such as grasslands and savannas, are regarded as some of the most suitable regions in which to maximise carbon sequestration (see Table S1 in the supplemental information online) due to favourable climatic and topographic conditions which promote rapid plant growth [4]. Tropical ecosystems are also highly biodiverse and offer billions of dollars in ecosystem services provision, such as acting as carbon sinks of ~1.26 Pg C per year [5], and helping sustain a large proportion of the most economically deprived parts of global society. In order to avert the climate crisis, tree planting commitments are ambitious but require a huge area of land. Assuming a single-species plantation productivity of 1.32 MgC/ha (www.bonnchallenge.org), an area of ~35 million km^2 (equivalent to the total summed area of the USA, the UK, China, and Russia) would have to be forested to sequester one year of emissions. If all the land area within the tropics was covered by tree plantations, we would only sequester ~1.7 years of emissions [6] (Figure 1).

Carbon-focused tree planting

Despite the broad range of ecosystem functions and services provided by tropical ecosystems, society has reduced value of these ecosystems to just one metric – carbon. Associated land-based carbon sequestration actions generally encompass interventions from natural forest regeneration, reforestation, agroforestry, exotic species plantations and afforestation, herbivore management, and fire abatement or a shift to early burning more typical of grassy ecosystems. It is broadly assumed that maximising standing carbon stocks also benefits biodiversity, ecosystem function and enhances socioeconomic co-benefits – yet this is often not the case [7]. Intact forests, relative to other forest states, present the most likely scenario where carbon stocks, biodiversity and ecosystem function can all be maximised, the strength of this relationship will depend on ecological context, spatial scale, and spatial extent [8]. Relatively high-standing carbon stocks can be reached in some timber plantations in tropical ecosystems [9] (see Table S1 in the supplemental information online), yet the negative effects of monoculture plantations are widely known. While they provide a carbon sequestration service and are economically valuable, the biodiversity of these plantations is often lower in comparison to their intact forests counterparts [7] (Figure 2A). Moreover, plantation monocultures (e.g., teak – *Tectona grandis* and eucalyptus – *Eucalyptus globulus* plantations) reduce various ecosystem functions from lowering streamflow to the acidification of the soil and reducing the growth of other local plants [10].

Intact savanna ecosystems have an evolutionary history shaped by interactions between grasses, droughts, fires, and herbivores (Figure 2B) [5]. Here, increasing woody cover represents structural homogenization and a reduction in the heterogeneity of ecosystem function and local adaptations. The disbenefits are stark for grassy ecosystems where increasing above-ground woody biomass generally represents a state of degradation (Figure 2B). Afforestation of grassy ecosystems prioritises carbon sequestration services over other multiple ecosystem services they provide (water, grazing land, nature-based tourism, and biodiversity) [4]. In this way carbon-focused tree planting exacerbates biodiversity loss, particularly of species adapted to open environments [11]. For example, in the Brazilian Cerrado (savanna) a 40% increase in woody cover resulted in a ~30% reduction in the diversity of plants and ants [11]. Afforestation or increased woody biomass also threatens critical ecosystem service provisions like forage for livestock on which many people rely, and threatens to reduce stream flow and deplete groundwater [10]. Catchment-based afforestation experiments in mesic grasslands demonstrate that afforestation reduced streamflow between 40% and 81% [10].

