Journal of Positive School Psychology http://journalppw.com
2022, Vol. 6, No. 7, 5830-5847

Insinuations Of Deforestation And Carbon Sequestration Potential In The Tropics

Mohammad Afsar Alam (PhD)

Department of Social Sciences, Fiji National University, Fiji Email: drmaalam92@gmail.com Orcid: 0000-0001-5989-6399

Abstract

The technique of collecting and storing atmospheric carbon dioxide is known as carbon sequestration. It is a technique of decreasing the quantity of carbon dioxide in the atmosphere in order to slow global climate change. There are two kinds of carbon sequestration: geologic and biological. The act of storing carbon dioxide in subsurface geologic formations is known as geologic carbon sequestration, while biologic carbon sequestration refers to the storage of atmospheric carbon in plants, soils, woody products, and aquatic habitats. Tropical deforestation accounts for about 20 per cent of yearly global greenhouse gas (GHG) emissions, and it must be reduced if catastrophic climate change is to be avoided. According to new research from 'The Nature Conservancy' World Resources Institute, and others, halting deforestation, restoring forests, and improving forestry practices could cost-effectively remove 7 billion metric tons of CO2 each year. According to estimates, deforestation and forest degradation are responsible for about 10 per cent of global warming. Carbon dioxide is not absorbed in the same proportion by all forest species. Teak absorbs the highest amount of carbon dioxide from the air. A teak tree can absorb 3.70 lakh tons of carbon dioxide from the atmosphere throughout its lifespan. This study aims to investigate the rate of deforestation and its impact on global warming by providing an overview of the implications of deforestation and carbon sequestration potential at the global level, particularly in the tropics. The study was primarily carried out using secondary data gathered from a variety of sources.

Keyword: Carbon Sequestration, Climate change, Deforestation, Potential, Tropics

Introduction

Forest ecosystems cover large parts of the terrestrial land surface and are major components of the terrestrial carbon cycle. Global forests are expected to contribute a quarter of the pledged mitigation under the 2015 Paris Agreement, by limiting deforestation and by encouraging forest regrowth (Grassi, G. et al., 2017). Most important, forest ecosystems accumulate organic compounds with long carbon residence times in vegetation, detritus and in particular the soil by the process of Carbon sequestration. Trees, the major components of forests, absorb large amounts of atmospheric carbon dioxide (CO2) by photosynthesis, and forests return an almost equal amount to the atmosphere by auto- and heterotrophic respiration. However, a small fraction of carbon remaining in forests continuously accumulates in vegetation, detritus, and soil. Thus, undisturbed forest ecosystems are important global carbon sinks.

The Brazilian Amazonia is the largest continuous tropical forest on Earth, occupying 3% of terrestrial land. It stores ~10% of the global forest carbon (120,000 Tg C) and between 2000 and 2010 (Baccini, A. et al., 2012 & Avitabile, V. et al., 2016) sequestered ~150 Tg C yr−1 through natural growth (5% of global land sink), while emitting ~143 ± 56 Tg C yr−1 through deforestation (~1.4% of global carbon emissions) (Hubau, W. et al., 2020 & Pan, Y. et al., 2011). As part of their Nationally Determined Contributions (NDC) to the Paris Agreement, Brazil has pledged to restore and reforest 12 million hectares of forests by 2030 to contribute to net emission reductions (Ministério do Meio Ambiente, 2016). Part of this reduction can be achieved by the natural regeneration of secondary forests on abandoned land, which are already regrowing on ~20% of deforested land in Amazonia (Bongers et. al., 2015 & Nunes et. al., 2020).

Though consciousness of climate change is inescapable; understanding and conduct commitment are far lower. Recommendations for mitigative "individual carbon budget” infer a requirement for open comprehension of the causes and consequences of carbon discharges to decrease the outflows, be that as it may, little has been done to think about the arranged implications of carbon and vitality in regular day-to-day life and decisions (Alam, M.A et.al., 2021).

The forest ecosystem service of carbon sequestration is central to the well-being of the human society and to the well-being of planet Earth. However, abrupt climate change threatens the carbon sink in forests as a consequence of burning of fossil fuels and land use changes, effectively disposing increasing amounts of CO2 in the atmosphere. Previous estimates of average net carbon uptake in young (<20 years old) secondary forest range between 2.95 ± 0.4 and 3.05 ± 0.5 Mg C ha−1 yr−1, 11–20 times larger than old-growth primary forests (Poorter, L. et al., 2016 & Requena Suarez, D. et al., 2019). These estimates, which are based on limited field data across the Neotropics, are unable to capture the different spatial patterns and rates of secondary forest carbon sequestration, which are influenced by several drivers. This includes environmental drivers such as shortwave radiation, precipitation, soil fertility and forest water deficit, as well as anthropogenic disturbances like fire and repeated deforestation cycles prior to regrowth (Poorter, L. et al., 2011 & Mercado, L. M. et al., 2019).

Thus the atmospheric CO2 concentrations and temperatures are increasing, and precipitation regimes are altered which may impact carbon sequestration processes in forest ecosystems. Recent abrupt climate change (ACC) has had limited consequences for the forest carbon sink compared to human activities such as deforestation for agriculture. However, future ACC as result of increasing fossil fuel emissions may turn forests into a source for atmospheric CO2 which will further exacerbate ACC impacts on forests by positive feedback. Thus, the ultimate solution for ACC is the de-carbonization of the global economy. Until effective technological measures are implemented, carbon sequestration in forest ecosystems can help to slow-down ACC. Also, sustainable, and adaptive forest management can better prepare forests for future ACC change. Sustainable and adaptive forest management practices must be implemented to ensure that future forests absorb carbon despite ongoing perturbations by ACC. International agreements on climate change must appreciate the role of forest ecosystems for ACC mitigation. Future international climate agreements will, in particular, address the importance of reducing deforestation and forest degradation (REDD). Important for carbon sequestration in forest ecosystems is the reduction in tropical deforestation, and the protection of the large amounts of carbon stored in peatland and old-growth forests.

The secondary forest carbon stock with very high-water deficit (−1200mmyr−1) can be up to 85% lower compared to no water deficit (0mmyr−1) regions in the Neotropics (Poorter, L. et al., 2016). The effects of these drivers are neither limited to secondary forest growth, nor are they static over space and time, affecting the magnitude of forest carbon sequestration and stocks (Anderegg, W. et al., 2020). A recent study showed that rising annual mean temperatures and drought reduced tree growth in Amazonian old-growth forests. This effect, coupled with ongoing deforestation suggests that the sink in these forests peaked in the 1990s and is now steadily declining (Hubau, W. et al., 2020). Considering these changes, it is important to obtain a wider spatial and temporal understanding of drivers affecting the magnitude and sustainability of secondary forest regrowth.

However, there is a lack of reference and textbooks for graduate and undergraduate students interested in understanding basic processes of carbon dynamics in forest ecosystems and the underlying factors and causes which determine the technical and economic potential of carbon sequestration. Remote sensing products can be used to study these effects, offering broad spatial and temporal coverage. With the availability of nearly four decades of Landsat data (30m spatial resolution), it is now possible to track the fate of deforested areas over time, which includes the changing demography of secondary forests across Amazonia (Nunes et. al., 2020 & Silva Junior, C. H. L. et al., 2020). According to satellite-based analysis, secondary forests are typically part of a 5–10-year cycle of clearance and abandonment since they are currently not protected by national policies aimed at curbing deforestation (Yang, Y, et. al., 2020 & Vieira et. al., 2014). These repeated deforestations are expected to decrease the carbon sink of future regrowth forests. Deforestation of secondary forests amounted to ~70% of total Amazonian Forest loss between 2008 and 2014 (Wang, Y. et al., 2020). This study provides the information on processes, factors, and causes influencing carbon dynamics in forest ecosystems. It illustrates the topic with appropriate examples from around the world and lists a set of questions at the end of each chapter to stimulate thinking and promote academic dialogue. Each chapter provides up-to-date references on the current issues and summarizes the current understanding while identifying the knowledge gaps for future research.

