The Future of Forests

FORESTS HAVE HAD A PERVASIVE INFLUENCE ON THE EVOLUTION OF terrestrial life and continue to provide important feedbacks to the physical environment, notably climate. Today, studies of the world's forests are taking place against a backdrop of unprecedented change, largely resulting either directly or indirectly from human activity. In this special issue, we focus particularly on the future of forests in light of these changes.

Current research on the relationships of forests and climate are considered in a Review by Bonan (p. 1444), which provides an overview of how climate and forests are connected through physical, chemical, and biological processes that affect the carbon cycle, the hydrologic cycle, atmospheric composition, and the flow of solar energy and heat through the Earth system.

For scientists interested in forest dynamics (the turnover of individual trees and species over time), long-term forest plots are yielding field data on processes that take place over time scales longer than a research career. Until recently, though, the development of predictive models of forest dynamics lagged behind observation. In a Perspective, Purves and Pacala (p. 1452) explain how advances in the mathematics of forest modeling and the ecological understanding of forest communities are generating exciting new possibilities for mapping future trajectories of forests over times from decades to centuries. At longer time scales, pollen and macrofossil records, along with genetic data, have revealed past movements of species as climates changed, which in turn provide pointers to the direction of future change, as discussed by Petit *et al.* in a Perspective (p. 1450).

Three further Perspectives deal with aspects of sustainable forest management. Miles and Kapos (p. 1454) consider the question of incentives for "avoided deforestation" in the context of the recent Bali conference on climate change; Canadell and Raupach (p. 1456) discuss how carbon sequestration can protect against the effects of climate change; and Chazdon (p. 1458) considers how forests and their ecosystem services can be restored on degraded lands. In another Perspective, Agrawal *et al.* (p. 1460) spotlight some recent trends in forest governance and ownership, which in effect define the limits and opportunities for sustainability.

The three News reports take a look at how humans have reshaped wooded landscapes across the globe. Stokstad (p. 1436) takes stock of a large-scale assessment of Amazonian biodiversity in regenerating forests and tree farms. Koenig (p. 1439) examines the precariousness of the extensive rainforests in the Democratic Republic of the Congo. Morell (p. 1442) reports on the success of preservation efforts in China's Hengduan Mountain Region, one of the richest temperate forest ecosystems.

Forests and trees have been intimately bound up with the emergence and cultural development of our own species. Their future, and that of human society, depends ever more on how humans treat them in the coming decades.

–ANDREW SUGDEN, JESSE SMITH, ELIZABETH PENNISI

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Science

REVIEW

Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests

Gordon B. Bonan

The world's forests influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition. These complex and nonlinear forest-atmosphere interactions can dampen or amplify anthropogenic climate change. Tropical, temperate, and boreal reforestation and afforestation attenuate global warming through carbon sequestration. Biogeophysical feedbacks can enhance or diminish this negative climate forcing. Tropical forests mitigate warming through evaporative cooling, but the low albedo of boreal forests is a positive climate forcing. The evaporative effect of temperate forests is unclear. The net climate forcing from these and other processes is not known. Forests are under tremendous pressure from global change. Interdisciplinary science that integrates knowledge of the many interacting climate services of forests with the impacts of global change is necessary to identify and understand as yet unexplored feedbacks in the Earth system and the potential of forests to mitigate climate change.

Forests cover ~42 million km^2 in tropical, temperate, and boreal lands, ~30% of the land surface (Fig. 1A). These forests provide ecological, economic, social, and aesthetic services to natural systems and humankind (1), including refuges for biodiversity, provision of food, medicinal, and forest products, regulation of the hydrologic cycle, protection of soil resources, recreational uses, spiritual needs, and aesthetic values. Additionally, forests influence climate through exchanges of energy, water, carbon dioxide, and other chemical species with the atmosphere.

Forests store ~45% of terrestrial carbon (Fig. 1B), contribute ~50% of terrestrial net primary production (2), and can sequester large amounts of carbon annually (Fig. 1C). Carbon uptake by forests contributed to a "residual" 2.6 Pg C year^{-1} terrestrial carbon sink in the 1990s, ~33% of anthropogenic carbon emission from fossil fuel and land-use change (3). Forests have low surface albedo and can mask the high albedo of snow (Fig. 1D), which contributes to planetary warming through increased solar heating of land. Forests sustain the hydrologic cycle through evapotranspiration, which cools climate through feedbacks with clouds and precipitation. The ratio of evapotranspiration to available energy is generally low in forest compared with some crops and lower in conifer forest than in deciduous broadleaf forest (Fig. 1E).

That forests influence climate has long been postulated. From the onset of European settlement of North America, it was believed that clearing of forests for cultivation, wood products, and settlement altered climate (4). Today, scientists have a diverse array of methodologies, including

eddy covariance flux towers, free-air CO_2 enrichment systems, satellite sensors, and mathematical models to investigate the coupling between forests and the atmosphere. It is now understood that forests and human uses of forests provide important climate forcings and feedbacks (3), that climate change may adversely affect ecosystem functions (5), and that forests can be managed to mitigate climate change (6). What is lacking, however, is science that integrates the many interacting climate services of forests with the impacts of global change to inform climate change mitigation policy.

Accordingly, this article reviews biosphere-atmosphere interactions in tropical, temperate, and boreal forests. Emphasis is placed on biogeophysical processes (albedo and evapotranspiration) (7), their comparison with biogeochemical processes (carbon cycle) (8), and alteration of forest-atmosphere coupling through biogeographical processes (land use and vegetation dynamics) (9).

The Ecology of Climate Models

The influence of forests on large-scale climate is difficult to establish directly through observations. Careful examination of climatic data can sometimes reveal an ecological influence, such as the effect of leaf emergence on springtime evapotranspiration and air temperature. Eddy covariance flux towers and field experiments provide local-scale insight to forest-atmosphere interactions, and advances in remote sensing science can aid extrapolation of this knowledge to larger spatial scales. More often, however, our understanding of how forests affect climate comes from atmospheric models and their numerical parameterizations of Earth's land surface (10). Paired climate simulations, one

serving as a control to compare against another simulation with altered vegetation, demonstrate an ecological influence on climate.

Atmospheric models require fluxes of energy, moisture, and momentum at the land surface as boundary conditions to solve numerical equations of atmospheric physics and dynamics. The first generation of land surface parameterizations developed in the late 1960s and 1970s used bulk aerodynamic formulations of energy exchange without explicitly representing vegetation [supporting online material (SOM)]. Soil water availability regulates latent heat flux, and the hydrologic cycle, when included, was simplified to a "bucket" model of soil water. In this approach, precipitation fills the soil column up to a specified water-holding capacity, beyond which rainfall runs off.

By the mid-1980s, the second generation of land surface parameterizations, included the hydrologic cycle and the effects of vegetation on energy and water fluxes. These models explicitly represent plant canopies, including radiative transfer, turbulent processes above and within the canopy, and the physical and biological controls of evapotranspiration (Fig. 2A). Snow cover, the soil water profile, and vegetation influences on the hydrologic cycle are also included (Fig. 2B). In the mid-1990s, plant physiological theory further advanced the incorporation of biological control of evapotranspiration in the third generation of models. Models now routinely link the biochemistry of photosynthesis with the biophysics of stomatal conductance. Leaf photosynthesis and conductance are scaled to the plant canopy based on the optimal allocation of nitrogen and photosynthetic capacity in relation to light availability. Simulations with these models have routinely demonstrated biogeophysical regulation of climate by vegetation through albedo, turbulent fluxes, and the hydrologic cycle (10).

The current generation of models has capability beyond hydrometeorology and incorporates ecological advances in biogeochemical and biogeographical modeling (10). Many models simulate the carbon cycle (Fig. 2C) and vegetation dynamics (Fig. 2D). In these models, the biosphere and atmosphere form a coupled system whereby climate influences ecosystem functions and biogeography, which feed back to affect climate. Much of the natural vegetation of the world has been cleared for agriculture (Fig. 3D), and some models also include land-use change.

Tropical Forests

Climate model simulations show that tropical forests maintain high rates of evapotranspiration, decrease surface air temperature, and increase precipitation compared with pastureland (SOM). The most studied region is Amazonia, where large-scale conversion of forest to pasture creates a warmer, drier climate. Surface warming arising from the low albedo of forests is offset by strong evapo-

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rative cooling. Similar results are seen in tropical Africa and Asia, and the climatic influence of tropical forests may extend to the extratropics through atmospheric teleconnections. However, forest-atmosphere interactions are complex, and small-scale, heterogeneous deforestation may produce mesoscale circulations that enhance clouds and precipitation.