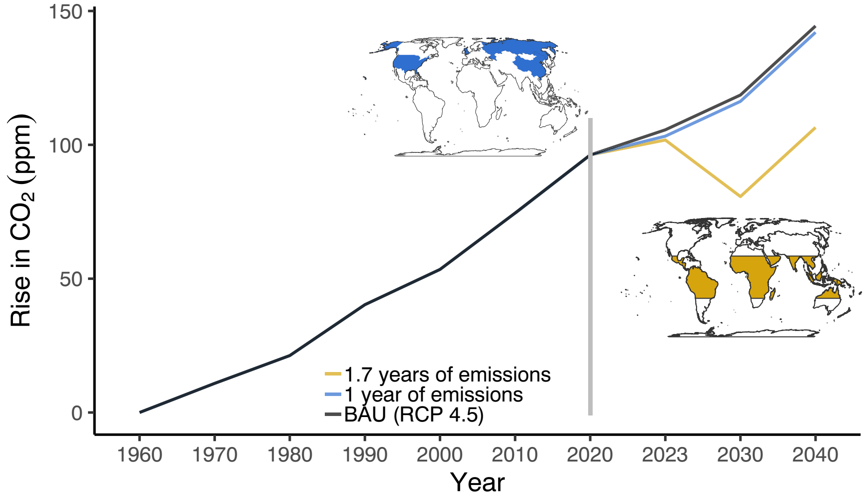

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Figure 1. Rise in current and future CO_2 from 1960 to present (source: co2levels.org) and from present to 2040 based on Representative Concentration Pathway (RCP) 4.5. Lines represent the business as usual (BAU) referring to the increase of emissions without significant tree planting efforts (black line), the scenario where one year of CO_2 emissions are sequestered by increasing tree cover (35 million km^2 forested needed; blue line and area in blue of inset map) and the scenario where tree cover expands the whole tropical area (23.5 to –23.5 degrees latitude; yellow line and area in yellow in inset map) and sequestered ~1.68 years of emissions. The grey vertical line centred in 2020 shows the hypothesised period where tree cover increases.

Forest and savannas provide ecosystem services and functions beyond carbon sequestration

Trade-offs between biodiversity and carbon capture occur across tropical ecosystems. Yet carbon capture only represents a small component of the pivotal ecological functions that tropical forests and grassy ecosystems perform such as exchanging carbon, nutrients, water, and energy [12]. The functioning of ecosystems is mediated by the traits of the species that inhabit them. These functional traits allow species to respond to environmental changes [13], to feedback on their environment, and to carry out ecosystem functions such as carbon fixation. Ecosystems that are compositionally and functionally diverse and heterogeneous have a higher resilience to environmental change impacts and can promote carbon sequestration [14]. Yet, in our quest for carbon sequestration, we are not achieving this. Instead, the bulk of tree planting commitments most commonly involve the establishment of agroforestry and tree plantations (mixed species and monocultures) where five tree species, *T. grandis* (commonly known as teak*), Swietenia macrophylla* (mahogany), *Cedrela odorata* (cedar)*, Grevillea robusta* (silk oak)*,* and *Acacia mangium* (black wattle), dominate the majority of projects with a focus on timber, pulp, and/or agroforestry [14]. By emphasising a particular ecosystem function at such large scales, we are effectively homogenising the functional trait composition of tropical ecosystems, for example, by selecting for species with fast carbon storage potential, we select for traits that confer rapid tree growth.

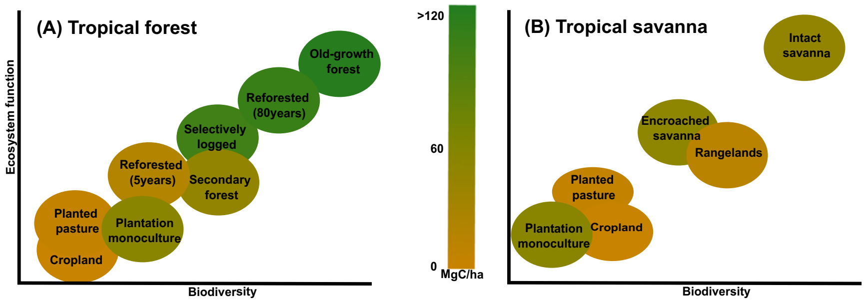

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Figure 2. Conceptual relationship between biodiversity, ecosystem functioning and carbon storage for tropical forests (A) and savannas (B) across pristine and human-modified landscapes. Carbon–biodiversity–ecosystem function cobenefits are most likely to be realised in intact or near intact forests although these relationships vary with spatial scale, extent and ecological context. However, carbon, biodiversity, and ecosystem function can all also be maximised across nonforested ecosystems such as savannas.