This study is the first to describe the effects of ACC on the various processes by which forests exchange C with the environment. Exchanges of carbon with the atmosphere and surrounding ecosystems occur through photosynthesis, respiration, and fluxes of carbon monoxide (CO), methane (CH4), biogenic volatile organic compounds (BVOCs), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate carbon (PC). In this study we used the land-cover product MapBiomas to identify secondary forests (Mapbiomas Brasil, 2018) and their ages from 1985 to 2017 and used the European Space Agency Climate Change Initiative (ESA-CCI) Aboveground Biomass product to model the regrowth of secondary forests across Amazonia (Santoro, M. & Cartus, 2019); (Supplementary Notes 1–3. Based on these two products, we identified and tested the effects of six key drivers on secondary forest regrowth and AGC accumulation: (1) Average annual shortwave (SW) radiation (Abatzoglou, 2018) ; (2) Average annual precipitation (Funk, C. et al., 2015) ; (3) Forest water deficit using the Maximum Cumulative Water Deficit index (MCWD) ; (Anderson, L. O. et al., 2018) ; (4) Soil fertility using the Soil Cation Concentration (SCC) as a proxy (Zuquim, G. et al. 2019) ; (5) Burned area (Didan, K, 2015) and (6) the number of deforestations since the start of the data in 1985 prior to the most recent regrowth, hereon simply termed as repeated deforestations.

The discussion of effects of ACC on forest ecosystem carbon sequestration processes is based on a broad review of current literature on the possible impacts of increasing atmospheric CO2 concentrations, temperature and altered precipitation regimes on ecosystem processes. However, there is no statistical difference in carbon accumulation under different SCC conditions, furthermore the expected trend, increased carbon accumulation with increased soil fertility, is reversed, probably due to the dominant effect of other environmental drivers, which act on larger regional scales (Poorter, L. et al., 2019). In areas of anthropogenic disturbance such as fires and repeated deforestations, the carbon accumulation rate was up to 75% lower and even plateaued within 11–40 years, thus potentially never recovering to old-growth forest AGC values. Our results showed that fire occurrence, a predominantly anthropogenic disturbance (Aragão, L. E. O. C. et al., 2014) has a similar importance ranking as the most important environmental driver influencing AGC, despite only affecting 29.2% of secondary forest plots.

Carbon sequestration is defined as the increase in the amount of carbon bound in organic compounds with long C residence times in vegetation, detritus, and soil. Major nutrient and water limitations on carbon sequestration in forest ecosystems are also described. Finally, the future roles of forests as bioenergy source and for ACC mitigation are discussed. This study focuses on carbon sequestration in existing forests and not in those established by afforestation and reforestation or in the forest products sector.

Undisturbed, old-growth forests not only serve to maintain the current carbon sink but also act as key sources of seeds for regeneration. However, disturbances to both old-growth and secondary forests have increased the proportion of low wood density and small-seeded tree species (Hawes, J. E. et al., 2020). Identifying the proximity of secondary forests to disturbed versus undisturbed forests could potentially be another driving variable impacting the regrowth rates we have calculated in this study. Datasets that differentiate disturbed from non-disturbed forests are only becoming available now (Bullock et. al., 2020). At present it is estimated that just 13% of Amazonian secondary forests are within 1 km proximity to areas with >80% old-growth forest (Smith, C. C. et al., 2020) but whether these forests are disturbed remains unclear. Recent research has shown that proximity to young forests also results in faster forest-cover recovery and more species rich regeneration (Toledo, R. M. et al., 2020). Research has shown that drought increases stem and seedling mortality, reducing regrowth and regeneration, respectively (Uriarte, M. et al., 2016).

Moreover, there has been a slow shift to more dry-affiliated Amazonian tree genera (Esquivel-Muelbert, A. et al., 2019) which have a lower biomass and are more savannah-like in nature (Levine, N. M. et al., 2016) as some species reach their adaptive limits to ongoing drier conditions (Esquivel-Muelbert, A. et al., 2020). Thus, this study is a valuable source of information intended for use by graduate and undergraduate students, scientists, forest managers and policy makers (Lorenz, K., & Lal, R., 2009).

Across Amazonia, we found fire was one of the most important drivers affecting secondary forest regrowth. Other studies have also shown the importance of fire in influencing regrowth (Wandelli, E. V. & Fearnside, P. M. 2015), but they have not quantitatively assessed the relative importance by region. Both fire and deforestation typically act on the local scale. In recent decades, the scale at which deforestation events occur has decreased even further, with more very small-scale (<1 ha) deforestation events being observed (Kalamandeen, M. et al., 2018).

Secondary forests will therefore not replace old-growth forests on policy-relevant timescales, stressing the continued need to conserve existing old-growth forests (Elias, F. et al., 2020).

Materials and Methods

This study is descriptive in nature and is based on carbon sequestration data from secondary sources. These data are collected from government offices, published books, articles, and unpublished softcopies sourced from the internet and software. Various website publications at different times have also been consulted. But the main source of carbon sequestration data are the books and research articles published from time to time. Information gathered from various sources has been presented in the form of tables and diagrams.

Data Analysis

Details of carbon sequestration were collected from a wide range of sources. Secondary sources such as case studies, and international policy updates were taken into consideration. In the absence of published literature, websites of international donors such as the World Bank, Global Environment Facility (GEF), and FACE Foundation were useful in collecting data on the carbon sequestration. Wherever possible, data were verified by accessing information from multiple sources. Clean device mechanism (CDM) specific information was obtained from the United Nations Environment Programme's (UNEP) Risoe Centre, which maintains an online database at different stages of approval. The carbon market is growing so rapidly that there are significant developments each month. Therefore, research institutes that keep a tab on these markets, such as the Ecosystem Marketplace are an important source of updated information. Finally, recent publications of Forest Trends and the International Institute for Environment and Development provided useful insights into this study.

Carbon Sequestration

The rate of increase in atmospheric CO2 concentration can be reduced through the process of C sequestration. The term 'carbon sequestration' is defined as the uptake of C containing substances, in particular CO2, into a long-lived reservoir (IPCC 2007). It is a natural process. Thus, the net flux of −1 Pg C year-1 from the atmosphere to vegetation, detritus and soil, and the net flux of −1.6 Pg C year−1 from the atmosphere to the ocean is C sequestration (Denman et al. 2007). More specifically, 'carbon sequestration' can be defined as the transfer and secure storage of atmospheric CO2 into other long-lived pools that would otherwise be emitted or remain in the atmosphere (Lal 2008). These pools are located in the ocean, biosphere, pedosphere, and geosphere. Most important for the short-term C cycle in forest ecosystems is the exchange with the atmospheric CO2 pool. Thus, C sequestration in forest ecosystems occurs primarily by uptake of atmospheric CO2 during tree photosynthesis and the subsequent transfer of some fixed C into vegetation, detritus, and soil pools for secure C storage (Lorenz, K., & Lal, R., 2009).

At a global scale, afforestation and reforestation has the potential to be our single largest natural climate solution (Griscom et al., 2017; Bastin et al., 2019), and recent years have seen numerous international policies and agreements with the aim of protecting and extending the world's forests. Article 5 of the Paris Agreement encourages parties to conserve and enhance carbon sinks, including forests (United Nations, 2015), while the Bonn Challenge (bonnchallenge.org), initiated by IUCN and the Government of Germany in 2011, has gathered 62 commitments by governments and other organizations to restore over 170 million hectares of woodland by 2030 to provide carbon sequestration and other benefits. Carbon credits, introduced by the Kyoto protocol, allow for carbon sequestration to offset emission elsewhere, providing funding for the developing of forestry projects (Kula, 2010).

