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Focus on the role of forests and soils in meeting climate change mitigation goals: summary

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Abstract

It is clear that reducing greenhouse gas emissions alone is insufficient to avoid large global temperature increases. To avoid atmospheric concentrations of greenhouse gases that result in dangerous alterations of the climate, large reductions in carbon dioxide emissions from fossil fuel combustion and land use changes must be accompanied by an increase in atmospheric carbon dioxide sequestration. Natural Climate Solutions have become a major focus of climate policy. Land and ocean ecosystems remove and store atmospheric carbon, and forests play a major role. This focus collection includes papers that address three important aspects of the role for forests in meeting climate change mitigation goals: (i) *Carbon Accounting* of forest sinks and reservoirs, process emissions and carbon storage in forest products, (ii) the carbon dioxide dynamics of using *Forest Bioenergy* and (iii) the carbon cycle of *Tropical Forests*.

Introduction

This focus collection of papers examines the importance of forests and forest soils in meeting climate change mitigation goals. The goal of the 1992 UN Framework Convention on Climate Change (UNFCCC 1992) called for 'stabilization of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' Since that time, most national policies have focused on reducing emissions from fossil fuel combustion with relatively little attention to stabilizing, or increasing atmospheric carbon removal rates. Twenty-three years after the climate treaty, the 2015 Paris Climate Agreement (UNFCCC 2015a) included the role of forests in removing additional carbon dioxide from the atmosphere, specifically emphasizing reducing emissions by forest protection and by avoiding deforestation and forest degradation (REDD+). At the twenty-fifth conference of the parties in 2019, governments failed to come to agreement on carbon trading in large part because proposals did not accurately account for carbon credits for forest sinks in accordance with the provisions of the Paris Agreement (Washington Post 2019).

Climate scientists recognize the importance of considering the full carbon cycle to avoid excessive increases of atmospheric carbon dioxide that would cause irreversible warming and damaging climate change (Solomon *et al* 2009). The Paris Agreement set stringent temperature limits that the IPCC concludes in its 1.5 Degree Report will require reducing *net* emissions by 45% by 2030 and reaching net zero by 2050 (IPCC 2018). The 2019 UN Emissions Gap Report finds that to meet the Paris goals requires reducing *net* carbon dioxide emissions by 7.6% per year below 2010 levels for the next ten years starting in 2020 (UN Emissions Gap Report 2019). This requires the simultaneous reduction in carbon emissions and increasing sequestration. Neither of these efforts have been successful to date. Forests and soils can play an increased role in meeting these goals, through long-term carbon storage in plant biomass and soils, and by accounting for additional factors described in this focus issue. Accurate Monitoring, Reporting and Verification of carbon stocks and flows are essential for meeting the 1.5 °C limit on global average temperature rise agreed to in the Paris Climate Agreement (UNFCCC 2015b). For forests, this requires accurate accounting of carbon dioxide emissions to the atmosphere from land use change, including those resulting from forest management practices, soil loss, and forest sequestration rates by trees, forest soils and forest products.

Carbon accounting

As atmospheric carbon dioxide emissions continue to increase, there has been a flurry of untested and unverified mitigation strategies marketed to reduce emissions. Comprehensive accounting of forest sector greenhouse gas (GHG) budgets must be applied to emerging and proposed technologies before their broad-scale application, including:

(i) Bioenergy with carbon capture and storage (BECCS).

(ii) Tall wooden buildings using cross laminated timber (CLT).

(iii) Wood pellets and chips as fuel for industrial scale heat and electricity to replace coal and gas.

Each of these requires transparent and robust complete-carbon accounting from the harvest activities themselves to the manufacturing, transportation, emissions throughout product use to decomposition in landfills. It should also include changes in the net ecosystem carbon balance, which is biological uptake and release minus losses from harvest and fires.

In this focus collection, Hudiburg *et al* (2019) developed an accurate, transparent, and transferable accounting method of all forest-derived carbon for Washington, Oregon and California. They laid out details of a regionally calibrated life-cycle assessment that calculates forest-to-landfill forest sector emissions and sequestration that builds upon their earlier work on life cycle assessments to determine emissions from harvest for bioenergy production (Hudiburg *et al* 2011). The approach relies on data from thousands of forest inventory and analysis (FIA) plots and data on forest product output in each region.

