Chapter 19

Synthesis and Conclusions

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If the world wants to meet its climate mitigation goals, forests – as both a sink and source – must be included. According to the 2007 IPCC report, deforestation and land use change currently account for a third of total anthropogenic global greenhouse gas emissions. Any comprehensive climate change policy must address this issue. At the same time, forests have a significant potential to sequester carbon. Their inclusion in a climate regime could have an immediate impact.

About half of terrestrial carbon is stored in forests, which can act as a sink or a source of carbon under different conditions and across temporal and spatial gradients. Best current estimates are that the terrestrial biome is acting as a small carbon sink, most likely occurring in forested ecosystems. Boreal and temperate forests are sequestering carbon (net sinks), while tropical forests are a net source of CO_2 emissions due to deforestation (land use change).

Understanding the role of forests in global carbon budgets requires quantifying several components of the carbon cycle, including how much carbon is stored in the world's forests (carbon pools), gains and losses of carbon in forests due to natural and anthropogenic processes (carbon fluxes), exchanges between the terrestrial carbon and other sinks and sources, and the ways in which such processes may be altered by climate change.

This extensive review of the literature on forest carbon science, management, and policy has produced several important conclusions, and elucidated what we currently do and do not know about forests, carbon, and climate change. They are summarized here as a contribution to the current knowledge base of how to preserve the carbon stock in the world's forests and potentially maintain forests as CO_2 sinks into the future.

THE SCIENCE OF CARBON UPTAKE AND CYCLING IN FORESTS

In order to better understand the ways in which future forests will change and be changed by shifting climates, it is necessary to understand the underlying **drivers of**

forest development and the ways these drivers are affected by changes in atmospheric carbon dioxide (CO_2) concentrations, temperature, precipitation, and nutrient levels. Successional forces lead to somewhat predictable **changes in forest stands** throughout the world. These changes can cause corresponding shifts in the dynamics of carbon uptake, storage, and release.

- Forest stands accumulate carbon as they progress through successional stages. Most studies show that the greatest rate of carbon uptake occurs during the stem exclusion stage, but mature stands also sequester and store significant quantities of carbon. This is even the case for old growth – particularly when such old forests represent significant portions of large areas such as the Amazon and Congo basins.
- Free Air Carbon dioxide Enrichment (FACE) experiments are suggesting that forest net primary productivity, and thus carbon uptake, usually increases with higher levels of atmospheric carbon dioxide, likely due to factors such as increased nitrogen use and water use efficiency and competitive advantages of shade tolerant species.
- Experiments dealing with drought and temperature change are providing evidence that water availability, especially soil moisture, may be the most important factor driving forest carbon dynamics.

Caveats

- Although we understand the stages of stand development, there is considerable unpredictability in the actual nature of species composition, stocking, and rates of development at each stage because of numerous positive and negative feedbacks that make precise understanding of future stand development difficult.
- Forest ecosystem experiments, such as FACE programs, have not been operating long enough to predict long term responses of forest ecosystems to increases in carbon dioxide. The expense and time constraints of field experiments force scientists to rely on multifactor models (the majority of which account for five or fewer variables) leading to results based on broad assumptions.

Soil organic carbon (SOC) stored and cycled under forests is a significant portion of the global total carbon stock, but remains poorly understood due to complex storage mechanisms and inaccessibility at depth.

- Alterations of soil carbon cycling by land use change or disturbance may persist for decades or centuries, confounding results of short-term field studies. Such differences must be characterized, and sequestration mechanisms elucidated, to inform realistic climate change policy directed at carbon management in existing native forests, plantations, and agroforestry systems, as well as reforestation and afforestation projects.

- Fine roots are the main source of carbon additions to soils, whether through root turnover or via exudates to associated mycorrhizal fungi and the rhizosphere.
- Bacterial and fungal, as well as overall faunal community composition, have significant effects (+/-) on soil carbon dynamics; fossil fuel burning, particulate deposition from forest fires, and wind erosion of agricultural soils are thought to affect microbial breakdown of organic matter and alter forest nutrient cycling.

Caveat

- The global nature of the carbon cycle requires a globally-distributed and coordinated research program, but thus far research has been largely limited to the developed world, the top 30 cm of the soil profile, temperate biomes, and agricultural soils. Forest soils in tropical moist regions are represented by only a handful of studies and even fewer have examined sequestration of mineral soil carbon at depth.