A large flux of CO2 is constantly being assimilated into the world's forests via photosynthesis, cutting off its return pathway to the atmosphere forms an effective carbon sink. It is estimated that a sustainable long-term carbon sequestration potential for wood burial is 10 ± 5 GtC y-1, and currently about 65 GtC is on the world's forest floors in the form of coarse woody debris suitable for burial. The potential is largest in tropical forests (4.2 GtC y-1), followed by temperate (3.7 GtC y-1) and boreal forests (2.1 GtC y-1). Burying wood has other benefits including minimizing CO2 source from deforestation, extending the lifetime of reforestation carbon sink, and reducing fire danger. There are possible environmental impacts such as nutrient lock-up which nevertheless appears manageable, but other concerns and factors will likely set a limit so that only part of the full potential can be realized (Zeng, N., 2008).

Forestry and land-use projects are valuable to combat climate change insofar as they generate certified emission reductions (CER) by putting land into or keeping land in a forested state. These CERs are rather like negative emissions of carbon; in the case of a reforestation project, the number of CERs produced is based on the level to which the forest sequesters carbon. The CERs are ultimately for sale to those whose carbon emissions are constrained because of policy decisions to limit global carbon emissions, i.e., the Annex I countries, which are basically OECD countries. If a seller and buyer have been able to find a mutually agreeable price, it is generally assumed that this price is greater than the seller’s return from alternative uses of the land, and less than the costs of the buyers’ other mitigation options, with a difference between the two greater than the transaction costs. Thus, a trade reduces the buyer’s costs by more than the supplier’s lost opportunities.

If the CERs are real and permanent, this trade has no net effect on greenhouse gas emissions. However, because a forest will grow for several years and then store its carbon until it is cut, we need to account for how CERs that are sold relate to actual inter-temporal emissions. Land and forestry CERs must be made comparable with other ways to reduce net carbon emissions, such as lowering fossil fuel emissions.

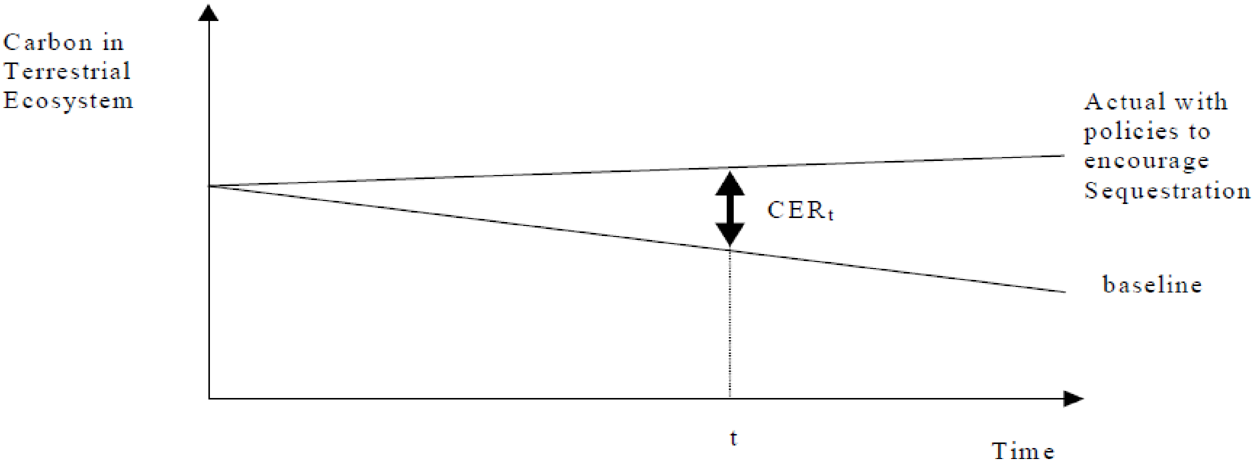
A CER created through carbon sequestration is not directly equivalent to a reduction in fossil fuel emissions. Because land-use changes can be reversed, CERs can disappear. At each point in time, the true amount of additional carbon sequestered is the difference between the quantity of carbon storage or accumulation attained if the project occurs, and the quantity expected in absence of the project (i.e., in the baseline). For example, if in the baseline a piece of land with climax vegetation will be cleared, but due to the project the forest remains intact, the CER generated by the project is the difference in carbon stock between climax vegetation and cleared land. Carbon stored in climax vegetation and rates of accumulation vary by the physical and climatic characteristics of the site; baselines and project impacts will have to account for such factors.

In many cases, however, the CER will be temporary. This is the case with a plantation of crops that is harvested upon reaching maturity where deforestation is delayed but not permanently avoided.3 When land is protected, a CER is created, and fossil fuel emissions can rise by the same amount as the CER. If the land is later cleared, fossil fuel emissions in the later year will have to be reduced to compensate for the resulting fall in the stock of sequestered carbon. Even a temporary CER, however, can be valuable to a buyer in a developed country, through allowing compliance with short-term obligations. Otherwise, necessary emissions reductions (e.g., based on fuel switching or improvements in energy efficiency) can be delayed until technology change lowers the cost of such improvements. Thus, temporary CERs can be a way to permit a transition period, and save costs, by loosening a binding constraint. With international trading, the total value of a permanent CER will be roughly equal to the cost of reducing the equivalent amount of carbon emissions in an alternative way. This will be the price of a carbon permit, defined as one unit of permanent CER. 4 Because of the temporary nature of sequestration CERs, we model the problem as though landowners are paid a lease price for every period that the carbon remains sequestered. The risk adjusted present discounted value of these annual payments is the international carbon permit price. (Suzi Kerr et. al., 2001).

Carbon sequestration through forestry and agroforestry can help mitigate global warming. For Africa, carbon sequestration also represents an opportunity to fund sustainable development through financial inflows. However, with a low share of global carbon trade, there are strong concerns that African countries are losing out on this valuable opportunity. Through a comprehensive review of 23 carbon sequestration projects across 14 countries, this paper discusses ways to overcome critical challenges to scale up carbon investments in Africa (Fig. 1).

These projects are expected to sequester 26.85 million tCO2 beyond the baseline situation. Within the continent, East Africa is the preferred destination for carbon investors. Most projects are non-Kyoto compliant and represent voluntary emission reductions. While project benefits such as increased local incomes and improved natural resources are promising, there are concerns that conversion of grasslands into tree plantations can harm local ecosystems. Insecure land tenure constrains new investments and increases the risk that local communities will lose access to forests. Another challenge is that projects with smallholders have high transaction costs. These costs can be overcome by building strong community institutions and simplifying project guidelines. To attract more projects, African governments will need to build their capacity to identify relevant opportunities (Rohit et. al., 2008).

Fig. 1: Definition of Certifiable Emission Reductions



Source: Kerr, S., Pfaff, A., & Sanchez, A. (2001).

Atmospheric CO2 concentration has increased from 280 to 380 ppmv (parts per million by volume; a 35% change) since pre-industrial time, largely due to carbon emissions from anthropogenic fossil fuel burning and deforestation (IPCC 2007). The emission rate of carbon from fossil fuel (oil, coal and gas) consumption is currently about 8 GtC y-1 (1015 g of carbon per year) (Canadell JG, et al., 2007) while the deforestation rate for the 1990s is estimated to be 1.6 (0.5–2.7) GtC y1. The cumulative fossil fuel emission since 1800 is 330 GtC, but only about half of that remains in the atmosphere; the remainder absorbed by carbon sinks in the ocean and on land (IPCC 2007). Fossil fuel emissions are projected to reach 9–20 GtC y-1 by 2050 in the absence of climate change policies, according to a range of emissions scenarios (Nakicenovic N, et al.,2000). Depending on how the current carbon sinks change in the future, the atmospheric CO2 concentration for the Special Report on Emissions Scenarios (SRES) A2 emissions scenario is between 450–600 ppmv by 2050, and 700–1000 ppmv by 2100, and global mean surface temperature may increase between 1.5–5.5°C (Friedlingstein P, et al., 2006), with related changes in sea-level, extreme events, and ecosystem shifts. Scientists have argued that severe consequences will occur once atmospheric CO2 concentrations reach between 450 and 600 ppmv (Hansen JE, 2005; O'Neill BC, Oppenheimer M, 2004; Schneider SH, Mastrandrea MD,2005). Beyond this point, global climate change would be very difficult and costly to deal with (Stern N, 2007).