They found that Washington, Oregon and California forests are still net carbon sinks because net forest carbon uptake resulting from biological processes exceed losses due to harvest, wood product use, and wildfire combustion. However, harvest removals reduced the natural forest sink the most and were 2–3x greater in Washington and Oregon than all other losses. More than 60% of carbon harvested in the region since 1900 has returned to the atmosphere, and the remainder is evenly divided between landfills and long-lived products. That is, long-lived products stored only 20% of the harvested carbon during the past 115 years. The researchers modified their life-cycle assessment to also track carbon losses from short- and long-lived products during operational use of buildings, and the net emissions from the forest sector was comparable to estimates in a previous paper (Law *et al* 2018) or sometimes higher. They found that Washington and Oregon have significantly underestimated forest sector emissions, and national inventories may underestimate the emissions (as a fraction of fossil fuel emissions) by 10%–24%, respectively (EPA 2018a). In high productivity forests of the western US, decreasing harvests on public lands and increasing rotation times on intensively-managed private forests are effective strategies for storing additional carbon in the forest sink and reducing emissions from the forestry sector.

Disagreement among life-cycle assessments occur because some analyses *assume* carbon neutrality up front, or ignore biogenic emissions from decomposition of wood products because the carbon released is *assumed* to be replaced by subsequent tree growth (EPA 2018b). Some analyses do not include the losses in the annual land carbon sink after harvest, or the combustion or decay of wood products. A large source of uncertainty is the credit taken for wood replacement for more fossil fuel intensive concrete and steel.

The paper by Harmon (2019) evaluated alternative approaches to quantifying substitution benefits. It has been claimed that substitution of wood for more fossil carbon intensive building materials like steel and concrete results in major climate mitigation benefits often exceeding those of the forests themselves. Harmon's sensitivity analysis of the underlying assumptions of these projections show long-term mitigation benefits may have been overestimated by two to one hundred times.

The uncertainty in claimed substitution benefits has been a contentious issue. Harmon indicated that analysis of potential substitution benefits must include the value and duration of the fossil carbon displacement, the actual longevity of buildings, and changes in the carbon budget of the forest supplying building materials. Previous studies assumed the energy substitution displacement values for wood increase over time because of improved efficiencies (e.g. Schlamadinger and Marland 1996). Harmon concludes that product substitution by wood will likely decrease over time because of improved technologies for producing cement and steel such as changing the composition of cement to reduce or eliminate emissions associated with heating limestone to 2700°F. However, increasing wood processing to create material suitable for tall buildings will increase emissions and thus decrease the displacement value. For example, laminated beams have 63%–83% more embodied energy than sawn softwoods, and because most of that energy is from fossil fuels, these beams sequester less net carbon than claimed.

Harmon concludes that if wood substitution for other materials is to be used as part of a climate mitigation strategy, then it will be necessary to avoid exceeding the amount of carbon displaced, reduce cross-sector leakage of carbon, and increase building longevity. In the Pacific Northwest which has high carbon density forests, this suggests that the best strategy depends upon the initial carbon balance of the forest and management conditions i.e. production forestry, or managed for multiple ecosystem services where timber production is not the primary motive. In previous studies it is found that conversion of mature and old forests with high carbon stocks to short rotation production forests leads to more net emissions to the atmosphere (Harmon *et al* 1990), even if some of the harvest is stored in long-term products and substitution for more fossil fuel intensive materials is counted.

In the third contribution on carbon accounting, Olguin *et al* (2018) assessed Mexico's climate mitigation potential for policy alternatives considered by the Mexican government. They included the carbon storage in forest ecosystems, harvested wood products and substitution benefits. They used the Canadian Carbon Budget model, inventory data, and a wood products model (Kurz *et al* 2009). They concluded that activities aimed at reaching a net-zero deforestation rate and a 10% increase in forest recovery can yield the highest net emissions reduction in the next few decades compared with business-as-usual (BAU). Scenarios that increased forest productivity and harvest rates always increased net emissions relative to BAU because the increased carbon uptake was too small to offset emissions associated with increasing harvest. The magnitude of emissions reduction among scenarios differed between subregions because of differences in their baseline deforestation rates and forest carbon density at maturity. The paper emphasizes the importance of assessing scenarios in different ecoregions where growth rates and historic management regimes differ and impact the baseline net ecosystem carbon balance. This is similar to findings in the Pacific North West US of Hudiburg *et al* (2019), where ~40% of the high productivity, high carbon density forests are private lands under short rotation forestry.