The presence of spatially extensive functionally similar landscapes, such as in tree plantations, both homogenises ecosystem processes and lowers ecosystem resilience to drivers of change (e.g., fires, pathogens, insects, and local droughts). An example is the mega-fires in Chile where monoculture plantations promote the spread of intense crown fires which then threaten indigenous non-fire-adapted forest remnants. Intact forests, in contrast to human-modified landscapes such as in tree plantations, have higher above- and belowground carbon storage and faunal complexity and are better buffered against the negative consequences of climate extremes. These intact forests also maintain a higher number of forest-dependent species, and have higher functional trait diversity and increased pollination and dispersal processes [8]. Similarly in grassy ecosystems, afforestation or increasing woody biomass produces structural and compositional homogenisation of the vegetation, and creates a distinct shift in plant functional trait composition. This shift erodes the reinforcing feedback loops that maintain ecosystem functions required for savanna existence; for example, trees shade out light-adapted C4 grasses, thus reducing the regular grass-fuelled fires, which are required to maintain savanna ecosystems. The loss of this feedback may also reduce carbon sequestration by (i) removing grass biomass which makes a significant contribution to the belowground carbon sink; and (ii) producing a shift in the ratio of carbon from belowground to aboveground where it is more vulnerable to disturbances like drought and fire. In contrast to (monoculture) plantation and afforestation, conserving natural ecosystems, maintains the local functional traits diversity pool, whilst also conserving high species taxonomic, functional, and phylogenetic diversity, which are elemental pillars of ecosystem resilience [13].

Other valuable ecosystem functions and services beyond carbon sequestration are less well quantified and need more direct support from economic incentives and from conservation initiatives (e.g., clean water provision, nutrient cycling, and pollination) [12]. Stopping the degradation of ecosystems globally and restoring degraded and transformed ecosystems to their natural state, and hence restoring their functional diversity, has the potential of sequestering ~9 Gt CO_2 per year by 2050 [15]. Such restoration and conservation approaches would maintain at the same time local ecosystem functions and services. Importantly, critical natural assets that provide a wide set of relevant ecosystem services, and that are largely in need of conservation efforts, occupy 30% of total land area, which coincides with biodiversity-rich and often largely intact natural ecosystems [12] such as those found across the tropics.

Forest and grassland functionality beyond carbon

The current trend of carbon-focused tree planting is taking us along the path of large-scale biotic and functional homogenisation for little carbon gain. Before these projects are initiated, an in-depth understanding on the impact of carbon-focused tree planting on biodiversity, function, and people's livelihoods is needed but clearly missing from a policy-making perspective. Despite claims that this is the case, accounting for negative impacts of carbon focused plantations, has not been widely operationalised as carbon is easy to measure at scale and is a commodity that is driving large economic benefits. In the case of savannas, this problem is exacerbated due to a persistent history of misclassification of ecosystems. The carbon market is also poorly regulated (e.g., tinyurl.com/GCJAGs), and thus there is little recourse when significant mal-mitigation actions happen. Ideally, we should be moving to a state where for any carbon project to be certified their additionality should surpass the benefits of conserving and restoring the ecosystem to their original state, so that not only carbon capture is maximised but also that no other diversity facet and ecosystem function and service is negatively impacted. Hence, an overarching view on maintaining original ecosystem functioning and maximising as many ecosystem services as possible should be prioritised above the ongoing economic focus on carbon capture projects. Current and new policy should not promote ecosystem degradation via tree plantations with a narrow view on carbon capture.

Overall, we argue that, aside from the obvious need to reduce fossil-fuel emissions, we should shift focus to conserving and restoring ecosystems. This strategy can contribute to both mitigation and adaptation goals while also supporting the provision of ecosystem services. There is a current financial incentive to maximise carbon gain and the current carbon-centric focus requires carbon additionality from ecosystems for them to be profitable. This can disincentive the protection of intact ecosystems and can lead to negative trade-offs between carbon, biodiversity, and ecosystem function. Conserving ecosystems and their functioning will only be possible by prioritising biodiversity beyond a single monetary-based metric such as carbon sequestration potential.

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Supplemental information

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