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PERSPECTIVE

Managing Forests for Climate Change Mitigation

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Forests currently absorb billions of tons of CO_2 globally every year, an economic subsidy worth hundreds of billions of dollars if an equivalent sink had to be created in other ways. Concerns about the permanency of forest carbon stocks, difficulties in quantifying stock changes, and the threat of environmental and socioeconomic impacts of large-scale reforestation programs have limited the uptake of forestry activities in climate policies. With political will and the involvement of tropical regions, forests can contribute to climate change protection through carbon sequestration as well as offering economic, environmental, and sociocultural benefits. A key opportunity in tropical regions is the reduction of carbon emissions from deforestation and degradation.

Forest ecosystems are important components of the global carbon cycle in at least two ways. First, terrestrial ecosystems remove nearly 3 billion tons of anthropogenic carbon every year (3 Pg C year^{-1}) through net growth, absorbing about 30% of all CO_2 emissions from fossil fuel burning and net deforestation (*1*, *2*). Forests are major contributors to this terrestrial carbon sink and its associated economic benefits (*1*). Second, 4 billion hectares of forest ecosystems (4×10^3 Mha; about 30% of the global land area) store large reservoirs of carbon, together holding more than double the amount of carbon in the atmosphere (*3*, *4*). Although the climate protection role of forests is in no doubt, it is complex to determine how much of the forest carbon sink and reservoir can be managed to mitigate atmospheric CO_2 buildup, and in what way.

A first approximation to the upper limit of carbon sequestration on land is the carbon emitted from historical land transformation, about 200 Pg C, mostly from the conversion of forests to nonforest land cover. Assuming that three-fourths of this carbon came from forest conversion and can be returned by reforestation over the next 100 years, the resulting potential sequestration of about 1.5 Pg C year^{-1} would reduce the atmospheric CO_2 concentration by 40 to 70 parts per million by 2100 (*5*). However, the achievable sequestration is only a fraction of this potential because of competing land needs (agriculture, bioenergy, urbanization, and conservation) and sociocultural considerations.

Four major strategies are available to mitigate carbon emissions through forestry activities: (i) to increase forested land area through reforestation (*6*), (ii) to increase the carbon density of existing forests at both stand and landscape scales, (iii) to expand the use of forest products that sustainably replace fossil-fuel CO_2 emissions, and (iv) to reduce emissions from deforestation and degradation.

Estimates covering a range of carbon prices suggest that reforestation could average 0.16 to 1.1 Pg C year^{-1} to 2100 (*7*–*9*) with land requirements up to 231 Mha. In one of the most comprehensive synthesis efforts undertaken so far, the Fourth Assessment of the Intergovernmental Panel on Climate Change estimated that an economic potential of 0.12 Pg C year^{-1} could be reached by 2030 at U.S. $20 per ton of CO_2, and more than 0.24 Pg C year^{-1} at U.S. $100 per ton of CO_2 (*10*, *11*). Land transformation requirements are large; for example, China has used 24 Mha of new forest plantations and natural forest regrowth to transform a century of net carbon emissions in the forest sector to net gains of 0.19 Pg C year^{-1} (*3*, *12*), offsetting 21% of Chinese fossil fuel emissions in 2000.

Net carbon sequestration can also be achieved by increased forest carbon density, through both stand-scale management and landscape-scale strategies such as longer harvesting cycles or reduced disturbances. Fire suppression and harvest exclusion in U.S. forests during the 20th century, although not implemented for the purpose of carbon sequestration, led to a 15% (8.1 Pg C) increase in forest biomass between 1927 and 1990 (*13*). The overall biophysical potential of management activities to increase carbon density can be substantial and comparable to that of reforestation (*10*).

Joint use of carbon sequestration and the provision of forest-derived products (e.g., timber and biomass for energy) will optimize the contribution of forestry in climate mitigation. Such options are particularly attractive in temperate regions where land availability is limited by high prices and strong competition with other land uses (Fig. 1). Although complexities in quantifying the net carbon benefits of some of these activities may limit their role in global carbon markets, they will have a place in national mitigation strategies, particularly when used synergistically with goals and policies other than climate mitigation. For instance, fire reduction policies that require the removal of undergrowth and occasional thinning can contribute to production of bioenergy.

Finally, reducing deforestation has high potential for cost-effective contributions to climate protection. Currently, 13 Mha year^{-1} are deforested, almost exclusively in tropical regions, with net emissions of 1.5 Pg C year^{-1} (*2*, *3*). Reducing rates of deforestation by 50% by 2050, and stopping deforestation when countries reach 50% of their current forested area, would avoid emissions equivalent to 50 Pg C (*14*). This "50:50:50:50" estimate shows that even with continuing deforestation over the next 40 years, the mitigation potential is large, in addition to protecting the sink capacity of forest for continued removal of atmospheric CO_2.