Flux tower measurements in the Brazilian Amazon confirm that forests have lower albedo compared with pasture, greater net radiation, and greater evapotranspiration, particularly during the dry season (*11, 12*), producing a shallow, cool, and moist boundary layer. Observations show that forest transpiration is sustained during the dry season (*11*); this is seen also in CO_2 fluxes (*12*) and satellite monitoring of vegetation (*13, 14*), to a greater extent than represented in many models.

Tropical forests contain ~25% of the carbon in the terrestrial biosphere (Fig. 1B), account for ~33% of terrestrial net primary production (NPP) (*2*), and can sequester large amounts of carbon annually (Fig. 1C). Deforestation released 1.6 Pg C year^{-1} during the 1990s, chiefly in the tropics (*3*). Atmospheric analyses suggest that tropical forests are carbon neutral or carbon sinks, which implies offsetting of carbon uptake by undisturbed tropical ecosystems (*3, 15*).

The net balance among these processes is likely a positive benefit that mitigates global warming through evaporative cooling and carbon sequestration (*8*). Yet a more complete analysis of forest-atmosphere interactions is required. The biogeochemistry of tropical forests and biomass burning affects atmospheric chemistry and aerosols, which can alter clouds and rainfall (*16*). Interannual climate variability modulates forest-atmosphere coupling. There is net release of carbon from the biosphere to the atmosphere during warm, dry El Niño years, seen in high atmospheric CO_2 growth rates (*3*), especially in the tropics (*17*). Drought makes tropical forests more susceptible to burning during land clearing (*18*). However, tropical forest productivity may be more resilient to drought than expected (*14*).

The future of tropical forests is at risk in a warmer, more populous 21st-century world. Tropical forests are vulnerable to a warmer, drier climate (*19*), which may exacerbate global warming through a positive feedback that decreases evaporative cooling, releases CO_2, and initiates forest dieback (*20*). Loss of natural forests worldwide in the tropics during the 1990s was as high as 152,000 km^2 year^{-1} (*1*), and Amazonian forests were cleared at a rate of ~25,000 km^2 year^{-1} (*19*). Such land-use pressures are expected to continue in the future and may shift the Amazo-

nian region to a permanently drier climate once a critical threshold of clearing is reached.

Boreal Forests

Climate model simulations show that the low surface albedo during the snow season, evident in local flux measurements (*21*) and satellite-derived surface albedo (Fig. 1D), warms climate compared to when there is an absence of trees (SOM). Consequently, the boreal forest has the greatest biogeophysical effect of all biomes on annual mean global temperature (*7*). Loss of boreal forest provides a positive feedback for glaciation (*22*), whereas forest expansion during the mid-Holocene 6000 years ago amplified warming (*23*).

Boreal forests differ in their partitioning of net radiation into sensible and latent heat fluxes. Conifer forests have low summertime evaporative fraction (defined as the ratio of latent heat flux to available energy) compared with deciduous broadleaf forests, producing high rates of sensible heat exchange and deep atmospheric boundary layers (*21*). Flux tower measurements illustrate the potential for changes in species composition, arising from change in the fire regime, to affect climate (*24*). Along an 80-year fire chronosequence in Alaska, annual net radiation declined by 31% at a 3-year-old postburn
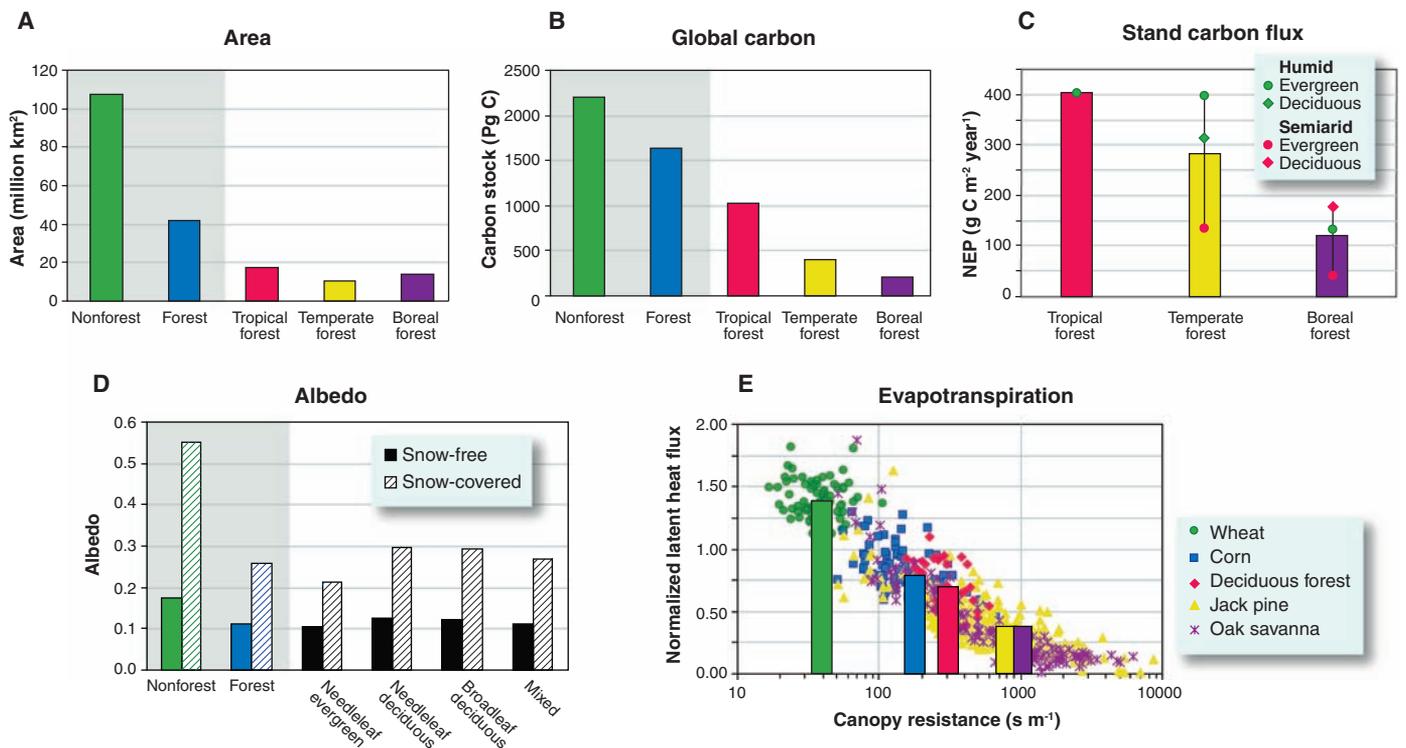

Fig. 1. Biogeochemical (carbon) and biogeophysical (albedo and evapotranspiration) processes by which terrestrial ecosystems affect climate (SOM). (**A** and **B**) Geographic extent and total (plant and soil) carbon stock of nonforest (green) and forest (blue) biomes (*2*). Individual forest biomes are also shown and sum to the forest total. (**C**) Net ecosystem production (NEP) for tropical, temperate, and boreal forest (*47*). Individual symbols shown mean NEP for humid evergreen tropical forest, three types of temperate forest, and three types of boreal forest. Vertical bars show NEP averaged across forest types. (**D**) Satellite-derived direct-beam albedo for snow-covered and snow-free nonforest (green) and forest (blue) biomes (*48*). Also shown are individual forest biomes. (**E**) Evapotranspiration normalized by its equilibrium rate in relation to canopy resistance for wheat, corn, temperate deciduous forest, boreal jack pine conifer forest, and oak savanna (*49, 50*). Shown are individual data points and the mean for each vegetation type.