Carbon Dynamics and Pools in Tropical forests

The Tropical biome occupies about 3,480 million hectares of which the humid tropics cover 1,451 million hectares (Reich and Eswaran 2006). Tropical forests are located between the tropics of Cancer and Capricorn although a consistent, precise, and universal definition of tropical forest does not exist. Before the 1990s, 460 million hectare of land area were covered by tropical deciduous forests and 1,740 million hectares by the evergreen forests

(Melillo et al. 1993). Thus, tropical evergreen forests (generally called rainforests) comprise the largest single forest biome in the world, and the Amazon basin is the largest land area covered by this forest type (Landsberg and Gower 1997). Furthermore, in 2005 mangrove forests covered 15.2 million hectares in sheltered coastlines, deltas and along riverbanks in the tropics and subtropics (FAO 2007). The long-term global trend in topical forest area is, however, difficult to track (Grainger 2008).

The climate of tropical evergreen forests is characterized by high temperatures, with little seasonal or diurnal fluctuations (20–25°C). The mean annual precipitation exceeds 2,000 mm year−1, and the relatively high humidity is observed uniformly throughout the year; Landsberg and Gower 1997). Due to its immense size, however, generalizations about the climatic conditions in the tropical forest biome are difficult to make. Tropical deciduous forests, in particular, differ based on the water balance. It is the drought that mainly controls the leaf shedding in the tropical deciduous forests. Tropical forests cool their climate through strong evaporative cooling (Bonan 2008).

Tropical evergreen forests have the highest tree diversity among all forest types. For example, the Amazonian Forest alone contains more than 2,500 tree species (Landsberg and Gower 1997). The most common species are Brosimum guianense (Aubl.) Huber, Casearia commersoniana Cambess., Rhamnus sphaerosperma Sw., Guarea guidonia (L.) Sleumer, Hymenaea courbarii L., and Trichilia quadrijuga Kunth. The tropical rainforests in the eastern regions contain more conifers. Otherwise, the African rainforests are relatively poor in species composition. Undisturbed tropical forests can have a complex and species-rich mycorrhizal fungal community but the importance of this complexity to tropical forest diversity is not known (Alexander and Selosse 2009).

Tropical forests have a strong vertical structure, with much of the leaf biomass and fruits in the brightly lit canopy, and seed germination, seedling growth, and juvenile recruitment in the dark understory (Gilbert and Strong 2007). Tropical forest canopies have a layered structure. Tall trees comprise the upper layer, followed by a main canopy layer, and a sub canopy of smaller trees and shrubs near the ground level (Landsberg and Gower 1997). Trees in tropical forests have relatively large leaves and are often characterized by buttresses, and palms, climbing plants, epiphytes, and hemi-epiphytes (Lewis 2006). In contrast to tropical evergreen forests, tree species diversity is lower in tropical deciduous forests. Furthermore, canopies are shorter, and the structure is more open compared to the tropical rainforests.

Fig. 2: Tree Species Diversity in Tropical Forest

Source: Tropical Forest (photo credit: H.-D. Viktor Boehm)

Tropical forests contain more than half of the Earth's terrestrial species (Myers et al. 2000). Furthermore, tropical forests predominantly contribute to global biodiversity 'hotspots' or areas featuring exceptional concentrations of endemic species and experiencing exceptional loss of habitat (Fig. 2). Biodiversity is generally high, but little is known as tropical forests are extensive, highly variable, and generally more difficult to study than any other vegetation type (Grace et al. 2001).

Old growth tropical forests contain large pools of C, and account for a major fraction of the global NPP (Denman et al. 2007). Changes in tropical forests may, thus, have significant effects on the global C balance but the importance of tropical forests for the global C cycle is not well understood (Grace et al. 2001). For example, a reevaluation of the terrestrial productivity gradient indicated that annual NPP in tropical forests is not different than annual NPP in temperate forests (Huston and Wolverton 2009). Also, whether tropical rainforests are sinks or sources of C is matter of debate (Levy 2007; Sierra et al. 2007; Malhi et al. 2008). Otherwise, combining all standardized inventory data from tropical Africa, America and Asia indicates a tree C sink of 1.3 Pg C year−1 across all tropical forests during recent decades (Lewis et al. 2009). Large-scale biomass inventories may, however, not adequately survey tropical forests, and not adequately consider tree mortality and dead wood decomposition (Denman et al. 2007; Fisher et al. 2008). Sampling biases are, however, too small to explain currently observed biomass gains for intact forests across the Amazon (Gloor et al. 2009). Large uncertainties still exist for the C budget of mangrove forests as >50% of NPP is unaccounted for (Bouillon et al. 2008). Less well known is also the role of mycorrhiza in maintaining tropical forest productivity (Alexander and Selosse 2009). The forest turnover rates, i.e., tree mortality and recruitment rates, are higher in tropical than in temperate forests (Stephenson and van Mantgem 2005). In contrast to temperate forests, climate is the primary driver of root and leaf litter decomposition, especially during early stages of decomposition (Cusack et al. 2009). The balance of a tropical forest based on atmospheric, eddy covariance or ground based studies may differ among each other (Clark 2007). The global CO2 flux caused by the land use changes, however, is dominated by tropical deforestation as about 13 million hectares' tropical forest are felled or grazed each year (FAO 2006; Denman et al. 2007). Relatively well studied is the largest tropical rainforest in the Amazon which is intimately connected to the global climate but lost 85% of the original area by 2003 (Soares-Filho et al. 2006; Malhi et al. 2008). In contrast, Africa has the second largest block of rainforest in the world but is the least known in terms of C stocks and rates of conversion (Baccini et al. 2008). The second largest rainforest in the Congo River Basin, in particular, is the least exploited yet most scantily studied of the world's humid forest regions (Koenig 2008). Furthermore, swamp forests in the Congo Basin have also received little attention (Keddy et al. 2009). The Congo River Basin Forest, however, has among the highest C contents per hectare of any rainforest.

Keeping the atmospheric CO2 concentration below 450–600 ppmv poses an unprecedented challenge to humanity. There are two main approaches: (1) to reduce emissions; (2) to capture CO2 and store it, i.e., sequestration. Since our economy depends heavily on fossil fuel, which comprises more than 80% of primary energy use, to reduce carbon emissions requires drastic changes in energy use efficiency and the use of alternative energy sources that are generally not economically competitive at present (Pacala S, &Socolow R, 2004; Hoffert MI, et al.: 2002). Even if advanced technologies such as hydrogen power and nuclear fusion become economical, the infrastructure switch will take many decades. It is thus very likely that at least some carbon sequestration will be needed in the near future to keep CO2 below a dangerous level.

Carbon sequestration involves two steps: (1) CO2 capture, either from the atmosphere or at industrial sources; (2) storage. Capture out of the atmosphere is assumed to be much more expensive because of the low CO2 concentration in the atmosphere relative to N2 and O2. For this reason, most current proposals seek to combine capturing CO2 with power generation, with several pilot power plants planned or underway (Schrag DP, 2007). The proposals for storing captured CO2 include pumping it into deep ocean where CO2 may react with water under the high pressure to form methane hydrates (Brewer et. al., 199) or stays in CO2 lakes, burying carbon inside deep ocean sediments where conditions are even more stable than ocean bottom (House et. al., 2006). The technique that has been most seriously considered, is to store captured CO2 in geological formations such as old mines and deep saline aquifers (BM et. al., 2005). There is also a spectrum of biospheric carbon sequestration methods, such as enhancing oceanic plankton productivity by iron fertilization, reforestation or altering forestry and agricultural management practices to maximize carbon stored in soil and vegetation, but the potential and permanence of these biospheric techniques have been unclear.