One of the major uncertainties in the analysis of future scenarios by Olguin *et al* (2018) was the quality of derived land use change data, which likely underestimated the rate of change and thus net emissions. The wood products model is not as detailed in tracking carbon as the Hudiburg *et al* (2019) life cycle assessment, and as indicated in Harmon (2019), the substitution benefits (displacement factors) have high uncertainty and are likely overestimated. Nonetheless, Olguin *et al* (2018) provide a valuable initial assessment of the potential biophysical greenhouse gas impacts of mitigation strategies identified in Mexico's Nationally Determined Contributions (NDCs) to reducing atmospheric carbon dioxide.

In the fourth paper in the focus collection, Favero *et al* (2018) conduct an economic analysis of the role of forests to mitigate climate change, and suggested albedo effects could be added to the analysis along with carbon sequestration. However, other research shows albedo effects on radiative forcing at the scale of actual land use change are minor and too weak to cause observable changes in temperature (Lee *et al* 2011). Simulations of afforestation of half of crop lands in boreal and temperate regions led to global cooling that was 20% lower than from carbon accounting alone (Betts 2011). In the tropics, afforestation was suggested to be more effective than carbon accounting alone because of increased evaporative cooling. If albedo were to be included in the analysis, then evapotranspiration should also be included (Cohn *et al* 2019). However, this is moot because the coarse scale of analysis is inadequate for accounting purposes at the scale of realistic mitigation activities.

Forest bioenergy

The five papers on forest bioenergy in this focus collection comprise a comprehensive set of analyses of the contribution to atmospheric carbon dioxide concentrations from burning wood for commercial scale heat and electricity. The amount of carbon emissions from utilizing forest bioenergy has been described by two competing narratives, and each is covered in this focus collection.

It has been argued by proponents that forest biomass is a renewable resource and is counted as such by the International Renewable Energy Agency (IRENA 2019). It is claimed to be low carbon by IEA Bioenergy (2019). This latter claim is based on the argument that if a replacement forest grows, it will eventually re-sequester the carbon dioxide released in combustion. The IPCC Fifth Assessment Report (IPCC AR5 2014). states unequivocally that 'The combustion of biomass generates gross GHG emissions roughly comparable to the combustion of fossil fuels.' In discussing the carbon neutrality claim, the AR5 notes the 'shortcomings of this assumption'.

The systems dynamics modeling by Sterman *et al* (2018a) in this issue, verifies that burning wood releases more carbon dioxide than coal per MWh of electricity, and that the time it takes replacement forests to reach atmospheric CO_2 concentration parity with coal may require up to a century or more. In other words, the average CO_2 concentration in the atmosphere is higher during the growth period than it would have been had the wood not been burned. During this time, the additional warming will cause changes such as melting glaciers and thawing permafrost that are not returned to their prior state once replacement trees recover the amount of carbon released in combustion.

Under favorable circumstances, a forest that has been harvested and burned may eventually absorb an amount of CO_2 equal to what it emitted. However, carbon neutrality is insufficient to meet climate goals because it is essential that more carbon dioxide be removed than is emitted in order to meet temperature limitation goals. An observation made by Sterman *et al* (2018a) and also by Law *et al* (2018) is that had the forest been permitted to continue growing beyond the first rotation, the forest carbon reservoir would now store substantially more carbon than at the end of the first period. This is additional carbon beyond carbon neutrality that is sequestered in forest biomass and soils, that is not in the atmosphere.