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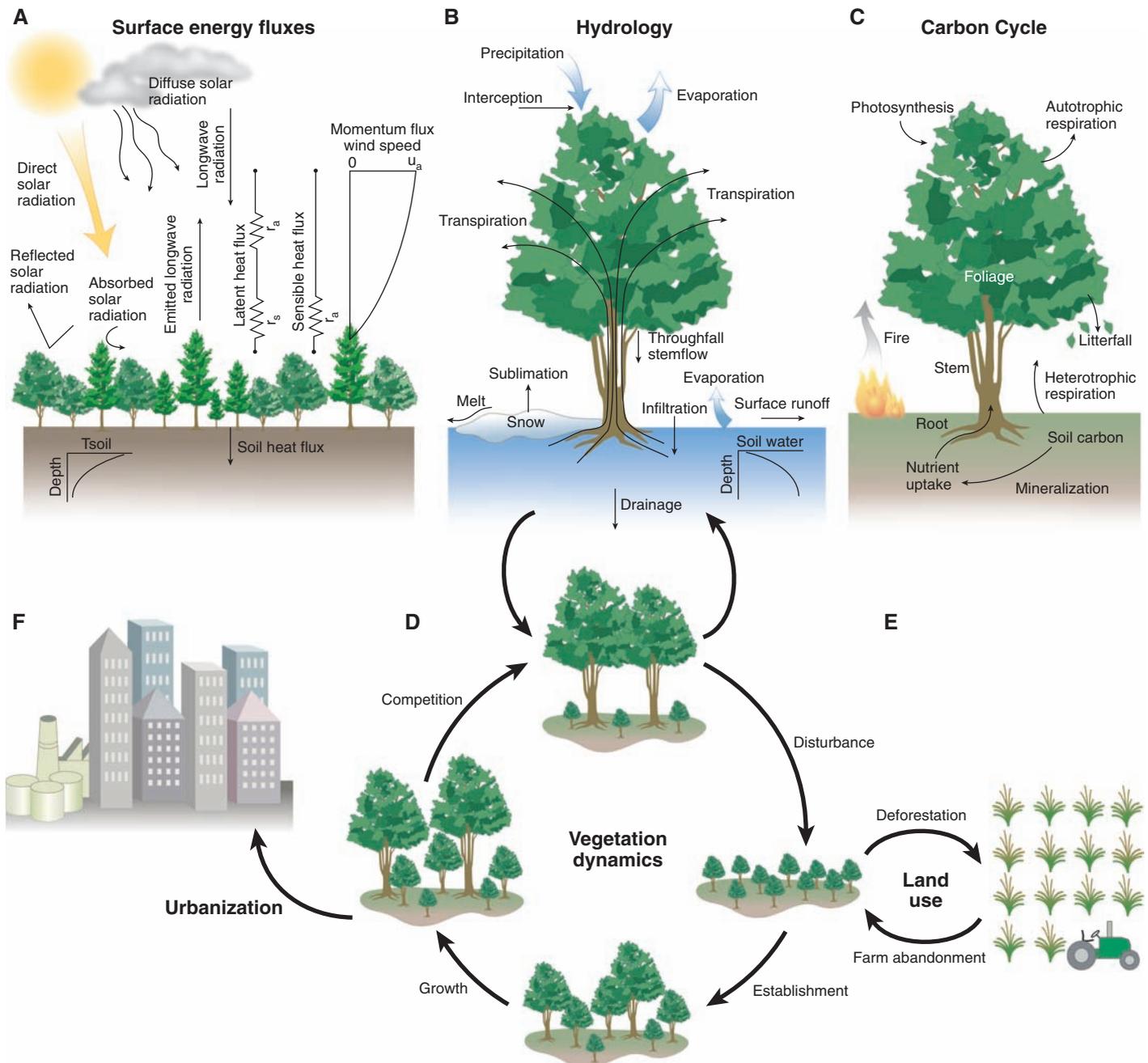**A** Surface energy fluxes   **B** Hydrology   **C** Carbon Cycle

Fig. 2. The current generation of climate models treats the biosphere and atmosphere as a coupled system. Land surface parameterizations represent the biogeophysics, biogeochemistry, and biogeography of terrestrial ecosystems. (**A**) Surface energy fluxes and (**B**) the hydrologic cycle. These are the core biogeophysical processes. Many models also include (**C**) the carbon cycle and (**D**) vegetation dynamics so that plant ecosystems respond to climate change. Some models also include (**E**) land use and (**F**) urbanization to represent human alteration of the biosphere.

site dominated by grasses and a 15-year-old aspen (*Populus tremuloides*) forest compared with an 80-year-old black spruce (*Picea mariana*) forest, primarily in spring and summer. Annual sensible heat flux decreased by more than 50% compared with the 80-year site, mostly in spring and summer. During summer, the aspen forest had the highest latent heat flux, lowest sensible heat flux, and lowest midday Bowen ratio (defined as the ratio of sensible heat flux to latent heat flux).

Boreal ecosystems store a large amount of carbon in soil, permafrost, and wetland (*2*) and contribute to the Northern Hemisphere terrestrial carbon sink (*3*), although mature forests have low annual carbon gain (Fig. 1C). The climate forcing from increased albedo may offset the forcing from carbon emission so that boreal deforestation cools climate (*8*). Similar conclusions are drawn from comprehensive analysis of the climate forcing of boreal fires (*25*). The long-term forcing is a balance between postfire increase in surface albedo and the radiative forcing from greenhouse gases emitted during combustion. Averaged over an 80-year fire cycle, the negative forcing from surface albedo exceeds the smaller positive biogeochemical forcing. Yet in the first year after fire, positive annual biogeochemical forcing from greenhouse gas emission, ozone, black carbon deposited on snow and ice, and aerosols exceeds the negative albedo forcing.

Boreal forests are vulnerable to global warming (*5*). Trees may expand into tundra, but die back

along southern prairie ecotones. In the main boreal forest, there may be loss of evergreen trees and a shift toward deciduous trees. Siberian forests may collapse in some areas and become more evergreen in the north. Increased disturbance from fire or insect outbreaks will shift the forest to a younger age class. Climate forcing arising from younger stand age may be comparable to that arising from biome shifts (*24*).

Temperate Forests

Much of the temperate forests of the eastern United States, Europe, and eastern China have been cleared for agriculture (Fig. 3D). Croplands have a higher albedo than forests (Fig. 1D), and many climate model simulations find that trees warm surface air temperature relative to crops (SOM). Masking of snow albedo by trees is important in cool temperate climates with snow. Studies of eastern United States forests find that trees also maintain a warmer summer climate compared with crops because of their lower albedo, augmented by evaporative cooling from crops and feedbacks with the atmosphere that affect clouds and precipitation (*26*). The influence of crops on evapotranspiration is seen in flux tower measurements. Growing season evaporative cooling is greater over watered crops compared with forests, and these plants exert less evaporative resistance (Fig. 1E).

Although global climate models find that temperate forests in the eastern United States warm summer temperature (*26*), mesoscale model simulations of the July climate of the United States find that trees increase evapotranspiration and decrease surface air temperature compared with crops (*27, 28*). Atmospheric feedbacks that alter cloudiness affect the magnitude of the temperature response in these simulations. Flux tower analyses show that conifer and deciduous broadleaf forests in North Carolina have lower surface radiative temperature than grass fields because of greater aerodynamic conductance and evaporative cooling of trees compared with grasses (*29*), but the same may not pertain to cropland (Fig. 1E).

Interannual climate variability affects biosphere-atmosphere coupling. In western Europe, forest and agricultural land have comparable surface radiative temperature when soil is moist but respond differently to drought (*30*). Forest maintains green vegetation, as indicated by the normalized difference vegetation index, although surface temperature and sensible heat flux increase with drought. Vegetation greenness in cropland declines by ~50%, the surface warms 13°C more than in forest, and the drought enhancement in sensible heat flux is greater than for forest. The different response to drought arises from the deep roots of trees and their access to deeper reservoirs of soil water.

Temperate forests hold ~20% of the world's plant biomass and ~10% of terrestrial carbon (Fig. 1B). Carbon sequestration rates of mature forests are high (Fig. 1C), but temperate forests in the United States historically have been carbon sources because of deforestation (*31*). Socioeco-

nomic trends in reforestation and fire suppression have shifted these forests to a carbon sink. Similar trends are seen in Europe (*3*).

The net climate forcing of temperate forests is highly uncertain. Competing biogeophysical forcings from low albedo during winter and evapotranspiration during summer influence annual mean temperature (*7*). Higher albedo with loss of forest cover could offset carbon emission so that the net climatic effect of temperate deforestation is negligible (*8*), or reduced evapotranspiration with loss of trees could amplify biogeochemical warming.

The future of temperate forests and their climate services is highly uncertain. The present carbon sink in eastern United States forests is likely to decline as recovering forests mature (*31*), and these forests face uncertain pressure from climate change, atmospheric CO_2 increase, and anthropogenic nitrogen deposition (*5*). Change in the balance between deciduous and evergreen trees is likely in the future. Temperate forests are particularly vulnerable to human land use. The trend over the past several decades has been toward farm abandonment, reforestation, and woody encroachment from fire suppression, but meeting the needs of a growing global population could place greater pressures on these forests.