CARBON BUDGETING AND MEASUREMENT

- Quantifying carbon sources and sinks is a particular challenge in forested ecosystems due to the role played by biogeochemistry, climate, disturbance and land use, as well as the spatial and temporal heterogeneity of carbon sequestration across regions and forest types.
- While forests have the capacity to sequester significant amounts of carbon, the natural and anthropogenic processes driving carbon fluxes in forests are complex and difficult to measure. Nevertheless, accurate measurement of carbon stocks and flux in forests is one of the most important scientific bases for successful climate and carbon policy implementation. A measurement framework for monitoring carbon storage and emissions from forests should provide the core tool to qualify country and project level commitments under the United Nations Framework Convention on Climate Change, and to monitor the implementation of the Kyoto Protocol.
- Land use change is widely considered the most difficult component to quantify in the global carbon budget. Current consensus is that carbon emissions from land use change have remained fairly steady over the last few decades; however, there have been significant regional variations within this trend. Specifically, deforestation rates in the tropics, particularly in Asia, have grown substantially. In contrast, forests outside the tropics have been sequestering incremental carbon due to increased productivity (possibly because of CO_2 fertilization, although the evidence is not clear) and forest re-growth on lands that had been cleared for agriculture prior to industrialization.

- There are four categories of methods currently used to measure terrestrial carbon stocks and flows: i) the inventory method, based on biomass measurement data; ii) remote sensing techniques using satellite data; iii) eddy covariance method using CO_2 flux data from small experimental sites; and iv) the inverse method, using CO_2 concentration data and transport models. Each has advantages and disadvantages and varying degrees of accuracy and precision. No single method can meet the accuracy and resolution requirements of all users. A country, user or site will make a choice of method based on the specifics of the circumstances.
- Climate change is likely to generate both positive and negative feedbacks in forest carbon cycling. Positive feedbacks may include increased fire and tree mortality from drought stress, insect outbreaks, and disease. Negative feedbacks may include increased productivity from CO_2 enrichment. While the net result from positive and negative climate feedbacks is generally thought to be greater net carbon emissions from forests, the timing and extent of these net emissions are difficult to determine.
- Forest products are a minor, but growing component of the global carbon budget; nevertheless, harvested wood products can be long term reservoirs of carbon, particularly through substitution for more fossil carbon-intensive materials.
- Recycling postpones carbon emissions of even short-lived harvested wood products, and is especially effective when products are transformed multiple times within a tight recycling chain and finally converted into bioenergy.

Caveats

- If a standardized verification system across projects, countries, and regions is ever to be attained, policymakers should be aware that there are different basic approaches to measuring forest carbon, which have advantages and disadvantages, and varying degrees of accuracy and precision.
- Land use change is widely considered the most difficult component to quantify in the global carbon budget. The underlying data is often incomplete and may not be comparable across countries or regions due to different definitions of forest cover and land uses. Deforestation rates in the tropics are particularly difficult to determine due to these factors as well as differences in the way land degradation, such as selective logging and fuelwood removals, are accounted for in national statistics.
- Knowledge of the amount of carbon stored within each pool and across forest types is limited. Even estimates using broad categories such as carbon in vegetation versus soils vary widely due to a lack of data or assumptions about where carbon is stored within the forest and at what rate carbon is sequestered or released.

- New processed wood products and paper manufacturing require large energy and heat inputs, making wood products and carbon a complex topic.
- Landfilling harvested wood products creates high levels of methane, and if capture systems for energy are not in place, then the potential of landfills to act as carbon sinks becomes very unlikely. Therefore, landfill gas capture systems must be required if this end-of-use pathway is to be promoted as a way to reduce carbon emissions.
- The substitution effects on greenhouse gas emissions of wood for other construction materials (e.g., steel and concrete) may be up to 11 times larger than the total amount of carbon sequestered in forest products annually. However, quantification of substitution effects relies on many assumptions about particular counterfactual scenarios, most importantly linkages between increased/decreased forest products consumption and total extent of forestland.

TROPICAL FORESTS

Tropical forests contribute nearly half of the total terrestrial gross primary productivity and contain about 40% of the stored carbon in the terrestrial biosphere, with vegetation accounting for 58% and soil 41%. This ratio of vegetation carbon to soil carbon varies greatly by tropical forest type. About 8% of the total atmospheric carbon dioxide cycles through these forests annually. Vast areas of the world's large intact forests are in the tropics. Nevertheless, because of high rates of deforestation, tropical forests play a disproportionate role in contributing to terrestrial biome CO_2 emissions that both affect and mitigate climate.