Additional studies support this conclusion. Erb *et al* (2018) demonstrate that forests could be absorbing twice as much carbon as currently, and Houghton and Nassikas (2018) estimate that if all secondary forests were allowed to continue growing, abandoned agricultural lands returned to forests and forest land conversion were halted, sequestration rates could be 4.3 GtC/y. A more recent study by Moomaw *et al* (2019) demonstrate that since the average age of most managed forests is so young, allowing some of them to grow to meet their ecological potential for carbon sequestration accelerates as the forest ages for decades to a century or more. They call this management practice Proforestation, and it has the advantage of being very low cost, much less labor intensive than afforestation or reforestation and does not require additional land. Brancalion *et al* (2019) find similar carbon storage benefits with forest restoration efforts. Lutz *et al* (2018) find that for 48 forests of all types globally, on average, half of the living biomass carbon is sequestered in the largest one percent diameter trees, and Stephenson *et al* (2014) determined that for hundreds of tree species, the sequestration rate increased with size. MacKey *et al* (2015), find sequestration continuing in primary intact forests. It is also known that forest soil carbon increases in older forests and can account for as much or more sequestered carbon as found in living trees.

In a comment on Sterman *et al* (2018a), Prisley *et al* (2018) only count the fossil fuel emissions associated with harvesting and producing wood pellets and claim that forest regrowth removes all of the carbon emitted during combustion. They pointed out that the scenarios used for calculating life-cycle emissions from harvested plantations described by Sterman *et al* (2018a) were unrealistically long, and identified additional differences between what was modeled and how forests are actually managed for bioenergy. Prisley calls for landscape scale accounting that is simultaneously absorbing carbon dioxide from remaining trees, and explains that productivity of plantations is maintained by high nitrogen and other nutrient inputs. However, neither Prisley nor the response by Sterman account for the very large contribution to global warming from nitrous oxide associated with nitrogen fertilization.

In their response, Sterman *et al* (2018b) demonstrates that landscape scale does not alter the amount of carbon in the atmosphere, and burning wood from sustainably managed plantations of short rotation stored even less carbon because these plantations never achieve high levels of carbon density during their lifetime. Similarly, the landscape scale does not alter the principle finding that there is more CO_2 in the atmosphere from burning wood for electricity for many decades to a century than from burning coal. Prisley also argues that the relatively low value of wood for forest bioenergy preferences timber production over bioenergy, but this ignores the very large subsidies being paid for forest biomass for electric power.

In addressing the argument that burning only forest residues for energy is carbon neutral, Booth (2018) develops a metric for determining the net equivalent emissions from this fuel source. She then determines the actual emissions over time using the net emissions impact factor (NEI). NEI is the 'ratio of cumulative net emissions to combustion, manufacturing and transport emissions.' This provides a means for comparing emissions from combustion of residues for energy and their alternative fate such as decomposition. She finds that pellet production from residues in the US result in 41%–95% of cumulative direct emissions that should be counted as contributing to atmospheric carbon additions by year ten. The lower value assumes that the alternative decomposition rate is rapid and the higher one that it is slow. These values decline over time, but are still significant after 50 years. This is less than the impact of burning whole trees, but is clearly not carbon neutral.

In a related literature review, Birdsey *et al* (2018) examine the climate, economic and environmental impacts of wood for bioenergy. They also examine bioenergy with carbon capture and storage (BECCS) that has been proposed as a means for closing the gap between emissions and sequestration rates (Jackson *et al* 2017). They find that BECCS is far from being developed to scale, and that the full implications of the vast plantation area needed for the fuel has not been demonstrated to be feasible. A study by Jacobson (2019) showed utilization of BECCS rather than using wind or solar to replace bioenergy always increases emissions and social cost. Birdsey *et al* conclude that net emissions of GHGs increase from forest bioenergy persists for decades or longer, in most cases and the increase depends on forest type, supply chain and impacts on forest ecosystems. They also note that alternative counterfactuals can lead to alternate conclusions on the net emissions. Importantly, they also consider albedo effects if replacement species differ from the original trees.

