Forests and decarbonization – roles of natural and planted forests

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Highlights

- Natural forests store more carbon than plantation forests, due to complex stand structures and accumulation of carbon belowground and in the forest floor. These features take centuries to emerge. Mature natural forests provide significant additional benefits and must be conserved, whilst regeneration of secondary natural forests is promoted.

- Policy-makers must avoid generating " perverse incentives" that can compromise or even destroy existing carbon sinks in forests, savannas, grasslands and peatlands. Newly planted forests can create " carbon debts" that take significant time to be repaid.

- Afforestation is likely to mitigate emissions most effectively when trees are planted in formerly forested, high-productivity sites, commonly found in tropical or sub-tropical ecosystems. Planting species mixtures frequently increases productivity, reduces disturbance impacts, and enhances biodiversity relative to monocultures.

- Total carbon capture associated with afforestation and reforestation can be enhanced by substituting long-lived harvested wood products for steel, cement, and aluminum, and by using harvest residues as bioenergy to replace fossil fuels.

Forests established by reforestation (planting trees on formerly forested land) and afforestation (planting trees where they historically did not exist) can enhance the terrestrial carbon sink, thereby slowing accumulation of CO_2 in the atmosphere. However, the potential magnitude of carbon uptake by newly planted trees is a topic of intense debate. Reforestation and afforestation compare favorably with other negative emissions technologies in terms of carbon capture potential, although land and water requirements are often high (Smith et al., 2016). Forests also provide important ecosystem services and generate wood products that can displace more fossil-fuel intensive materials. However, as we discuss in detail below, realizing these co-benefits requires site-specific attention to forest management techniques, and careful consideration of the landscape context of new forests.

How Much Carbon Can Forests Capture?

Currently existing forests store ~45% of the organic carbon on land in their biomass and soils (Bonan, 2008). Together, extant old-growth and regenerating forests absorb ~2 gigatonnes of carbon (GtC) annually, making an important contribution to the terrestrial carbon sink (Pugh et al., 2019). A recent analysis suggested that planting trees on an additional 0. 9 billion hectares could capture 205 GtC (Bastin et al., 2019), which is approximately one-third of total anthropogenic emissions thus far (~600 GtC). However, it would take over 100 years to reach this C storage potential, assuming a typical C allocation rate into wood of 2 tC ha $^{-1}$ year $^{-1}$ (Bonan, 2008). Moreover, this figure likely over-estimates both the potential for forest carbon capture (Lewis et al., 2019a) and the availability of suitable land and water for reforestation (Veldman et al., 2019). More conservative approaches suggest that large-scale afforestation and reforestation efforts could remove between 40 and 100 GtC from the atmosphere once forests reach maturity (Lewis et al., 2019a ; Veldman et al., 2019) – an impressive quantity that nonetheless represents only a decade's worth of anthropogenic emissions at current rates.

Moreover, in assessing the effect of land C sequestration on atmospheric CO_2 it is essential to consider the " airborne fraction" (about 0. 45). A little less than half of the CO_2 that is emitted by human activities remains in the atmosphere, due to the uptake of C by the oceans and land. Similarly, if CO_2 is removed from the atmosphere by increasing tree biomass, the CO_2 concentration in the atmosphere declines by a little less than half of this amount, due to the release of C by the oceans and land. Assuming reforestation sequesters an additional 60–90 GtC in tree biomass, this would reduce atmospheric CO_2 concentrations by only 17–31 ppm (House et al., 2002). Conversely, converting all existing forests to grasslands or croplands would *increase* atmospheric CO_2 concentrations by 130–290 ppm, emphasizing the need to protect extant forest.