- First and foremost, the primary risk to the carbon stored in tropical forests is deforestation, particularly converting forests to agriculture. Expanding crop and pasture lands have a profound effect on the global carbon cycle as tropical forests typically store 20-100 times more carbon per unit area than the agriculture that replaces them.
- In addition to the important role the remaining large intact forests play in the global carbon cycle, their protection from land conversion yields highly significant co-benefits. Evidence suggests that large, intact forests have significant cooling effects on both regional and global climates through the accumulation of clouds from forest evapo-transpiration, which also recycles water and contributes to the region's precipitation.
- Intact forests exist because of the geography of remoteness: low populations, lack of foreign investment, and lack of government presence have resulted in poor infrastructure development and the inability to integrate these regions into larger market structures.

- The significant drivers of deforestation (transportation infrastructure, agricultural commodity prices, national economic policies, agricultural technologies) are frequently context-specific and are affected by local political, socioeconomic, cultural, and biophysical factors. The roles of population growth and poverty in driving deforestation have often been overstated for certain regions (Africa may be an exception).
- The difference between the annual stand level growth (uptake: 2%) and mortality (release: 1.6%) of Amazonia is currently estimated to be 0.4%, which is just about enough carbon sequestered to compensate for the carbon emissions of deforestation in the region. This means that either a small decrease in growth or a small increase in mortality in mature forests could convert Amazonia from a sink to a source of carbon.
- CO_2 emitted from tropical soils is positively correlated with both temperature and soil moisture, suggesting that topical rain forest oxisols are very sensitive to carbon loss with land use change.
- Old growth ever-wet and semi-evergreen forests are experiencing accelerated stand dynamics and their biomass is increasing, particularly in Amazonian and Central African forests, potentially in response to increased atmospheric CO_2.
- Contrary to past assumptions, a significant portion of stored carbon exists below ground in tropical forests. Current estimates of root soil carbon in tropical forests could be underestimated by as much as 60%.
- If drought becomes more common in tropical ever-wet and semi-evergreen forests, as some climate models predict, the likelihood of human-induced fires escaping and impacting large portions of the landscape increases.
- Reduced impact logging (RIL) is an important practice to lessen carbon loss, but it is necessary to move beyond RIL to substantially increase carbon storage by developing more sophisticated, planned forest management schemes with silvicultural treatments that ensure regeneration establishment, post establishment release, and extended rotations of new stands.
- Land managers should not manage tropical forests only for timber production, but also to maximize and diversify the services and products they obtain from their forests. This approach will provide an increase in net present value and a possible solution to the problem of exploitation and land conversion.
- The largest potential source of carbon sequestration in the tropics is the development of second growth forests on old agricultural lands and agricultural plantation systems that have proven unsustainable. Every incentive should be provided to encourage this process. Many logged over and second growth forests are ideal candidates for rehabilitation through

enrichment planting of supplemental long-lived canopy trees for carbon sequestration.

- The overarching issues to be decided in developing an international policy to reduce emissions from tropical deforestation and forest degradation (REDD) include: the scope of the forestry activities to be covered; the scale of accounting for forestry activities and the baseline for measuring reference emissions levels; the type of financing to be provided for REDD activities; how to address fundamental issues of capacity and governance; and the consideration of co-benefits.

Caveats

- Large intact forests of the tropics are increasingly at risk of deforestation attributable to governmental stimulus plans, road building programs, and subsidies for livestock production.
- A lack of governance, coupled with the presence of infrastructure, is often a precondition for widespread illegal operations that promote deforestation (e.g. logging, illicit drug trade). On the other hand, a lack of governance with no infrastructure inhibits illegal operations that promote deforestation.
- Tropical dry deciduous and montane forests are almost a complete unknown because so little research has been done on these forest types. While the majority of dry deciduous forests in the Americas and Asia have been cleared, there is still a significant amount remaining in Africa.
- Uncertainties in both the estimates of biomass and rates of deforestation contribute to a wide range of estimates of carbon emissions in the tropics. Only three studies have analyzed land surface-atmosphere interactions in tropical forest ecosystems. It is essential to understand how carbon is taken up by plants and the pathways of carbon release, and how increasing temperatures could affect these processes and the balance between them.
- More research is needed on how the application of silvicultural practices affects carbon uptake and storage in tropical forests at all levels. Some work has been done in the rainforest regions (ever-wet and semi-evergreen), but only in very specific places; almost none has been done in montane or seasonal (dry deciduous) forests.
- It is clear that REDD policies are only part of the solution to reduce deforestation and promote carbon sequestration. What is required is a combination of policies and market mechanisms that simultaneously promote sustainable economic growth and reduce poverty and economic inequalities, while protecting forests from further clearing for agriculture.