These findings highlight the problematic nature of the accounting system in which bioenergy emissions are counted in the land sector and only noted, but not counted in the energy sector. This point has also been made by the IPCC expert meeting on quantifying carbon in the Agriculture, Forestry and Other Land Uses (AFOLU) sector and by Hudiburg *et al* (2019). Current accounting provisions have the perverse effect of allowing the European Union, to import wood pellets from the US, and claim significant reductions in emissions by replacing emissions from coal in Europe with land use emissions that should be claimed by the United States (Searchinger *et al* 2009). Furthermore, the Renewable Energy Directive in the EU declares forest bioenergy to be zero carbon by definition regardless of what the scientific analysis determines. The US government also declares all forest bioenergy from 'sustainably managed' forests to be carbon neutral as well (Scientific American 2018). Because harvesting wood, preparing wood pellets and shipping them across the Atlantic and burning them is not carbon neutral nor is it economically viable, so European governments must subsidize this leakage (in UNFCCC parlance these are 'displaced emissions'). There are increasing calls from the scientific community to revise both UNFCCC accounting procedures and those of the European Union (Norton *et al* 2019).

Tropical forests

The importance of tropical forests in helping to meet climate change mitigation goals is widely recognized. There has been extensive past research on the topic, including the magnitude of atmospheric carbon sequestration potential (Bonan 2008, Pan *et al* 2011), the influence of deforestation and degradation on net carbon fluxes (Brando *et al* 2019, Fan *et al* 2019), and the co-benefits of tropical forests for simultaneously securing carbon stocks, preserving biodiversity and providing myriad ecosystems services and livelihoods (Stickler *et al* 2009, Jantz *et al* 2014). Indeed, tropical forests are a key component of international climate change mitigation policies, most notably policies that address reducing deforestation and forest degradation (REDD+), consistent with the 2015 Paris Agreement agreed to by the parties of the United Nations Framework Convention on Climate Change (UNFCCC). Goetz *et al* (2015) describe the increased capability of remote sensing to identify changes in carbon density in tropical and other forests to comply with REDD+.

This section includes four papers that specifically address the role of tropical forests in climate change mitigation. One of these (Cohn *et al* 2019) focuses on the role of deforestation on regional temperature, showing forest loss in the Amazon basin leads to both increasing air and land surface temperatures up to 50 km from the site of disturbance, with the most pronounced effects within a distance of 10 km. Specifically, using the global forest loss maps of Hansen *et al* (2014), they show maximum temperatures measured at 209 meteorological stations in undisturbed locations captured the influence of non-local land cover conversion as a result of advective transport across varying length-scales. These results are important because they demonstrate the impact of forest conversion on surface temperature is much greater than previously documented, with important implications for regional to global circulation patterns and precipitation.

Sanderman *et al* (2018) provide a global map of mangrove forest soil carbon at a resolution of 30 meters. The authors determine organic carbon stock (OCS) and organic carbon density (OCD) of the top 2 meters of mangrove forest soil, and utilize forest cover remote sensing to estimate the carbon changes between 2000 and 2015. They find that 77% of mangrove soil-carbon losses occurred in just three countries, Indonesia, Myanmar and Malaysia with two-thirds of that loss from Indonesia. The major cause is the conversion to aquaculture, agriculture and urban uses. The paper contains an especially useful table comparing the global area of mangrove forests and fourteen other ecosystems with estimates of the total soil carbon and carbon density of each type of ecosystem. While the total carbon in mangrove forest soil is relatively small compared to other ecosystems, the carbon density is high and many of these systems are continuing to accumulate carbon as sea levels rise.

The other two papers in this collection that focus on tropical forests address the economics of mitigating deforestation, particularly by considering the marginal abatement costs of emissions reduction relative to various types of agricultural plantations (Lu *et al* 2018) and the cost-effectiveness of emission reduction strategies out to 2050 (Busch and Engelmann 2017). Plantations in southeast Asia have expanded dramatically in recent years, generating tremendous income for countries exporting these commodities across the globe. At the same time, conversion of tropical forests to plantations has produced a wide range of negative environmental impacts, particularly when placed on peatlands resulting in massive carbon emissions from drying peat soils (Van der Werf *et al* 2009). Lu *et al* (2018) address a long-standing debate on the role of plantations within the REDD+ framework regarding the carbon sequestration benefits of plantations relative to natural forests and the various co-benefits and ecosystem services natural forests provide. Using a marginal abatement cost approach, they show that plantations in Kalimantan Indonesia established on degraded lands for agricultural purposes (e.g. oil palm and rubber) have an economic cost of emissions abatement that results in positive impacts on carbon stocks in areas that currently have low carbon density vegetation. Importantly, they also identify cases where plantations are not economically viable relative to participation in REDD+ compensation mechanisms, and thus where emissions that result from clearing natural forests for such activities can be avoided.