Here, I suggest a biospheric carbon sequestration approach in which wood from old or dead trees in the world's forests is harvested and buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood. This can be supplemented by selective cutting of other suitable trees. On the storage side, high-quality wood can also be stored in shelters for future use. In this technique, CO2 capture is done by the natural process of photosynthesis, and storage is low tech and distributed, thus attractive in two important aspects: cost and safety.

Assessment of Carbon Sequestration through Wood Burial

The possibility of carbon sequestration via wood burial stems from the observation that natural forest is typically littered with dead trees (Fig. 3). It is hypothesized that large quantities of organic carbon were buried and preserved for over one hundred thousand years under the great Northern Hemisphere ice sheets during the Pleistocene glacial-interglacial cycles (Zeng N, 2003 & 2007). Other studies have shown that organic matter, especially wood, in municipal landfills decomposes extremely slowly (Micales JA, Skog KE, 1997). With these, it became clear that wood harvesting and burial could be a viable method for carbon sequestration.

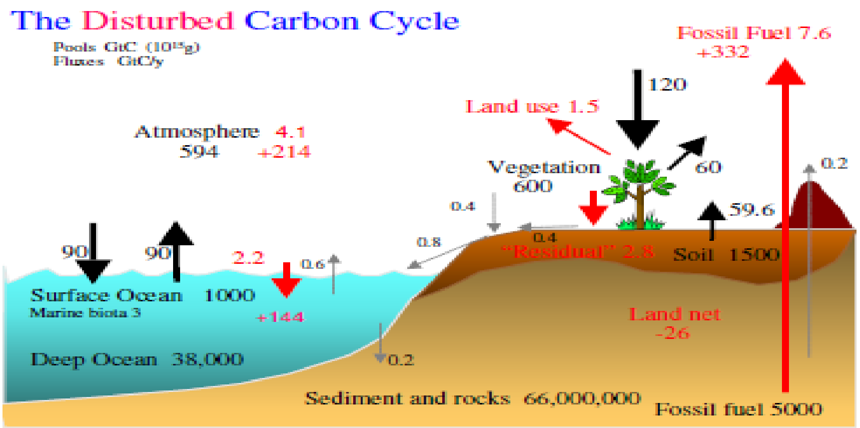
Globally, approximately 60 GtC y-1 are temporarily sequestered by land vegetation (Net Primary Productivity or NPP; Fig. 9.4). This carbon is continuously returned to the atmosphere when vegetation dies and decomposes (heterotrophic respiration, Rh). In a steady state, the death rates of these carbon components equal to their respective decomposition rates and add up to NPP such that the net land-atmosphere carbon flux is near zero (NPP = Rh). If we can stop or slow down a part of the decomposition pathway, we have the hope to sequester CO2 at a rate that may rival the current fossil CO2 emission of 8 GtC y-1.

Fig. 3: Dead Trees on Forest Floor in a Natural State

Source: Zeng, N. (2008). Carbon sequestration via wood burial.

Since woody material is most resistant to decomposition due to its lignin cellulose fiber structure which also minimizes nutrient lock-up, the study focuses on this carbon pool. In this diagram red color indicating anthropogenic fluxes for 2000–2006 and cumulative pools for 1800–2006 (Fig. 4).

Fig. 4: Major Pools and Fluxes of the Global Carbon Cycle

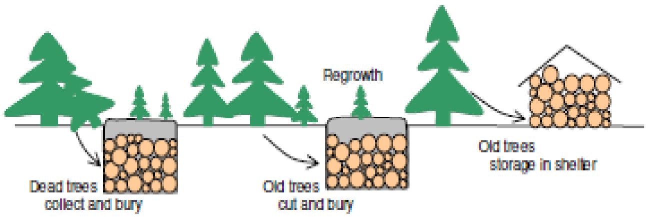


Source: Zeng, N. (2008). Carbon sequestration through wood burial.

Unfortunately, there is a general lack of knowledge of dead wood on the forest floor, and this carbon pool is often neglected in carbon budget accounting. Since death rate is fundamentally limited by growth rate, the dead wood production rate cannot exceed the world total NPP of 60 GtC y-1. Then the key question is how NPP is partitioned into the three main carbon pools: leaf, wood, and root. Leaves grow and fall in a deciduous forest each year but may last a few years in an evergreen forest. Fine woody material such as twigs and small branches may break and fall often, but tree trunks and major branches have a lifespan of decades to centuries and longer. Thus, even though wood biomass is much larger than leaf biomass, its long lifetime suggests a production rate that is much smaller than otherwise. Root biomass can be large, and the death rate is also substantial as roots constantly grow to search for nutrient and water. A 'naïve' first guess could be that NPP is partitioned equally into these three pools, leading to a 20 GtC y-1 wood growth rate, thus 20 GtC y-1 wood death rate at steady state. Since fine woody debris decompose more quickly and more difficult to handle, coarser material such as trunks and major branches are more suitable for burial. Assuming half of the woody material is coarse, then about 10 GtC y-1 dead wood may be available for burial, thus leading to a 10 GtC y-1 carbon sink. Assuming an average residence time of 10 years for dead trees on the forest floor, about 100 GtC (10 GtC y-1 times 10 years) in the form of coarse woody debris would be already on the forest floor. These dead wood materials are under various stages of decay, but even if half of that can be collected and buried, it provides a substantial readily available carbon sink.

The proposal is to (1) collect dead trees on the forest floor and (2) selectively log live trees. Then the tree trunks are either buried in the trenches dug on the forest floor (burial) or suitable landfills, or logs piled up above ground sheltered away from rain (Fig. 5). The buried woody material will have significantly longer residence time, and it effectively transfers carbon from a relatively fast decomposing pool (about 10 years) to a much slower carbon pool (100–1000 years or longer). In the case of (1), it reduces part of the heterotrophic respiration, and is thus an immediate effective carbon sink. In the case of (2), the subsequent regrowth in the 'gaps' left by tree cut is a carbon sink, which would depend on the rate of regrowth. In practice, (1) and (2) probably do not differ a lot, as fallen trees leave gaps for smaller trees to grow in a way very similar to case (2).

Fig. 5: Schematic Diagram of Forest Wood Burial and Storage



Source: Zeng, N. (2008).

Quantification of Carbon Sequestration Potential

To quantify the size of this potential carbon sink, the global dynamic vegetation and terrestrial carbon model VEGAS was used. While the model simulates the full terrestrial carbon cycle, only the carbon pools and fluxes relevant to the purpose here are discussed. The simulation did not include agricultural land; thus, the estimates will be potential rates. The model was driven by modern observed climatology with seasonal cycles of precipitation, temperature, sunshine, wind speed, and vapor pressure. The simulation was run until convergence at a steady state where tree growth is balanced by mortality.

The modeled global NPP is 57 GtC y-1, of which 19 GtC y-1 goes into dead leaf, 17 GtC y-1 into dead wood, and 21 GtC y-1 to dead root structures. Since fine wood (twigs and small branches) decomposes quickly, is more difficult to handle (costlier to clean up the leaves, etc.), and may occupy more burial space, only coarse wood will be considered as suitable for burial. Forestry literature generally makes a distinction between fine and coarse woody debris, typically using 10 cm stem diameter to separate the two classes. Unfortunately, the relative contribution to the total wood death from fine and coarse wood is difficult to quantify, in part due to the different lifetime (smaller stems generally have shorter life than the whole tree). It is sometimes unclear how these pools and fluxes are defined and what the reported numbers represent in forestry literature.

The carbon sequestration potential of coarse wood for various geographical regions is given in table 1. The tropical forest has a 4.2 GtC y-1 carbon sequestration potential, temperate forest has 3.7 GtC y-1, while the boreal region has 2.1 GtC y-1. Since the model considers only potential vegetation (no agriculture) the temperate regions may have substantially smaller potential.