The potential for carbon capture via afforestation is likely to be further constrained by cost, logistical challenges and biophysical limitations (e. g., poor water availability constrains growth and increases mortality; Smith et al., 2016 ; Adams and Pfautsch, 2018). Once land requirements for nature conservation and agricultural production are accounted for, about 10% of global net primary production (5 GtC/year) can be considered available for C sequestration in forests (Running, 2012). Just managing this quantity more efficiently – ensuring it is not released through disturbance, but rather stored in long-term products or used to replace fossil fuels – would have tangible effects in the next decade. Ultimately, however, afforestation will be insufficient to mitigate increases in atmospheric CO_2 unless paired with immediate and dramatic reductions in fossil fuel emissions (IPCC, 2018 ; Anderson et al., 2019). Nonetheless, afforestation and reforestation can generate a wide range of ecosystem services in addition to carbon capture, and tree planting should be included in diverse portfolios of methods to reduce atmospheric CO_2 (Chazdon and Brancalion, 2019).

How Can Tree Planting Efforts Be Optimized to Maximize Environmental Benefit?

The effectiveness of tree-planting efforts to create new forests hinges upon three critical parameters: (1) the choice of site; (2) selection of species and site management; and (3) the fate of the wood that is produced.

Location

Paradoxically, planting trees in some non-forest ecosystems can *increase* carbon emissions and warming. At high latitudes, low-lying native vegetation is often covered in reflective snow, whereas taller, dark-colored trees absorb more solar energy and cause warming (Jackson et al., 2008 ; Winckler et al., 2019). Draining and subsequent afforestation of peat bogs frequently leads to large losses of carbon from soil organic matter, which can outweigh carbon capture in newly planted trees (Sloan et al., 2018). Planting trees in grasslands and savannas may enhance the risk of fire, leading to carbon loss from vegetation and soils (Veldman et al., 2019). By contrast, reforestation efforts in tropical regions that have historically supported forest are likely to be most effective in drawing down atmospheric CO_2 (Lewis et al., 2019b ; Griscom et al., 2020).

Species Selection and Early Site Management

Ecologically sensitive species selection will help optimize ecosystem services in planted forests. The vast majority (> 99%) of new plantation forests in the past 50 years have been monocultures (Nichols et al., 2006). Globally, plantations are dominated by a handful of fast-growing trees such as eucalypts, pines and poplar. Despite the ubiquity of monocultures, there is strong evidence that sequestering carbon over the long term would benefit from greater diversity. Mixtures of tree species tend to have greater survival rates and faster rates of growth (Paquette and Messier, 2011 ; Liang et al., 2016 ; Grossman et al., 2018 ; Liu et al., 2018), both of which enhance stand-scale carbon sequestration. Even in situations where species diversity and productivity are not strongly correlated (e. g., Ratcliffe et al., 2017 ; Staples et al., 2019), polycultures may promote other desirable ecosystem services. For example, greater species richness frequently buffers carbon capture against inter-annual variability in climate (Osuri et al., 2020), improving landscape-scale resilience to disturbance (Paquette et al., 2018). This is important because disturbance events, especially in young plantations, can negate the C sequestered over several years. Plantation polycultures can also protect biodiversity: in the world’s largest reforestation scheme – China’s “ Grain-for-Green” program – mixed species plantings enhance bird diversity relative to monocultures (Hua et al., 2016).

Species identity also plays a key role in mediating ecosystem services provided by plantations. Provenance trials have been utilized for decades to identify tree varieties that are best equipped to cope with the particular environmental limitations of a given site (Koskela et al., 2014). An emerging body of research harnesses genetic techniques to study the adaptive potential of tree species and genotypes in agroforestry plantations, recognizing that most planted forests will face increasing climatic variability (Alfaro et al., 2014). Species selection is also critical in the context of ecological restoration, as prior land use and the identity of planted species interact to influence the trajectory of forest recovery (César et al., 2018). Additionally, native tree species are associated with higher plantation biodiversity than exotic species (Bremer and Farley, 2010). Successful examples of matching between species and site arise from two very different economies and geographic regions: the British Isles (4 Mio. ha or 10% of land area) and China (62 Mio. ha or about 1% of land area; Mason and Zhu, 2014).