Busch and Engelmann (2017) also address the importance of emissions abatement costs by conducting a comprehensive analysis focused on projecting the cost-effectiveness of policies to reduce future deforestation across the tropics. Their effort leverages a suite of geospatial data layers to (i) project tropical deforestation from 2016 to 2050 under alternative policy scenarios and (ii) construct and apply marginal abatement cost curves for reducing emissions from tropical deforestation. Under a business-as-usual scenario, they project that about one-seventh the total area of tropical forest in the year 2000 (some 289 million hectares, the size of India) would be deforested between 2016 and 2050, with annual deforestation emissions rising by 42% and cumulatively releasing some 169 Gt CO_2. About half of these emissions would come from Latin America. To avoid such an outcome, which would further reduce the likelihood of limiting globally averaged surface temperature to a 2C increase by 2100, they focus on the potential effectiveness of introducing carbon pricing policies. They show a carbon price of \$50/tCO_2, with an average cost to land users of \$21/tCO_2, would reduce emissions from deforestation by 77.1 Gt CO_2 (45.7%) from 2016 to 2050. They conclude that reducing emissions from tropical deforestation via carbon pricing is a cost-effective action for mitigating climate change that could effectively augment implementation of national and subnational anti-deforestation policies, bilateral agreements, and pay-for-performance incentives under the REDD+ framework.

Summary

This special issue covers a range of topics linking forests and soils to climate change. The case is made that accurate accounting of forest carbon is essential for any governance system that seeks to manage carbon dioxide in the atmosphere. There has been disagreement on how to count carbon stored in long-lived products and from forest bioenergy. These papers provide clear evidence that natural forests are much better at storing carbon in trees and soils than in managed forests or forest products. Soil carbon is considered in the carbon analysis by Hudiburg and by Sterman and found to be a significant reservoir for carbon for the temperate forests studied. Sanderman's study of mangrove soils demonstrates not only their importance as a carbon sink and reservoir, but also the large economic benefits they create.

Tropical forests are especially important in addressing climate change because of the large reservoir of carbon stored in above-ground biomass, as well as for their extensive biodiversity that is essential to their continued existence. The accelerating loss of tropical forests significantly reduces the possibility of preventing excessive CO_2 atmospheric concentrations with potentially irreversible temperature increases along with massive declines in biodiversity. However, temperate and boreal forests also are major carbon sinks and reservoirs. Since temperate forests have been managed through frequent harvesting to remain relatively young and small, there is a major opportunity for them to sequester significant additional carbon as they rebound from earlier harvests.

Traditional forest management has been for the purpose of producing timber, fiber or energy. There is an urgent need to prioritize more forests to sequester additional carbon, support dwindling biodiversity and provide resilience to flooding from increasingly intense precipitation. The question is, 'which forests should be managed as industrial forests for products and which for addressing climate, biodiversity and related sustainability issues?' Forest management practices for commercial logging favor harvesting trees when they are economically optimal rather than allowing them to reach their potential for carbon storage. This keeps the average age of managed forests relatively young and trees small, yet carbon accumulation increases over time when forests are permitted to continue growing. Additional carbon could be stored in forests and forest soils if some forests were managed by proforestation to achieve their ecological potential for carbon storage. The carbon reservoir is greatest for intact, high biodiversity forests compared with forests managed primarily for timber and fuel production and will provide many additional resiliency and ecosystem services.

Atmospheric carbon dioxide and other greenhouse gases continue to increase despite 25 years of climate and forest agreements by governments to reduce emissions and increase sequestration rates. As the papers in this focus collection demonstrate, it is imperative that transparent carbon accounting accurately reflect what is actually happening in all types of forests, in soils, in forest products as well as when forest biomass is used as a fuel. Inaccurate claims and accounting will have serious adverse consequences for society in a rapidly changing climate.

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Data availability statement

No new data were created or analysed in this study.

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