Table 1: Carbon sequestration potential of coarse wood production for various geographical regions.

Global	Tropics	Temperate	Boreal
10	4.2	3.7	2.1

Source: Estimated by VEGAS assuming potential vegetation for the main regions of the world.

Implementation Strategy

The implementation of a wood burial scheme will involve three major steps:

(1) Enabling access to the forest if not already in place.

(2) Site selection, trench digging for burial or building a shelter for above ground storage.

(3) Selective tree cutting, or the collection of dead wood followed by trimming, shortening and burial or storage, repeated at an appropriate return interval.

Results and Discussion

Tropical Forests Are Losing their Carbon Absorption Capability

Tropical forests are taking up less carbon dioxide from the air, reducing their ability to act as carbon sinks and bringing closer the prospect of accelerating climate breakdown. New research has found that the Amazon could turn into a source of carbon in the atmosphere, instead of one of the biggest absorbers of the gas, as soon as the next decade, owing to the damage caused by loggers and farming interests and the impacts of the climate crisis. If that happens, climate breakdown is likely to become much more severe in its impacts, and the world will have to cut down much faster on carbon-producing activities to counteract the loss of the carbon sinks.

One of the most worrying impacts of climate change has already begun, said Simon Lewis, professor in the school of geography at Leeds University, one of the senior authors of the research. “This is decades ahead of even the most pessimistic climate models.” For the last three decades, the amount of carbon absorbed by the world’s intact tropical forests has fallen, according to the study from nearly 100 scientific institutions. They are now taking up a third less carbon than they did in the 1990s, owing to the impacts of higher temperatures, droughts and deforestation. That downward trend is likely to continue, as forests come under increasing threat from climate change and exploitation. The typical tropical forest may become a carbon source by the 2060s, according to Lewis. Humans have been lucky so far, as tropical forests are mopping up lots of our pollution, but they can’t keep doing that indefinitely. We need to curb fossil fuel emissions before the global carbon cycle starts working against us. The time for action is now. At this year’s UN climate talks, known as Cop26 and to be held in Glasgow in November, many countries are expected to come forward with plans to reach net zero emissions by mid-century. But some rich countries and many companies plan to reduce their emissions via offsetting, often by preserving, replanting or growing new forest.

This study shows that relying on tropical forests is unlikely to be enough to offset large-scale emissions.

“There is a lot of talk about offsetting, but the reality is that every country and every sector need to reach zero emissions, with any small amount of residual emissions needing to be removed from the atmosphere. The use of forests as an offset is largely a marketing tool for companies to try to continue with business as usual.

The uptake of carbon from the atmosphere by tropical forests peaked in the 1990s when about 46bn tons were removed from the air, equivalent to about 17% of carbon dioxide emissions from human activities. By the last decade, that amount had sunk to about 25bn tones, or just 6% of global emissions. The difference is about the same as a decade of fossil fuel emissions from the UK, Germany, France, and Canada put together.

Climate scientists have long feared the existence of “tipping points” in the climate system, which when passed will condemn the world to runaway global heating. There are many known feedback mechanisms: for instance, the melting of Arctic ice leaves more of the sea uncovered, and, as it is darker than the reflective ice, it absorbs more heat, thus leading to more melting.

These feedback mechanisms have the potential to accelerate the climate crisis far ahead of what current projections suggest. If forests start to become sources of carbon rather than absorbers of it, that would be powerful positive feedback leading to much greater warming that would be hard to stop. Forests lose their ability to absorb carbon as trees die and dry out from drought and higher temperatures, but the loss of forest area from logging, burning and other forms of exploitation is also a leading factor in the loss of carbon sinks.

Tom Crowther, founder of the Crowther Lab, who was not involved with the research, told the Guardian: “This analysis provides concerning evidence that, along with continuing deforestation rates, the carbon sequestration rate of tropical forests could also be threatened by increasing tree mortality under climate change. This is very important information, as the capacity of tropical forests to capture anthropogenic carbon emissions could be severely impaired.”

The study, published in the journal Nature, tracked 300,000 trees over 30 years, providing the first large-scale evidence of the decline in carbon uptake by the world’s tropical forests. The researchers combined data from two large research networks of forest observations in Africa and the Amazon, as well as years spent travelling to remote field sites, including a week spent in a dug-out canoe to reach Salonga national park in the troubled Democratic Republic of the Congo.

They used aluminum nails to tag individual trees, measuring the diameter and estimating the height of every tree within 565 patches of forest, and returning every few years to repeat the process. This enabled them to calculate the carbon stored in the trees that survived and those that died. They found that the Amazon sink started weakening first, but that African forests are now rapidly following. Amazonian forests are exposed to higher temperatures, faster temperature increases, and more frequent and severe droughts, than African forests. Their projection that the Amazonian Forest will turn into a carbon source in the mid-2030s is based on their observations and a statistical model and trends in emissions, temperature, and rainfall to forecast changes in how forests will store carbon up to 2040 (The Guardian, 2020).

Conclusions

The increased natural land sink has so far occurred despite increased large-scale human disruptions to ecosystems, such as deforestation and degradation of natural areas, but it cannot be taken for granted in the future. There is now evidence that some of the largest carbon sinks of the planet have already saturated, particularly in tropical ecosystems, due to different reasons. First, there are processes that could eventually limit the sink. In particular, low availability of certain nutrients such as nitrogen and phosphorus, reduce the ability of global ecosystems to translate the increased photosynthesis into increased biomass and thus carbon storage. Recent studies highlight how CO_2 fertilization effects on vegetation photosynthesis are globally declining as a result of these and other offsetting factors such as water limitations. Second, there are regionally specific processes that determine the net balance of the natural land sink and the net land-use change flux. While certain tropical regions appear to be at or near sink saturation, other regions such as boreal and temperate zones continue to see their sink capacity increasing. The decrease of the net sink in the tropics is mainly due to human LUC such as deforestation, while several factors drive increase in boreal forests, such as growing season extension and regrowth of forests from past disturbances. In some regions there is also an increase in forest mortality due to changes in the frequency of extreme weather events. This research shows that relying on tropical forests is unlikely to be enough to offset large-scale emissions. Several knowledge gaps exist regarding the future potential of the natural land sink and although it is now widely acknowledged that CO_2 affects the productivity of global ecosystems, it is still unclear exactly to what extent this occurs. Better quantification of land-use change fluxes is thus key for a better understanding of the natural land sink. Land management is still an important unknown, but practices that focus on decarbonization and simultaneously address food security, land-degradation and desertification are urgently needed. There is a lot of talk about offsetting, but the reality is that every country and every sector need to reach zero emissions, with any small amount of residual emissions needing to be removed from the atmosphere. The use of forests as an offset is largely a marketing tool for companies to try to continue with business as usual. Thus, this study is a valuable source of information intended for use by graduate and undergraduate students, scientists, forest managers and policy makers.

Recommendations

The future will depend on how we manage land. Different climate strategies based on nature-based solutions, such as the protection and sustainable management of ecosystems, the application of ecosystem-based approaches and of soil carbon sequestration (SCS) currently exist. If well implemented, these strategies could potentially contribute to the goal of staying well below 2°C. However, approaches based on global afforestation need to take into account the potential negative impacts and trade-offs of tree planting. Focused attention on these knowledge gaps can help narrow down projections of the expected trajectory of the land sink under various socio-economic pathways, to better inform effective policy design.