Long-Term Management of Carbon in Trees

The fate of carbon captured in growing trees plays an important role in determining the carbon capture of both natural and planted forests. Some of the carbon sequestered in tree biomass will ultimately be incorporated into the soil via litterfall and rhizodeposition, where it may remain for decades to millennia (Hemingway et al., 2019). Soils contain more carbon than terrestrial plants and the atmosphere combined, so even small changes in the size of this pool will have large impacts on the strength of the forest carbon sink. Reforestation and afforestation generally have positive effects on soil carbon accumulation at decadal timescales (Paul et al., 2002 ; Nave et al., 2018), although in some cases, particularly on high carbon soils such as peatlands and many grasslands, tree planting can trigger carbon loss (Berthrong et al., 2009 ; Chen et al., 2016 ; Richards et al., 2017).

Recent research is changing our perceptions of long-term carbon storage in forests. For example, it was once widely held that the chemical composition of substrates added to soils dictated their longevity. We now know that specific biomolecules, such as lignin, are not preserved during the formation of soil organic matter (Schmidt et al., 2011). Instead, the fate of plant-derived carbon in soils is largely determined by the physiology of decomposer microorganisms and their interactions with soil minerals (Dungait et al., 2012 ; Cotrufo et al., 2013). This new knowledge emphasizes the need to better understand soil properties if we seek to optimize carbon storage (Hemingway et al., 2019). Forest management can also strongly impact the turnover of soil carbon. For example, old soils in the tropics and light-textured sandy soils often require significant nutrient inputs to optimize productivity (Adams and Pfautsch, 2018). Fertilizers, in turn, can affect the cycling and stabilization of soil organic matter (Averill and Waring, 2018).

The fate of wood harvested from plantations is also important. Substituting wood products for fossil-fuel intensive steel and cement, wherever possible, can reduce the climate impacts of the construction sector (Lippke et al., 2014 ; Leskinen et al., 2018), which accounts for approximately one-fifth of global greenhouse gas emissions (Lucon et al., 2014). The use of wood in place of steel, stone, and concrete generally displaces between 1 and 3 tons of carbon emissions per ton of wood carbon (Sathre and O'Connor, 2010), and contributes to an urban carbon sink in buildings and other infrastructure (Churkina et al., 2020). Climate mitigation potential can be further amplified through displacement of fossil fuels with wood biomass energy. Here though, some caution is warranted since there are many specific examples where poor choices of changes to land use, or inadequate attention to longer-term management, can easily negate the benefits. Tree plantations established specifically for bioenergy are land-intensive and often managed in ways that are incompatible with conservation of biodiversity; bioenergy production from wood residues may be a more ecologically friendly alternative (Groom et al., 2008). Finally, efforts to lengthen the afterlife of wood products will benefit from more rigorously applying long-known understanding of forest growth and structure. Thinning, for example, provides opportunities to ensure net primary production is shared among fewer, but larger trees. The flow-on benefits include larger portfolios of wood products, especially longer-life products (Braun et al., 2016). Sustainable supply of wood products will generate revenue for local often rural population that can be in turn used to expand the forest area.

How Can Policymakers Encourage Climate-Smart Forests?

Managing forests as a climate mitigation tool requires consideration of multiple trade-offs. Policymakers and land managers must decide how to allocate resources to conservation of existing forest vs. planting new forests. In plantations, management techniques must weigh optimization of timber harvest vs. carbon sequestration.