Carbon Cycle Feedbacks

The carbon cycle has long been recognized as important for understanding climate change. Climate models that include the terrestrial and oceanic carbon cycle simulate a positive feedback between the carbon cycle and climate warming that increases the airborne fraction of anthropogenic CO_2 emission and amplifies warming (*3, 32*). In a comparison of 11 models of varying degrees of complexity, carbon cycle–climate feedbacks increase atmospheric CO_2 at the end of the 21st century by 4 to 44% (multimodel mean, 18%), equivalent to an additional 20 to 224 (parts per million) (ppm) (multimodel mean, 87 ppm) (*3*). Analyses of observed atmospheric CO_2 concentrations indicate that such a decline in the efficiency of the carbon cycle to store anthropogenic CO_2 in ocean and land is occurring, and to a greater extent than estimated by models (*33*).

Much of the model uncertainty arises from the terrestrial biosphere (*3, 32*). Plants respond to rising atmospheric CO_2 through photosynthetic enhancement, and this "CO_2 fertilization" is a negative feedback to higher atmospheric CO_2 concentration. In the multimodel comparison, land carbon storage increases with higher atmospheric CO_2 in all models, driven by a 12 to 76% increase in NPP with CO_2 doubling (multimodel mean, 48%), offset slightly by enhanced heterotrophic respiration (*3*). Free-air CO_2 enrichment studies in forests find that a ~50% increase in atmospheric CO_2 concentration sustained over several years enhances NPP by 23% (*34*), but the long-term outcome is unclear, especially when interactions with nitrogen availability are considered (*5*).

Climate change reduces carbon storage from CO_2 fertilization. Terrestrial carbon storage declines

with warming in the 11 models (multimodel mean, –79 Pg C °C^{-1}), but this varies greatly among models (*3*). Soil carbon turnover rate increases by 2 to 10% °C^{-1} in all models in a positive climate feedback (multimodel mean, 6% °C^{-1}). Terrestrial NPP decreases by up to –6% °C^{-1} in seven models (multimodel mean, –3% °C^{-1}) and increases by 1 to 2% °C^{-1} in four models. Climate change can enhance NPP (negative feedback) in boreal forests where temperature increases and decrease NPP (positive feedback) in tropical forests where greater evaporative demand dries soil (*35*).

Ecological responses to climate change alter the biogeophysical functioning of forests and also provide climate feedback. These "indirect" carbon cycle feedbacks include changes in stomatal conductance, leaf area index, and species composition. Decreased stomatal conductance with higher atmospheric CO_2 concentration reduces evapotranspiration and reinforces warming (SOM). More extensive tree cover may enhance warming in boreal forests by decreasing surface albedo. Reduced evapotranspiration in a drier climate may initiate a positive climate feedback leading to loss of tropical forest (*20*).

Land-Use Forcing

Although carbon emission from forest clearing has long been studied, only recently has the biogeophysical forcing of climate from land use been recognized. Vast tracts of forestland have been converted to agriculture (Fig. 3D), and climate warming over the industrial era may be smaller than that expected from rising atmospheric CO_2 alone, primarily from increased spring albedo with loss of extratropical forests (*36*).

Carbon emission from land use dampens biogeophysical cooling. The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere. Biogeophysical cooling may outweigh biogeochemical warming at the global scale (*37*) or may only partially offset warming (*38*). The net effect of these competing processes is small globally but is large in temperate and high northern latitudes where the cooling due to an increase in surface albedo outweighs the warming due to land-use CO_2 emission.

Climate trends over the 21st century, too, should be driven by interactions among CO_2 emission, land use, and forest-atmosphere feedbacks. The biogeophysical land-use forcing of climate may in some regions be of similar magnitude to greenhouse gas climate change. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 narrative storyline has high CO_2 emission (SOM), and climate model simulations of Feddema *et al.* (*39*) produce 2°C warming of planetary temperature over the 21st century in the absence of land cover change. The A2 storyline describes widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population (fig. S1). Forest loss leads to additional warming in Ama-
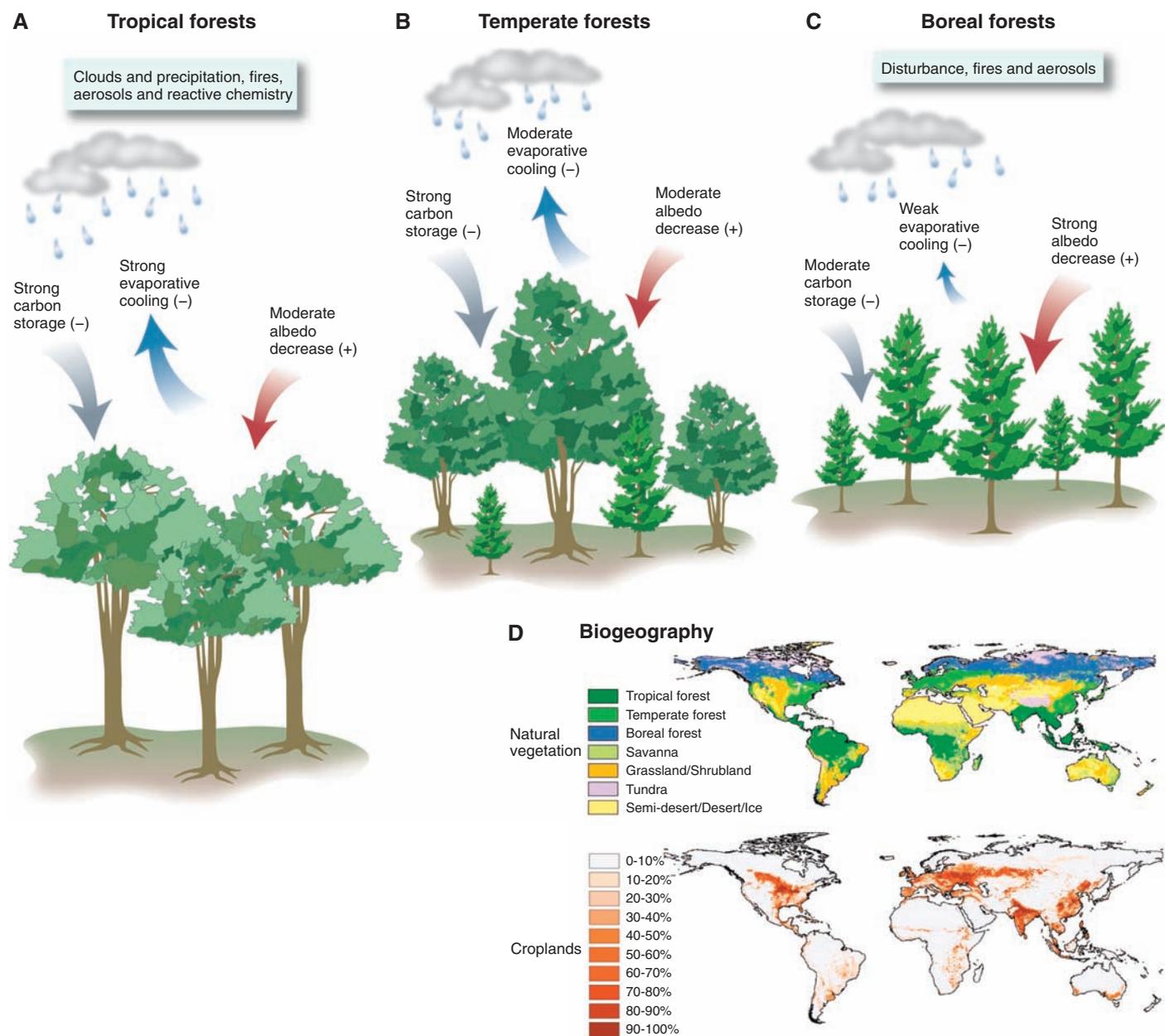
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Fig. 3. Climate services in (**A**) tropical, (**B**) temperate, and (**C**) boreal forests. Text boxes indicate key processes with uncertain climate services. (**D**) Natural vegetation biogeography in the absence of human uses of land and cropland (percent cover) during the 1990s. Vegetation maps are from (*51*).

zonia, but cooling that mitigates warming in mid-latitudes (*39*). The B1 narrative storyline is a low greenhouse gas emission scenario. Farm abandonment and reforestation yield loss of farmland by 2100 because of assumed increases in agricultural efficiency and declining population (fig. S1). The model simulates 1°C warming in the absence of land cover change and weaker land-use forcing.