References

1. Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A. & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015. Sci. Data 5, 1–12.
2. Alam, M.A, et.al., (2021), Knowing Climate Change: Knowledge, Perceptions, and Awareness (KPA) among Higher Education Students in Eritrea, Disaster Advances, Volume. 14, No. 3, pp.30-39.
3. Alexander I, Selosse M-A (2009). Mycorrhizas in tropical forests: a neglected research imperative. New Phytol 182:14–16.
4. Almeida, C. Ade et al. (2016). High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data. Acta Amaz 46, 291–302.
5. Anderegg, W. et al. (2020). Climate-driven risks to the climate mitigation potential of forests. Science 368, eaaz7005.
6. Anderson, L. O. et al. (2018). Vulnerability of Amazonian forests to repeated droughts. Philos. Trans. R. Soc. B Biol. Sci. 373, 20170411.
7. Aragão, L. E. O. C. et al. (2014). Environmental change and the carbon balance of Amazonian forests. Biol. Rev. 89, 913–931.
8. Aragão, L. E. O. C. et al. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nat. Commun. 9, 536.
9. Avitabile, V. et al. ((2016). An integrated pan-tropical biomass map using multiple reference datasets. Glob. Chang. Biol. 22, 1406–1420.
10. Baccini A, Laporte N, Goetz SJ, Sun M, Dong H (2008). A first map of tropical Africa's aboveground biomass derived from satellite imagery. Environ Res Lett 3, doi:10.1088/1748-9326/3/4/045011.
11. Baccini, A. et al. ((2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nat. Clim. Chang. 2, 182–185.
12. Bastin, J.F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C.M., Crowther, T.W., (2019). The global tree restoration potential. Science 365 (6448), 76–79.
13. Bonan GB (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449.
14. Bongers, F., Chazdon, R. L., Poorter, L. & Peña-Claros, M. (2015). The potential of secondary
15. forests. Science 348, 642–643.

16. Bouillon S, Borges AV, Castañeda-Moya E, Diele K, Dittmar T, Duke NC, Kristensen E, Lee SY, Marchand C, Middelburg JJ, Rivera-Monroy VH, Smith III TJ, Twilley RR (2008). Mangrove production and carbon sinks: a revision of global estimates. Global Biogeochem Cy 22, GB2013, doi:10.1029/2007GB003052. Brewer PG, Friederich C, Peltzer ET, Orr FM, (1999). Science, 284:943.
17. Bullock, E. L., Woodcock, C. E., Souza, C. & Olofsson, P. (2020). Satellite-based estimates reveal widespread forest degradation in the Amazon. Glob. Chang. Biol. 26, 2956–2969.
18. Canadell JG, et al., (2007). Proceedings of the National Academy of Sciences, 104:18866.
19. Chazdon, R. L. et al. (2016). Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. Sci. Adv. 2, e1501639.
20. Clark DA (2007). Detecting tropical forests' response to global climatic and atmospheric change: current challenges and a way forward. Biotropica 39:4–19.
21. Cook-Patton, S. C. et al. (2020). Mapping carbon accumulation potential from global natural forest regrowth. Nature 585, 545–550.
22. Crouzeilles, R. et al. (2020). Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. Conserv. Lett. 13, 1–9.
23. Cusack DF, Chou WW, Yang WH, Harmon ME, Silver WL, Team TLIDET (2009). Controls on long-term root and leaf litter decomposition in neotropical forests. Global Change Biol 15:1339–1355.
24. Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran S, da Silva Dias PL, Wofsy SC, Zhang X (2007). Couplings between changes in the climate system and biogeochemistry. In: Intergovernmental panel on climate change (ed). Climate change 2007: the physical science basis, Chapter 7. Cambridge University Press, Cambridge.
25. Didan, K. (2015). MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006. NASA EOSDIS Land Processes DAAC.
26. Elias, F. et al. (2020). Assessing the growth and climate sensitivity of secondary forests in highly deforested Amazonian landscapes. Ecology 101, e02954.
27. Esquivel-Muelbert, A. et al. (2019). Compositional response of Amazon forests to climate change. Glob. Chang. Biol. 25, 39–56.
28. Esquivel-Muelbert, A. et al. (2020). Tree mode of death and mortality risk factors across Amazon forests. Nat. Commun. 11, 5515.
29. FAO (Food and Agricultural Organization of the United Nations) (2007). The world's mangroves 1980–2005. FAO Forestry paper 153. FAO, Rome.
30. Fisher JI, Hurtt GC, Thomas RQ, Chambers JQ (2008). Clustered disturbances lead to bias in large-scale estimates based on forest sample plots. Ecol Lett 11:554–563. forests. Science 348, 642–643.
31. Friedlingstein P, et al., (2006). Journal of Climate, 19:3337.
32. Funk, C. et al. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 1–21.
33. Gilbert GS, Strong DR (2007). Fungal symbionts of tropical trees. Ecology 88:539–540.
34. Gloor M, Phillips OL, Lloyd JJ, Lewis SL, Malhi Y, Baker TR, López-Gonzalez G, Peacock J, Almeida S, Alves de Oliveira AC, Alvarez E, Amaral I, Arroyo L, Aymard G, Banki O, Blanc L, Bonal D, Brando P, Chao K-J, Chave J, Dávila N, Erwin T, Silva J, Di Fiore A, Feldpausch T, Freitas A, Herrera R, Higuchi N, Honorio E, Jiménez E, Killeen T, Laurance W, Mendoza C, Monteagudo A, Andrade A, Neill D, Nepstad D, Núñez Vargas P, Peñuela MC, Peña Cruz A, Prieto A, Pitman N, Quesada C, Salomáo R, Marcos Silveira M, Schwarz J, Stropp F, Ramírez H, Ramírez A, Rudas H, ter Steege N, Silva N, Torres A, Terborgh J, Vásquez R, van der Heijden G (2009). Does disturbance hypothesis

explain the biomass increase in basin-wide Amazon forest plot data? Glob Change Biol doi: 10.1111/j.1365-2486.2009. 01891.x.

35. Grace J, Malhi Y, Higuchi N, Meir P (2001.) Productivity of tropical rain forests. In: Roy J, Saugier B, Mooney HA (eds) Terrestrial global productivity. Academic, San Diego, CA, pp 401–426.
36. Grainger A (2008). Difficulties in tracking the long-term global trend in tropical forest area. Proc Natl Acad Sci USA 105:818–823.
37. Grassi, G. et al. ((2017).) The key role of forests in meeting climate targets requires science for credible mitigation. Nat. Clim. Chang. 7, 220–226.
38. Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikam¨aki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., (2017). Natural climate solutions. Proc. Natl. Acad. Sci. U. S. A. 114 (44), 11645–11650.
39. Hansen JE, (2005). Climatic Change, 68:269.
40. Hawes, J. E. et al. (2020). A large-scale assessment of plant dispersal mode and seed traits across human-modified Amazonian forests. J. Ecol. 108, 1373–1385.
41. Hoffert MI, et al., (2002). Science, 298:981
42. House KZ, Schrag DP, Harvey CF, Lackner KS, (2006). Proceedings of the National Academy of Sciences of the United States of America, 103:12291.
43. Hubau, W. et al. ((2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579, 80–87.
44. Huston MA, Wolverton S (2009). The global distribution of net primary production: resolving the paradox. Ecol Monogr 79:343–377.
45. IPCC: (2005). Special Report: Carbon Dioxide Capture and Storage Edited by: BM et al. Cambridge University Press.
46. IPCC: (2007). Climate Change Cambridge University Press.
47. Jakovac, C. C., Peña-Claros, M., Kuyper, T. W. & Bongers, F. (2015). Loss of secondary-forest resilience by land-use intensification in the Amazon. J. Ecol. 103, 67–77.
48. Jindal, R., Swallow, B., & Kerr, J. (2008). Forestry-based carbon sequestration projects in Africa: Potential benefits and challenges. In Natural Resources Forum (Vol. 32, No. 2, pp. 116-130). Oxford, UK: Blackwell Publishing Ltd.
49. Kalamandeen, M. et al. (2018). Pervasive rise of small-scale deforestation in Amazonia. Sci. Rep. 8, 1–10.
50. Keddy PA, Fraser LH, Solomeshch AI, Junk WJ, Campbell DR, Arroyo MTK, Alho CJR (2009). Wet and wonderful: the world’s largest wetlands are conservation priorities. Bioscience 59:39–51.
51. Kerr, S., Pfaff, A., & Sanchez, A. (2001). The dynamics of deforestation and the supply of carbon sequestration: Illustrative results from Costa Rica. Central America Project, Environment: Conservation and Competitiveness, 409-431.
52. Koenig R (2008). Critical time for African rainforests. Science 320:1439–1441.
53. Kula, E., (2010). Afforestation with carbon sequestration and land use policy in Northern Ireland. Land Use Policy 27, 749–752.
54. Landsberg JJ, Gower ST (1997). Applications of physiological ecology to forest management. Academic, San Diego, CA.
55. Lennox, G. D. et al. (2018). Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Glob. Chang. Biol. 24, 5680–5694.
56. Levine, N. M. et al. (2016). Ecosystem heterogeneity determines the ecological resilience of the Amazon to climate change. Proc. Natl Acad. Sci. USA 113, 793–797.
57. Levy S (2007). Running hot and cold: Are rainforests sinks or taps for carbon? Bio Science 57:552–557.