Balancing Forest Conservation, Assisted Regeneration, and Re/Afforestation

A key issue is ensuring local retention of the broader economic and societal benefits of establishing plantation forests (Schirmer and Bull, 2014). Designing policy to balance these objectives is challenging. Ideally, the concepts of natural capital would be applied (e. g., Bekessy and Wintle, 2008). Inattention to social context, incentives and valuation schemes can generate “ perverse outcomes” where plantations replace natural forests (van Oosterzee et al., 2010), with concomitant negative consequences for a raft of ecosystem services and biodiversity. A promising approach is the TRIAD scenario, in which landscapes are divided into discrete zones: fully protected natural forest, selectively logged natural forest, and intensively managed plantation (Paquette and Messier, 2010). With refinement according to location, similar approaches can help build timber production industries as well as increasing carbon sequestration and enhancing conservation efforts (Carpentier et al., 2017).

Protecting natural forests (both mature and secondary) must be a central component of forest-based climate mitigation because these forests store more carbon than plantations (Liao et al., 2010 ; Lewis et al., 2019b). Although the rate of productivity declines as forests age (Gower et al., 1996), the total quantity of carbon in living biomass, coarse woody debris, and soils continually increases even as stand age surpasses 200 years (Pregitzer and Euskirchen, 2004). Moreover, it is possible for a single large tree to produce more new wood in a single year than is contained in the entire biomass of a smaller individual tree (Stephenson et al., 2014). However, calculating the contribution of large trees to ecosystem carbon stocks can be complicated, as such estimates hinge on assumptions (e. g., absence of internal fungal decay) that underlie the allometric equations used (Clark, 2002 ; Roxburgh et al., 2006). Nonetheless, the ecological features of natural forests – heterogeneity in tree size, and large carbon pools in dead wood, litter, and soils – are difficult to replicate in plantations, especially those managed for harvest. Thus, facilitating forest regeneration is a particularly effective and low-cost strategy to enhance carbon capture at the landscape scale. In Latin America and the Caribbean, for example, secondary forests occupy nearly one-third of the total land area, and account for the bulk of the total carbon capture potential of the region (Chazdon et al., 2016).

Optimizing Forest Management

Managing plantation forests for timber and carbon requires care and a well-trained workforce. Wood products that can be substituted for steel, concrete, and aluminum have specific physical properties that frequently relate to log size and species (Oliver et al., 2014). The trade-off between forest age (productivity slows as stands mature) and wood yield (larger logs yield more merchantable wood) is well known, and must be carefully considered to optimize rotations. Moreover, sound management can reduce the vulnerability of new forests to disturbances (like wildfires or storm damage), which are predicted to increase in frequency and severity across much of the world (Pechony and Shindell, 2010 ; Seidl et al., 2017). For example, establishment of homogenous, even-aged forests across large portions of the landscape can increase fire risks, which can in turn be mitigated by fuel reduction treatments and changing to uneven-aged forests (Shive et al., 2014 ; Zald and Dunn, 2018). Reforestation efforts should consider predicted changes in ecosystem fire regimes, as well as the tolerance of species to fires of varying severity (Stephens et al., 2013).

Conclusion

Efficient protection and management of existing forest is essential to maximizing carbon uptake and carbon fluxes into long-lived *in-situ* pools, or wood products that can be used to replace those requiring fossil fuels. Beyond this, reforestation and afforestation are needed to further reduce atmospheric CO_2 concentrations while protecting biodiversity, enhancing other ecosystem services and supporting local economies.

Realizing the greatest possible benefits of tree planting requires sensitivity to both ecological and sociological contexts. Wherever possible, we should protect carbon stocks in natural ecosystems, including savannas, grasslands, and both undisturbed and naturally regenerating forests. However, there is also an important role for managed forests: plantations can reduce pressure on unmanaged forests, and they yield wood products that may displace fossil fuels. Ultimately, however, tree planting is not a panacea to mitigate climate change, as only immediate and drastic reductions in greenhouse gas emissions can limit warming to 1. 5°C above pre-industrial levels (IPCC, 2018 ; Anderson et al., 2019).

Author Contributions

BW wrote the first draft. MA and MS initiated the work. All authors contributed to and edited the manuscript subsequently.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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