When the carbon cycle is included, the different SRES storylines of fossil fuel emission and land use may yield similar 21st-century climates despite vastly different socioeconomic trajectories (*9*). Widespread expansion of agriculture in A2 leads to biogeophysical cooling. Biogeophysical processes lead to warming in B1, primarily because

of temperate forest regrowth. In the A2 and B1 storylines, net carbon loss from deforestation causes biogeochemical warming, greatest in A2 because of extensive deforestation and weaker in B1 because of temperate reforestation and less tropical deforestation. Biogeochemical warming offsets biogeophysical cooling in A2 to provide net global warming. The B1 net warming is similar to A2 because moderate biogeophysical warming from temperate reforestation augments weak biogeochemical warming from tropical deforestation.

Research Needs

Through albedo, evapotranspiration, the carbon cycle, and other processes, forests can amplify or damp-

en climate change arising from anthropogenic greenhouse gas emission. Negative climate forcing in tropical forests from high rates of carbon accumulation augments strong evaporative cooling (Fig. 3A). The combined carbon cycle and biogeophysical effect of tropical forests may cool global climate, but their resilience to drought, their status as carbon sinks, interactions of fires, aerosols, and reactive gases with climate, and the effects of small-scale deforestation on clouds and precipitation are key unknowns. The climate forcing of boreal forests is less certain (Fig. 3C). Low surface albedo may outweigh carbon sequestration so that boreal forests warm global climate, but the net forcing from fire must also be considered, as well as effects of dis-

turbance and stand age on surface fluxes. The climate benefit of temperate forests is most uncertain (Fig. 3B). Reforestation and afforestation may sequester carbon, but the albedo and evaporative forcings are moderate compared with other forests and the evaporative influence is unclear.

Much of our knowledge of forest influences on climate, and our ability to inform climate change mitigation policy, comes from models. Models of climate and the biosphere are abstractions of complex physical, chemical, and biological processes in the Earth system. Extrapolation of process-level understanding of ecosystem functioning gained from laboratory experiments or site-specific field studies to large-scale climate models remains a daunting challenge. Biosphere models must be better constrained with observational data across a range of scales from in situ experimentation, flux tower measurements of ecosystem functioning, ecological syntheses of long-term ecosystem research, satellite monitoring of vegetation, and atmospheric monitoring of CO_2. Synthesis of flux tower data from a variety of boreal, temperate, and tropical regions in various stages of ecosystem development is essential to understand the functioning of forests across wide gradients of climate, soils, disturbance history, and plant functional types (40). Large-scale monitoring of Northern Hemisphere "greening" (41) or the response of vegetation to drought (42) provide essential tests of model response to perturbations. Global atmospheric CO_2 analyses provide key constraints to biospheric functioning to augment process-level model validation at specific locales (15).

Global models of the biosphere-atmosphere system are still in their infancy, and processes not yet included in the models may initiate unforeseen feedbacks. The effect of nitrogen on carbon uptake (43), physiological effects of high ozone concentration (44), photosynthetic enhancement by diffuse radiation (45), and disturbance (46) are poorly represented, if at all. Realistic depictions of vegetation dynamics, especially the time scales of vegetation response to disturbance, long a mainstay of forest ecosystem modeling, are barely considered in the current generation of models. Nor are fires, aerosols, and reactive chemistry well represented in the models.

The carbon cycle and its response to multiple interacting drivers of global change is a key aspect of the biospheric forcing of climate. So, too, are human uses of land and the socioeconomic trends and societal responses to a changing climate that drive land use. What are the greatest uncertainties in simulating the carbon cycle of the 21st century? The prevailing paradigm of current models is that CO_2 fertilization drives terrestrial carbon sinks, weakened by global warming (3, 32). This carbon cycle–climate feedback will almost certainly be refined with further studies that incorporate the nitrogen cycle. Accounting for disturbance from wildfires and insect outbreaks further weakens terrestrial carbon sequestration in Canadian forests (46). Trajectories of land use driven by socioeconomic needs and policy implementation will also come into play

and have competing biogeophysical and biogeochemical impacts on climate (9).

As the climate benefits of forests become better understood, land-use policies can be crafted to mitigate climate change (6). It has been inferred, for example, that tropical afforestation is likely to "slow down" global warming, whereas temperate afforestation has "little to no" climate benefit and boreal afforestation is "counterproductive" (8). These policies must recognize the multitude of forest influences, their competing effects on climate, their different spatial and temporal scales, and their long-term effectiveness and sustainability in a changing climate.

An integrated assessment of forest influences entails an evaluation beyond albedo, evapotranspiration, and carbon to include other greenhouse gases, biogenic aerosols, and reactive gases. The geographic impact of these processes varies, as does their time scale of climate forcing. Greenhouse gases are well mixed in the atmosphere and influence global climate; biogeophysical feedbacks have a regional impact. Biogeophysical processes influence climate more immediately than does the carbon cycle. Slow rates of carbon accumulation in boreal forest may in the short-term be offset by more rapid albedo effects. How forests attenuate or amplify climate change will vary with global warming. Vegetation masking of snow albedo becomes less important in a warmer world with less extensive snow cover. The evaporative cooling of forests declines if droughts become more common. The interrelatedness of climate change science, climate impacts on ecosystems, and climate change mitigation policy requires that these be studied together in an interdisciplinary framework to craft strong science in the service of humankind.

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PERSPECTIVE

Forests of the Past:
A Window to Future Changes

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The study of past forest change provides a necessary historical context for evaluating the outcome of human-induced climate change and biological invasions. Retrospective analyses based on fossil and genetic data greatly advance our understanding of tree colonization, adaptation, and extinction in response to past climatic change. For instance, these analyses reveal cryptic refugia near or north of continental ice sheets, leading to reevaluation of postglacial tree migration rates. Species extinctions appear to have occurred primarily during periods of high climatic variability. Transoceanic dispersal and colonization in the tropics were widespread at geological time scales, inconsistent with the idea that tropical forests are particularly resistant to biological invasions.

For Heraclitus, a 6th-century BCE Greek philosopher and naturalist, "change is the only constant in nature." Trees are organisms of exceptional size and longevity, and are symbols of stability and resilience in the living world. Yet, trees are no exception to Heraclitus' rule. Their ranges have been and continue to be extremely dynamic. In some parts of the world, tree species have started to shift their distributions in response to anthropogenic climatic warming (*1*, *2*). Given the long generation time of trees, and possible migrational lags, these shifts foreshadow the more pronounced future changes.

Knowledge of past forest change can inform current predictions and conservation options. Paleo-studies offer abundant evidence for climatic changes and vegetation shifts at various spatial and temporal scales. During the Quaternary period (roughly 1.8 million years ago to the present), glacial-interglacial climatic variations occurred as a result of changes in controlling factors such as Earth's orbital parameters, continental ice sheets, sea-surface temperature, and atmospheric CO_2 concentration. Abrupt climatic events at much shorter time scales have also occurred (*3*), some of which have pronounced magnitudes and rates (e.g., temperature shifts of up to ~10°C within a few decades during the last glacial-interglacial transition in some areas). Networks of fossil pollen and plant macrofossils show that in response to these climatic fluctuations, the biosphere has experienced dramatic changes, with large-scale species' range shifts, population contractions and extinctions, as well as aggregation and disassociation of forest communities. At low latitudes, forests experienced altitudinal shifts and range fragmentation, although many tropical and subtropical tree species we see today persisted in the same region through glacial and interglacial intervals (*4*). At mid-latitudes, forest development after the end of the last glaciation involved species reshuffling, changes in relative abundances, and local and permanent extinctions (*5*, *6*). Forests in high-latitude regions became established within the Holocene (past 11,600 years) as a result of population invasions from southern glacial refugia into previously ice-covered terrains and local expansions of small tree populations that survived the Last Glacial Maximum (~20,000 years ago) in "cryptic refugia" (*7*, *8*).