TEMPERATE FORESTS

Twenty-five percent of the world's forests are in the temperate biome. They include a wide range of forest types, and the exact boundaries with boreal forests to the north and tropical forests to the south are not always clear. There is a great variety of species, soil types, and environmental conditions which lead to a diversity of factors affecting carbon storage and flux. Deforestation is not a major concern at the moment, and the biome is currently estimated to be a carbon sink of about 0.2 to 0.4 Pg C/year, with most of the sink occurring in North America and Europe.

- The future of the temperate forest biome as a carbon reservoir and atmospheric CO_2 sink rests mainly on its productivity and resilience in the face of disturbance. The small "sink" status of temperate forests could easily change to a "source" status if the balance between photosynthesis and respiration shifts even slightly.

- There is tremendous variability in carbon stocks between forest types and age classes; carbon stocks could easily be lost if disturbance or land use change shifts temperate forests to younger age classes or if climate change shifts the spatial extent of forest types. On the other hand, if temperate forests are managed for longer rotations, or more area in old growth reserves, then the carbon stock will increase.

- Temperate forests have been severely impacted by human use – throughout history, all but about 1% have been logged-over, converted to agriculture, intensively managed, grazed, or fragmented by sprawling development. Nevertheless, they have proven to be resilient – mostly second growth forests now cover about 40-50% of the original extent of the temperate forest biome.

- Soil carbon under temperate forests appears to be stable under most disturbances, such as logging, wind storms, and invasive species, but not with land use change. Huge losses can occur when converting forests to agriculture or development.

- Temperate forests are strongly seasonal, with a well-defined growing season that depends primarily on light (day length) and temperature. This is probably the most important determinant, along with late-season moisture, of temperate forest productivity and hence carbon sequestration.

- Natural disturbances, particularly windstorms, ice storms, insect outbreaks, and fire are significant determinants of temperate forest successional patterns. The frequency of stand-leveling windstorms (hurricanes, tornadoes) is expected to increase under a warmer climate in temperate moist broadleaf and coniferous forest regions, so that fewer stands would reach old-growth stages of development.

- If changing climate alters the frequency and intensity of fires, re-vegetation and patterns of carbon storage will likely be affected, particularly in interior coniferous forests.
- Storage of carbon in forests has played a major role in U.S. emission reduction efforts, particularly in the voluntary carbon markets. Considerable efforts have been underway to reduce emissions of greenhouse gases at the regional (Northeastern U.S.), state (California), municipal, corporate, and individual levels.

Caveats

- Atmospheric pollution, primarily in the form of nitrogen oxides (NOx) emitted from burning fossil fuels, and ozone (O_3) is a chronic stressor in temperate forest regions. Because most temperate forests are considered nitrogen-limited, nitrogen deposition may also act as a growth stimulant (fertilizer effect). Under current ambient levels, nitrogen deposition is most likely enhancing carbon sequestration; however, the evidence regarding long-term chronic nitrogen deposition effects on carbon sequestration is mixed.
- Data on mineral soil carbon stocks in temperate forests can only be considered approximations at this time as there is very little research on deep soil carbon (more than 100 cm).
- Global circulation models predict that increasing concentrations of atmospheric CO_2 will increase the severity and frequency of drought in regions where temperate forests are found. However, there is a great deal of uncertainty about how drought will affect carbon cycles.
- Although afforestation and reforestation projects are being considered under various global and national carbon policies, it is important to consider whether it is ecologically beneficial for the land to support trees. Afforestation or reforestation activities that require soil drainage or conversion of wetlands, as well as those that add stress to water-scarce areas, could create more public detriment than benefits.

BOREAL FORESTS

As one of the largest and most intact biomes, the boreal forest occupies a prominent place in the global carbon budget. While it contains about 13% of global terrestrial biomass, its organic-rich soils hold 43% of the world's soil carbon. At present this forest biome acts as a weak sink for atmospheric carbon. However, the conditions that make this true are tenuous, and evidence of rapid climate change at northern latitudes has raised concern that the boreal forest could change to a net source if the ecophysiological processes facilitating carbon uptake are sufficiently disrupted.