Combining all forestry activities together, there is economic potential to achieve 0.4 Pg C year^{-1} by 2030 using carbon sequestration and avoidance at U.S. $20 per ton of CO_2, and double this amount for prices under U.S. $100 per ton of CO_2 (*10*). These levels of carbon sequestration, of which one-third to one-half would be through avoided deforestation, could offset 2 to 4% of the 20 Pg C year^{-1} of projected emissions by 2030 on the basis of current growth rates (*2*, *15*). Tropical regions would account for 65% of the total offset (*10*).

Climate mitigation through forestry carries the risk that carbon stores may return to the atmosphere by disturbances such as fire and insect outbreaks, exacerbated by climate extremes and climate change. A recent increase in areas affected by wildfires and insect outbreaks has driven Canadian forests from a CO_2 sink (before 2000) to a source expected to continue for at least the next two to three decades (*16*). Similarly, increased forest biomass in the western United States caused by fire suppression and reduced harvesting rates over the past century is now threatened by a factor of 4 increase in fire frequency due to longer and hotter dry seasons (*17*). These new patterns of disturbances are reshaping the view held in the past that vast forest resources anywhere would always play a major role in climate mitigation.

There is indeed uncertainty about the future size and stability of the terrestrial carbon sink and stock. Most global coupled climate-carbon models show carbon accumulation during this

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century, largely aided by the fertilization effect of increasing atmospheric CO_2 (*18*). However, there are large uncertainties in the magnitude of the CO_2 fertilization effect (*19*), and vulnerable regions with large carbon stores have been identified that could lead to the release of hundreds of Pg C by the end of this century (*20*); these include peat swamp forests in Southeast Asia where climate models uniquely agree on a future drying trend (*21*), further stressing the need for conservation and reduced human impacts.

Although sequestering carbon in forests is good for the climate, forests also affect biophysical properties of the land surface such as sunlight reflectivity (albedo) and evaporation, with further implications for radiative forcing of climate. Climate models suggest that large reforestation programs in boreal regions would have limited climate benefits because of the substitution of bright snow-dominated regions for dark forest canopies (*22*, *23*). Conversely, the climate benefits of reforestation in the tropics are enhanced by positive biophysical changes such as cloud formation, which further reflects sunlight. These patterns of full radiative forcing reinforce the large potential of tropical regions in climate mitigation, discourage major land use changes in boreal regions, and suggest avoiding large albedo changes in temperate regions to maximize the climate benefits of carbon sequestration.

Forestry, and reforestation in particular—like any large-scale transformation of land use patterns—can lead to unintended environmental and socioeconomic impacts that could jeopardize the overall value of carbon mitigation projects. Concerns include decreased food security, reduced stream flows, and loss of biodiversity and local incomes (*24*). However, well-directed carbon sequestration projects, along with the provision of sustainably produced timber, fiber, and energy, will yield numerous benefits, including additional income for rural development, prospects for conservation and other environmental services, and support for indigenous communities (*10*, *25*). Principles of sustainability must govern the resolution of trade-offs that may arise from ancillary effects in order to simultaneously maximize climate change protection and sustainable development.

The challenges facing sustainable mitigation through forestry activities, anywhere but particularly in the tropics, are surmountable but large. They include the development of appropriate governance institutions to manage the transition to new sustainable development pathways. An example of this difficulty is the lack of a sustainable tropical timber industry despite two decades of national and international efforts. Currently, only 7% of all tropical timber trade comes from sustainably managed forests (*26*).

The potential of carbon sequestration will depend on the degree to which climate protection and ancillary benefits are aligned. The magnitude of this potential will be increased by high carbon prices driven by aggressive emission reduction targets, and by the political will to include forestry activities as part of mitigation portfolios. Sustainable involvement of tropical regions is essential to take up the full global potential for climate change mitigation through forestry.

Fig. 1. Plantations of *Pinus radiata* and *Eucalyptus nitens* in Gippsland (Victoria, Australia).

PHOTO: MICHAEL RYAN

References and Notes

1. Terrestrial land sink over the period 2000–2006 was 2.8 Pg C $year^{-1}$ (*2*) or 10.3 Pg CO_2 $year^{-1}$; forests and woodlands are the dominant component of this sink. Price of a ton of CO_2 in the European Trading Scheme was €25 in April 2008, with €1 ≈ U.S. \$1.56.
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