A key recent development in studies of past vegetation is the fusion of genetic and fossil data. Fossil records are indispensable for vegetation reconstruction and can help constrain inferences of historic events from genetic data. But fossil records rarely offer any information on population-level processes (e.g., founder events, migration of specific lineages). Geographic patterns of DNA polymorphisms are traces, albeit often somewhat fuzzy, of such processes. When fossil and genetic data are combined, much information can be acquired about the whereabouts of small populations during the last glaciation and the trajectories of postglacial population spread (Fig. 1). Recent studies that applied this integrative approach have offered new insights. For example, some temperate and boreal trees apparently survived the Last Glacial Maximum in periglacial
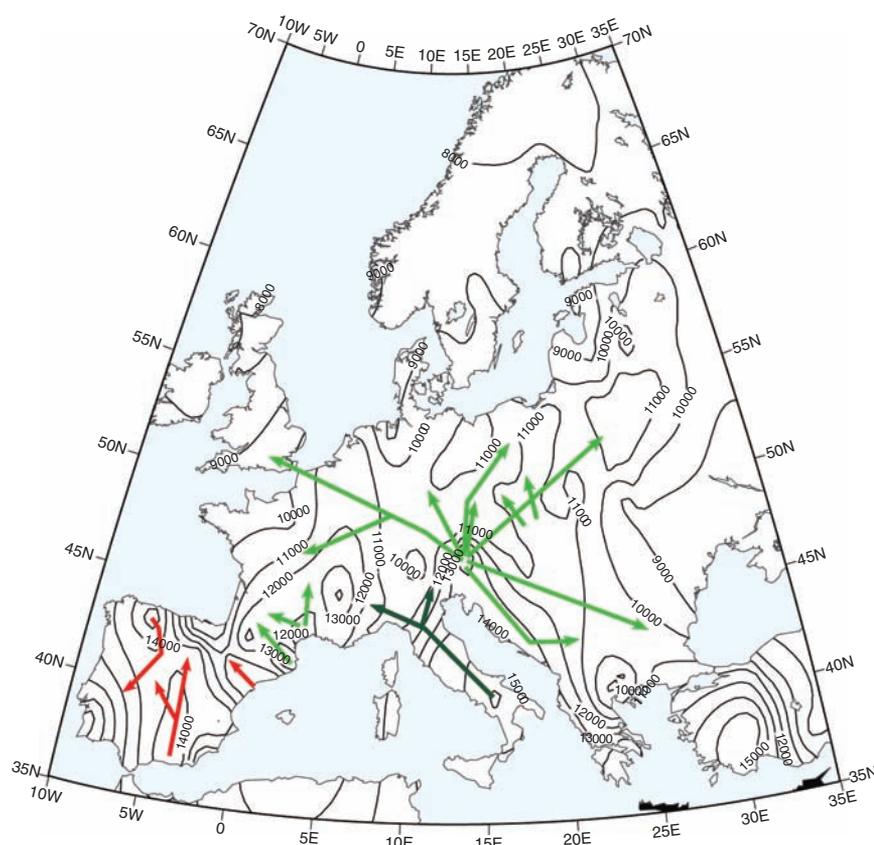
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Fig. 1. Migration timing (isochrone curves) and routes (arrows) of *Pinus* in Europe inferred from paleobotanical and modern genetic data. The red, light green, and dark green arrows correspond to the migration routes for different maternal lineages of *Pinus sylvestris* (*8*).

Fig. 2. Sparsely distributed spruce considered to be analogous to glacial-refuge populations. DNA and fossil pollen data suggest that such small populations survived the Last Glacial Maximum in Alaska and that they were important for boreal-forest development after the end of the last glaciation (7).

environments probably tens of kilometers from ice sheets (8, 9) and even in ice-free areas north of ice sheets (7). Thus, it appears that small populations of trees can endure extreme climatic conditions for tens of thousands of years (Fig. 2).

However, these studies also imply that the capacity of trees to keep up with the rate of future warming is probably more limited than suggested by previous estimates from fossil data. Extremely fast tree migrations during the early Holocene were inferred from the fossil records of certain tree species, on the assumption that northern refugia did not exist during the Last Glacial Maximum (5, 10). On the basis of more recent fossil and DNA studies, it appears that the actual rates may be an order of magnitude lower, e.g., <100 m/year for two North American deciduous tree species (11). These estimates are far below what would be necessary for species migration to track future climatic warming (3000 to 5000 m/year), raising interest in the possibilities of "assisted migration"—the translocation of populations to areas where future climate might be favorable.

The role of adaptive responses to climatic change has rarely been considered in interpreting Quaternary paleoecological records, because of the perception that evolution occurs more slowly than climatic change (12). At the DNA-sequence level, evolution of trees is indeed exceptionally slow, in line with their exceptional longevity, but their high genetic diversity and large population sizes do allow rapid adaptive responses, within one or a few generations (13). There is therefore a growing recognition that short-term evolutionary responses of trees should be accounted for in models of forest dynamics (12).

Although local evolutionary responses to climate change are likely to have occurred with high frequency, there is no evidence for change in the absolute climate tolerances of species (14). Thus, future extinctions of tree species in response to climate change are probable, especially if their geographic distribution or climatic range is already highly restricted. Here again, the retrospective approach could be illuminating. Europe lost at least 89 tree genera during the climatic transitions of the Late Tertiary to the Quaternary (15). A key question is whether past extinctions took place during glacial or interglacial periods. If extinctions had taken place mostly during interglacial periods, this would support pessimistic views of the consequences of future global warming on population and species survival. However, extant Asian and American congeners of extinct European tree species are less cold-tolerant than currently widespread European trees (16). This suggests that most extinction events took place during glacial rather than interglacial periods. In contrast, a 320,000-year history of vegetation and climate in Hungary showed that species extinctions clustered near times of high climate variability (17). This interpretation is consistent with the case of a now-extinct North American spruce, *Picea critchfieldii*, which was abundant during the Last Glacial Maximum but vanished during the last deglaciation, at a time of rapid climate change (18).

The retrospective approach also provides a context for understanding species invasions resulting from human activities. Invasive trees (i.e., "tree weeds," such as pines escaped from plantations in the Southern Hemisphere) have caused damages to ecosystems worldwide, especially (but not only) in originally treeless areas (19). In contrast to the assumption that tropical forests are particularly resistant to invasions, invasions turn out to be frequent in these regions over geological times scales as a result of "sweep-

stakes dispersal," the dispersal of species across wide physical barriers such as oceans (20). For instance, sweepstake dispersal of the wind-dispersed rainforest kapok tree, *Ceiba pentandra*, was inferred on the basis of DNA-sequence phylogeography and molecular clock methods: African populations established through oceanic dispersal from Neotropical sources at least 13,000 years before the present (21). Many other tropical tree taxa are shared across the Atlantic. Although these forest similarities were previously attributed to Gondwana vicariance, molecular phylogenetic studies point to a predominant role of oceanic dispersal in establishing this range disjunction. In an Amazon forest inventory plot in Ecuador, at least 21% of the tree species (232 out of 1104) were derived from clades that had arrived in South America via long-distance dispersal (20). Thus, natural invasions of trees explain some of the similarity between tropical forests across continents, contradicting the idea that diversity could provide sufficient protection against invasions. Evaluating the frequency and consequences of sweepstakes dispersal into different communities could help predict the consequences of modern invasions into more or less "naïve" floras characterized by different levels of endemism.

Many lessons can be drawn from the study of past forest change, and our ability to acquire such knowledge is improving thanks in particular to the interactions between paleoecologists and geneticists. The integration of paleoclimate data, fossil records, and genealogical analyses within a hypothesis-testing modeling framework represents a particularly fruitful direction (8, 22). However, novel climates will appear, leading to "no-analog" communities (23), which may limit the retrospective approach discussed here. Indeed, while no-analog communities are well documented in the paleorecord (4), they cannot offer a direct guide to what we may have in stock for the future because the combinations of climate and other drivers (e.g., human land use) differ drastically between the past and the future. Nonetheless, these unique paleo-communities, when coupled with paleoclimate information, provide a way to examine climate-species relationships outside the modern realm and should help validate ecological models for simulating future changes.

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PERSPECTIVE

Predictive Models of Forest Dynamics

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Dynamic global vegetation models (DGVMs) have shown that forest dynamics could dramatically alter the response of the global climate system to increased atmospheric carbon dioxide over the next century. But there is little agreement between different DGVMs, making forest dynamics one of the greatest sources of uncertainty in predicting future climate. DGVM predictions could be strengthened by integrating the ecological realities of biodiversity and height-structured competition for light, facilitated by recent advances in the mathematics of forest modeling, ecological understanding of diverse forest communities, and the availability of forest inventory data.