- Increased fire frequency could greatly increase carbon release, especially if it increases the decomposition of "old" carbon from the soil pool by increasing soil temperatures, degrading permafrost, and enhancing the rate of heterotrophic respiration.
- While fire is recognized as the dominant natural disturbance type over much of the boreal forest, insect outbreaks (and "background" insect damage during non-outbreak years) are also critically important. In some forest types, insect outbreaks exert the primary influence on age class distribution.
- It appears that climatic warming is shortening the fire return interval in many boreal forests, and speeding up the life cycles of damaging insects. This could result in a large release of carbon, quickly turning the boreal forests from a sink to a source of carbon. Canadian forests in particular are poised to release massive amounts of carbon as the result of die-off from insect infestations.
- The question of whether moisture availability will decline with climatic warming will probably determine whether warming enhances the boreal carbon sink or turns it into a source.
- Lichens and bryophytes in lowland saturated sites contain upwards of 20% of the above ground carbon. These communities have important effects on how carbon is stored in boreal soils. Thick moss layers limit heat gain from the atmosphere, creating cold and wet conditions that promote the development of permafrost, with limited decomposition, thus are important for carbon storage.
- If all the carbon pools, inputs and outputs are considered together, it appears that clearcut stands in boreal forests are carbon sources for the first decade after harvest (thanks to transient increases in respiration), after which they switch to sinks.

Caveats

- There is a tremendous amount of uncertainty in estimates of boreal carbon pools, because there have been so few studies in relation to the vast extent of the biome, and most have been done only in Canada and Fennoscandia.
- There is little quantifiable information about several important carbon pools, including fine root biomass and mycorrhizae, bryophyte and understory layers, and coarse woody debris and litter in Russia.
- Considering the importance of fire in boreal carbon dynamics, there is much that is not well understood, including extent, frequency, and intensity across the biome; and the interactions among fire intensity, nitrogen, and carbon.

MANAGING TEMPERATE AND BOREAL FORESTS FOR CARBON

Increasing forest carbon stocks in temperate and boreal regions is a matter of making adjustments to existing forests vs. undergoing extensive reforestation/afforestation. Most boreal and temperate forests are second growth and land conversion is minimal when compared to other regions of the world. Therefore, providing additional carbon storage is a matter of refining silvicultural practices to take advantage of site nuances and enhancement potential.

- Many forest management activities result in net carbon release and thus cannot demonstrate carbon additionality. Mechanisms should be developed to credit managers who can reduce carbon loss, not simply increase carbon gain.
- Resiliency treatments (such as fuel reduction thinning and prescribed fire) result in lowered vegetative carbon storage, but they help produce forests that are significantly less susceptible to catastrophic disturbance (with accompanying drastic carbon release).
- Regeneration harvests significantly reduce the carbon stocks in vegetation and also cause a transient increase in soil respiration, although the annual rate of carbon uptake will be greater in the regenerating stand. Harvested areas often remain net carbon sources for 10-30 years, after which they return to sinks.
- Drainage of wetlands for increased tree production can result in either net carbon gain or loss, depending on how deep the drainage is.
- Studies have shown that many forest practices have a minimal impact on the soil carbon pool, which is the most difficult pool to measure. Thus, it may be possible that offsets involving certain forestry practices could go forward without strict quantification of this pool. This should be tempered by the fact that little is known about the effects of harvesting on deep soil carbon pools
- Managing stands for maximum sustained yield or financially optimum rotation can result in non-optimal carbon storage. Such rotations are often too short to allow the stand to attain maximum biomass. As such, it is often possible to increase carbon sequestration by extending rotations.

Caveat

- If old forests *already exist*, however, it is almost never better to convert them to younger forests. Old-growth forests, especially in productive zones, often have very large pools of vegetative, bryophyte, and soil carbon in comparison to younger, managed forests.

SUMMARY

Forests are critical to the global carbon budget, and every effort should be made to conserve intact forests, whether they are primary tropical and boreal forests, or second growth, temperate forests. All evidence points to the global forest estate being a weak sink for atmospheric CO_2, as a result of a tenuous balance between the carbon sink from productivity in the temperate and boreal biomes and the net CO_2 emissions from the tropics due to large-scale deforestation. Changes in disturbance regimes (fire, storms, insect outbreaks, harvesting) in any of the major forested regions could easily tilt this balance one way or the other. And as these forests mature, their capacity to take up increasing levels of carbon commensurate with increases in CO_2 emissions will diminish. Future climate change effects on the forest carbon balance are difficult to predict: however, higher temperatures are likely to significantly influence the factors driving disturbance such as moisture, storms, and pest species ranges. Evidence of a "CO_2 fertilization effect" on forests is mixed, therefore it is difficult to predict whether or not continued increases in atmospheric CO_2 will counteract the negative influence of changes in disturbance frequency and intensity. Land use change, however, overwhelms all other factors, since continued deforestation in the tropics will most certainly push the "global forest" to being a net source of carbon emissions to the atmosphere instead of the sink it could be.