58. Lewis SL (2006). Tropical forests and the changing earth system. Philos Trans R Soc Lond B 361:195–210.

59. Lewis SL, Lopez-Gonzalez G, Sonké B, Affum-Baffoe K, Baker TR, Ojo LO, Phillips OL, Reitsma JM, White L, Comiskey JA, M-N DK, Ewango CEN, Feldpausch TR, Hamilton AC, Gloor M, Hart T, Hladik A, Lloyd J, Lovett JC, Makana J-R, Malhi Y, Mbago FM, Ndangalasi HJ, Peacock J, S-H PK, Sheil D, Sunderland T, Swaine MD, Taplin J, Taylor D, Thomas SC, Votere R, Wöll H (2009). Increasing carbon storage in intact African tropical forests. Nature 457:1003–1007.

60. Lorenz, K., & Lal, R. (2009). Carbon sequestration in forest ecosystems. Springer Science & Business Media.
61. Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA (2008). Climate change, deforestation, and the fate of the Amazon. Science 319:169–172.
62. Mapbiomas Brasil. (2018). Project MapBiomas—Collection 3.1 of Brazilian Land Cover and Use Map Series.

63. MCT. (2016). Third National Communication of Brazil to the United Nations Framework Convention on Climate Change.
64. Melillo JM, McGuire AD, Kicklighter DW, Moore B III, Vorosmarty CJ, Schloss AL (1993) Global climate change and terrestrial net primary production. Nature 363:234–240.

65. Mercado, L. M. et al. (2009). Impact of changes in diffuse radiation on the global land carbon sink. Nature 458, 1014–1017.
66. Micales JA, Skog KE: International Biodeterioration & Biodegradation 1997, 39:145.
67. Ministério do Meio Ambiente (2016). REDD+ and Brazil’s Nationally Determined Contribution.
68. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000). Biodiversity hotspots for conservation priorities. Nature 403:853–858.
69. Nakicenovic N, et al., (2000). Special Report on Emissions Scenarios Cambridge University Press.
70. Nunes, S. Jr., Oliveira, L., Siqueira, J., Morton, D. C. & Souza, C. M. (2020). Unmasking secondary vegetation dynamics in the Brazilian Amazon. Environ. Res. Lett. 15, 034057.
71. O'Neill BC, (2004). Oppenheimer M: Proceedings of the National Academy of Sciences of the United States of America, 101:16411.
72. Pacala S, Socolow R, (2004). Science, 305:968.9,10.
73. Pan, Y. et al. (2011). A large and persistent carbon sink in the world’s forests. Science 333, 988–993.
74. Poorter, L. et al. (2016). Biomass resilience of Neotropical secondary forests. Nature 530, 211–214.

75. Poorter, L. et al. (2019). Wet and dry tropical forests show opposite successional pathways in wood density but converge over time. Nat. Ecol. Evol. 3, 928–934.
76. PRODES, (2020). TerraBrasilis—Taxas anuais de sesmatamento na Amazônia Legal Brasiliera.
77. Reich P, Eswaran H (2006). Global resources. In: Lal R (ed) Encyclopedia of soil science. Taylor & Francis, Boca Raton, FL, pp 765–768.
78. Requena Suarez, D. et al. (2019). Estimating aboveground net biomass change for tropical and subtropical forests: refinement of IPCC default rates using forest plot data. Glob. Chang. Biol. 25, 3609–3624.
79. Santoro, M. & Cartus, O. (2019). ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the year 2017, v1. Centre for Environmental Data Analysis.
80. Schneider SH, Mastrandrea MD, (2005). Proceedings of the National Academy of Sciences of the United States of America, 102:15728.
81. Schrag DP, (2007). Science, 315:812.
82. Sierra CA, Harmon ME, Moreno FH, Orrego SA, Del Valle JI (2007). Spatial and temporal variability of net ecosystem production in a

tropical forest: testing the hypothesis of a significant carbon sink. Glob Change Biol 13:838–853.

83. Silva Junior, C. H. L. et al. (2020). Benchmark maps of 33 years of secondary forest age for Brazil. Sci. Data 7, 269.
84. Smith, C. C. et al. (2020). Secondary forests offset less than 10% of deforestation mediated carbon emissions in the Brazilian Amazon. Glob. Chang. Biol.
85. Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA, Voll E, McDonald A, Lefebvre P, Schlesinger P (2006). Modelling conservation in the Amazon basin. Nature 440:520–523.
86. Song, X. P., Huang, C., Saatchi, S. S., Hansen, M. C. & Townshend, J. R. ((2015). Annual carbon emissions from deforestation in the Amazon basin between 2000 and 2010. PLoS ONE 10, 1–21.
87. Stephenson NL, van Mantgem PJ (2005). Forest turnover rates follow global and regional patterns of productivity. Ecol Lett 8:524–531.
88. Stern N, (2007). The Economics of Climate Change Cambridge University Press, Cambridge, UK.
89. The Guardian (2020). Trees and Forests: Tropical forests losing their ability to absorb carbon, study finds.
90. Toledo, R. M. et al. (2020). Restoring tropical forest composition is more difficult, but recovering tree-cover is faster, when neighbouring forests are young. Landsc. Ecol. 35, 1403–1416.
91. Uhl, C., Buschbacher, R. & Serrão, E. A. (1988). Abandoned pastures in Eastern Amazonia. I. Patterns of plant succession. J. Ecol. 76, 663–681.
92. United Nations, (2015). Paris Agreement.

93. Uriarte, M. et al. (2016). Impacts of climate variability on tree demography in second growth tropical forests: the importance of regional context for predicting successional trajectories. Biotropica 48, 780–797.
94. Vieira, I. C. G., Gardner, T., Ferreira, J., Lees, A. C. & Barlow, J. (2014). Challenges of governing second-growth forests: A case study from the Brazilian Amazonian state of Pará. Forests 5, 1737–1752.
95. Wandelli, E. V. & Fearnside, P. M. Secondary vegetation in central Amazonia: land-use history effects on aboveground biomass. Forest Ecol. Manag. 347, 140–148. (2015).
96. Wang, Y. et al. (2020). Upturn in secondary forest clearing buffers primary forest loss in the Brazilian Amazon. Nat. Sustain.
97. Yang, Y., Saatchi, S., Xu, L., Keller, M. & Corsini, C. R. (2020). Interannual variability of carbon uptake of secondary forests in the Brazilian Amazon (2004–2014). Glob. Biogeochem. Cycles.
98. Zeng N: (2003). Advances in Atmospheric Sciences, 20:677.
99. Zeng N: (2007). Clim Past, 3:135.
100. Zeng, N. (2008). Carbon sequestration via wood burial. Carbon Balance and Management, 3(1), 1-12.
101. Zuquim, G. et al. (2019). Making the most of scarce data: mapping soil gradients in data-poor areas using species occurrence records. Methods Ecol. Evol. 10, 788–801.