There are approximately a trillion canopy trees on Earth (*1*) from around 100,000 species (*2*). The trees store approximately as much carbon as is currently in the atmosphere, and forest ecosystems harbor two-thirds of terrestrial biodiversity (*3*). The challenge of predictive forest modeling is to forecast how this collection of trees will develop in the future, in response to the many perturbations to which it is being subjected, including deforestation, logging, pollution, nitrogen deposition, the loss of pollinating and seed-dispersing animals, and the effects of increased atmospheric CO_2, both direct (the job of a leaf is to convert CO_2 into plant material) and indirect (altered climate).

The most exciting recent advance in forest modeling has been the appearance of dynamic global vegetation models (DGVMs), which simulate the distribution, physiology, and biogeochemistry of forests and other vegetation at global scales, under present, historic, or simulated future climates (*4*). DGVMs have shown that future changes in global forest carbon storage could greatly affect the response of Earth's climate system to anthropogenic CO_2 emissions over the next century (*5*). However, because DGVMs were developed recently, with limited information, their predictions are currently highly uncertain (Fig. 1), making vegetation dynamics one of the largest sources of uncertainty in Earth system models. Reducing this uncertainty requires

work on several fronts. For example, physiological parameters need to be better constrained with data (*6*), and we need better models of disturbances, including fire (*7*) and land-use change (*8*). But more fundamental improvements could be achieved by incorporating the ecological realities of biodiversity and competition for light. A recent explosion in forest inventory data might make this possible.

The only reason to build a trunk—to become a tree—is to overtop your neighbors and capture light before they do. This game-theoretic competition for resources is responsible for the enormous amounts of carbon stored in living trees and in undecomposed organic matter and fossil fuels, most of which began as wood. Foresters and forest ecologists have developed individual-based, height-structured models that can accurately predict productivity (*9*) and species composition (*10*). At every turn, these have revealed nonlinearities in forest dynamics caused by competition for light. For example, increased growth leads to increased overtopping, which increases mortality, which increases forest carbon loss; with the functions at each stage being nonlinear. In contrast, current DGVMs reduce whole forested regions to the total biomass in compartments (such as leaves, roots, and trunks), with simple phenomenological rules for how the carbon generated from photosynthesis is allocated to, and lost from, these compartments. Moreover, competition among species [or at least among plant functional types (PFTs)], which needs to be represented to predict biome boundaries, follows rules with weak empirical support that differ among models (*11*).

Therefore, DGVMs could be substantially improved by basing them on the height-structured models developed by foresters and forest ecologists. But because these models are individual-based, this would require simulating every tree on Earth, which would be immensely computationally demanding. A more efficient approach would be to derive so-called macroscopic equations to scale correctly from the parameters governing individual trees to the dynamics of forested regions, in the same way that the Navier Stokes equations scale correctly from molecular motion to fluid dynamics. Recent progress implies that macroscopic equations will soon form the basis of DGVMs. Moorcroft *et al.* (*12*) introduced a demographic method to scale up individual-based forest models, which has since been used to provide tractable macroscopic equations to scale from trees to stands and to scale from stands to forests (*13*).

Macroscopic equations will allow global simulations of individual-based forest models, but here arises the problem of biodiversity. The (approximately) 100,000 tree species vary hugely in properties that drive the carbon cycle, such as growth, mortality, decomposition of dead wood, and their dependency on climate. Because of a lack of appropriate data or theory, current DGVMs reduce biodiversity to a small number of PFTs, within which all parameters are constant. The PFTs represent simple morphological and biogeographical aggregations, such as broadleaf versus needleleaf or tropical versus temperate. But these aggregations are unlikely to be optimal for capturing the effects of biodiversity on dynamics, because the among-species differences within PFTs dwarf the average difference between them. For example, the PFT temperate deciduous broadleaf contains the northernmost tree species (Arctic birch) along with subtropical oaks; and evergreen needleleaf contains cold-adapted spruces and firs and heat-adapted pines. Even within a forest composed of a single PFT, species parameters typically vary by an order of magnitude (*14*). Moreover, the mix of species, and hence parameters, found at a given location is strongly correlated with climate (*15*), with obvious implications for modeling the climate dependency of forest dynamics. By ignoring most biodiversity, DGVMs could be overestimating the strength of some climate responses because they fail to account for the fact that deleterious effects can be mitigated by increases in those species best

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adapted to the new conditions (*16*). But they could be underestimating other responses; for example, increased temperature could both increase the growth of extant trees and select for warm-adapted species, which have higher growth rates (*17*). Therefore, there is a need for a substantial increase in the amount of biodiversity represented in DGVMs.

However, adding biodiversity and height-structured competition into DGVMs would increase the complexity of models that are already severely underconstrained. DGVMs contain large numbers of parameters, which are hand-selected from literature values in order to qualitatively match model predictions to sparse observations of ecosystem fluxes (such as productivity) and states (such as biome boundaries). Physiological parameters are beginning to be objectively estimated with measurements from flask networks and eddy-covariance flux towers (*6*). But these data contain almost no information about the long-term dynamics of individuals, populations, or communities. Luckily, these dynamics are recorded in a kind of data that has become much more available recently. Forest inventories consist of sample plots within which trees are measured regularly (about every 5 to 10 years). The measurements are low-tech: for example, stem diameter, species, alive or dead. But the sample sizes are large, running into millions of trees in some cases (*18, 19*). The few published biogeochemical analyses of forest inventory data have yielded results with major implications for our understanding of the global carbon cycle (*18–20*).

To constrain DGVMs, the tree-level measurements in forest inventories could simply be summed to provide long-term average carbon dynamics to compare with DGVM predictions. But this approach discards most of the information in the data. In contrast, if DGVMs were based around models of individual trees, the individual growth and mortality records could be used to directly estimate key tree-level parameters; although few if any inventories contain sufficient information to estimate all parameters, because they lack measurements of (for example) light, belowground carbon, nutrients, and seed dispersal. In the low-diversity boreal and temperate zones, the abundance of inventory data might be sufficient to estimate parameters for every dominant tree species. In addition to improving predictions for the carbon cycle, this might allow realistic predictions for particular species; for example, climate-induced shifts in species ranges,

which to date have been predicted using only correlative methods (*21*).

In high-diversity forests, species-specific parameterization is not feasible. Instead, species need

Fig. 1. DGVMs have shown that the terrestrial biosphere could be crucial in determining the future of Earth's climate. But this figure [from (*5*)] shows how divergent the predictions of DGVMs currently are. For comparison, current anthropogenic CO_2 emissions are 7.6 ± 0.6 Gt of carbon/year. True DGVMs, with a responsive global distribution of PFTs, are labeled (*5*). The remainder have a dynamic carbon cycle but a fixed distribution of PFTs. Some of the variation in Fig. 1 results from different climate models, but a large spread was also seen when different DGVMs were run uncoupled from global climate models under a common, fixed climate trajectory (*11*). LLNL, Lawrence Livermore National Laboratory climate model; BERN-CC, Bern carbon-cycle climate model; CLIMBER2-LPJ, Climate-Biosphere model, coupled to the Lund-Potsdam-Jena DGVM; UVic-2.7, University of Victoria Earth system climate model, version 2.7; UMD, University of Maryland coupled carbon-climate model; HadCM3LC, Hadley Centre coupled climate-carbon cycle model.

to be aggregated to reduce the number of parameters to be estimated. And although any such aggregation must result in a loss of biological information, evidence suggests that, with the correct aggregation, this loss could be minimal. This is because wherever parameters have been estimated for different tree species, they have been found to be subject to life history tradeoffs: strategic axes appearing as among-species correlations in parameters (*22*). Moreover, similar tradeoffs appear to be structuring different forest communities, such as the shade-tolerance spectrum from fast-growing, short-lived pioneers to slow-growing, long-lived species (*22*). These tradeoffs imply that most of the effects of biodiversity would be retained in models that reduced the state of a forest to the distribution of individual trees along tradeoff axes, regardless of taxonomic identity. Such models could capture the effects of biodiversity on select aspects of forest function (such as carbon dynamics), either by defining a new set of PFTs spread optimally along the axes or by treating the distribution of species as a continuum. Either approach would require fewer data than species-specific parameterization (*14*), and

the continuous approach extends naturally to include parameter variation within species. These approaches correspond closely to the discrete and continuous lumping techniques used to model heterogeneous systems of chemical reactions (*23*).

All of the above add up to a major scientific challenge. We have proven individual-based, height-structured models which, using new scaling methodologies, could be implemented at global scales. We are beginning to understand the trade-off structure of forest communities sufficiently to capture the effects of biodiversity on forest function. And for the first time, we have millions of observations of individual trees with which to constrain the structure and parameters of global models. If these pieces could be put together properly, the result could be a new generation of ecologically realistic, better-constrained DGVMs. A benchmark of success for this endeavor might be that forest dynamics are no longer one of the major sources of uncertainty in predicting the future of Earth's climate.
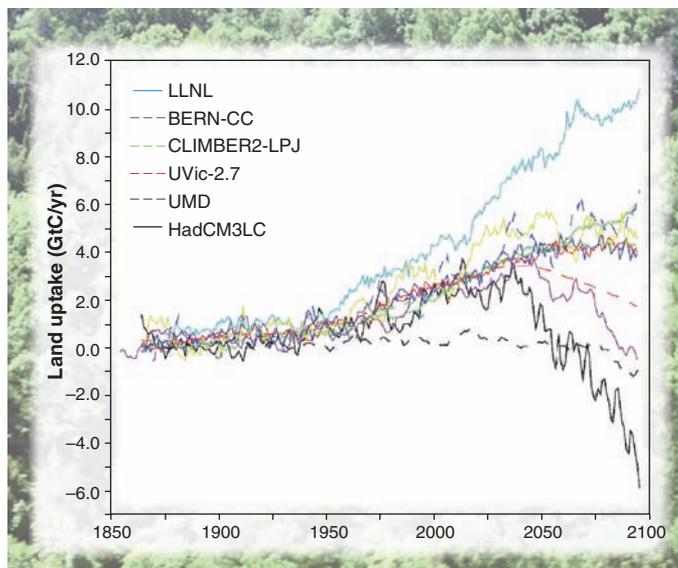
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PERSPECTIVE

Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications

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Recent climate talks in Bali have made progress toward action on deforestation and forest degradation in developing countries, within the anticipated post-Kyoto emissions reduction agreements. As a result of such action, many forests will be better protected, but some land-use change will be displaced to other locations. The demonstration phase launched at Bali offers an opportunity to examine potential outcomes for biodiversity and ecosystem services. Research will be needed into selection of priority areas for reducing emissions from deforestation and forest degradation to deliver multiple benefits, on-the-ground methods to best ensure these benefits, and minimization of displaced land-use change into nontarget countries and ecosystems, including through revised conservation investments.

Tropical deforestation makes a major contribution to emissions of greenhouse gases, especially if the additional emissions from subsequent land use are counted (1). The United Nations Framework Convention on Climate Change (UNFCCC) is considering the introduction of a financial mechanism to reduce emissions from deforestation and forest degradation (REDD) in developing countries. Many environmentalists have welcomed this initiative because it may direct substantial new resources to tackling this issue (2–5). A REDD mechanism would probably credit entire nations, rather than individual projects, for their achievements in reducing deforestation. However, there is ongoing debate and hence much uncertainty about the form of the mechanism, including issues such as the deforestation baseline to be used, the role of developing countries that have a low recent rate of deforestation, and the protocols for measurement and validation of emissions reductions. The UNFCCC's Conference of Parties (CoP) in December 2007 established indicative guidance for a demonstration (pilot) phase in the period to 2012. This focuses on emissions measurement and explicitly includes forest degradation, resolving one hotly debated issue. The form of any final mechanism will affect the area and location of forests encompassed and thus the scope for co-benefits (such as biodiversity conservation, livelihoods, and watershed protection) to result. It is widely anticipated that negotiations for the next emissions reduction agreement will be completed at the fifteenth CoP in December 2009. If agreement is reached, then a major new driver for forest conservation may be born.

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There is some controversy over how REDD should be funded. Some of the national parties to the UNFCCC wish to see the issue tackled through a traditional grant funding mechanism. Others, led by the Coalition of Rainforest Nations, seek an eventual market-based mechanism, on the basis that carbon is one of the more easily marketable ecosystem services (4, 6, 7). This may generate more funds over a longer time scale. A trading mechanism would allow developing countries to sell carbon credits on the basis of successful reductions in emissions from deforestation and forest degradation, to help developed countries achieve stringent emissions targets. Such credits would probably relate to national-scale emissions rather than being attached to individual sites, although discussions continue on the precise details.

Any such mechanism would generate significant additional funding to reduce deforestation rates in developing countries. One estimate, based on a relatively low carbon price of U.S. $10 per ton and an estimate of individual countries' ability to slow deforestation, suggests a potential market of U.S. $1.2 billion a year (2); a more recent estimate suggests that U.S. $10 billion may be a realistic figure (8). These are large sums in comparison with current investment in forest protection. For example, World Bank funding directed to forest biodiversity conservation and related activities in 2002 totaled U.S. $257 million (9). In the mid-1990s, total protected area expenditure in the developing world was estimated at U.S. $695 million annually; not exclusively invested in forests (10). In contrast, forestry exports from the developing world were worth over U.S. $39 billion in 2006 (11). By generating an income of the same order of magnitude, REDD could provide strong incentives for forest conservation.

These resources mean that the scale of intervention being discussed under the UNFCCC is truly huge, but few decision-makers are aware of the full breadth of its implications. It was initially assumed by many that the effects of REDD on forest-related livelihoods and conservation would only be positive, and it is certainly true that many species, ecosystems, and ecosystem services will benefit. However, it is unlikely that an international mechanism under UNFCCC will explicitly support forest ecosystem services other than carbon storage, and its implementation may generate pressures that adversely affect other ecosystems. It is crucial that decision-makers recognize and plan for potential risks as well as benefits from the resulting effects on land use.

REDD is unlikely to benefit all forests equally. For REDD to make a successful contribution to combating climate change, countries implementing it will have to target threatened forests with a total high volume of carbon in their biomass and soils (12, 13). Although individual sites would not be "marketed" within most proposed REDD mechanisms, countries will still be implementing REDD actions at a site scale. Priority areas for tackling deforestation to reduce emissions will not always reflect other forest values (e.g., conservation, livelihoods support, or delivery of fresh water). Some sites may be less valuable from a carbon perspective but of high priority for other reasons. The need for additional resources to prevent deforestation at such sites will vary depending on the carbon price, the carbon content of the ecosystem, and the cost of avoiding deforestation (Fig. 1). Where the combination of the first two factors outweighs the latter, resources from REDD should be sufficient to enable forest retention. In some parts of the world, estimates of opportunity cost for REDD are very low. Lower costs and/or higher carbon prices could combine to protect more forests, including those with lower carbon content. Conversely, where the cost of action is high, a large amount of additional funding would be required for the forest to be protected.

The limited funds available for conservation will need to be carefully targeted in this context. To conserve the diversity of ecosystems and their related species and services, it may be more efficient to focus conservation funds on nonforest ecosystems and low-carbon forests rather than on forests covered by the new mechanism (Fig. 2). This would require revision of organizational and national investment strategies. The delay between planning and action means that these issues should be considered long before any mechanism comes into effect.

One obvious risk associated with REDD is the displacement of pressures, resulting from continuing demand for food, timber, and increasingly biofuels, to ecosystems perceived to contain low carbon levels. The least-productive forest ecosystems may become the most threatened simply because they are the only remaining accessible source of land and forest products. Other areas experiencing increased pressure could include nonforest ecosystems such as savannas or wetlands and forests in tropical countries not participating in REDD (Fig. 2). The demand for timber from temperate and boreal forests may also increase.
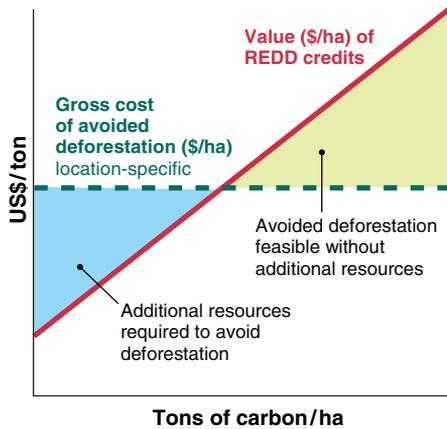
Fig. 1. Under any REDD scheme, the income generated will depend upon the total carbon stocks retained (solid line). Although the cost of avoiding deforestation (dotted line) will vary with location, it is not necessarily related to carbon stocks. Forests in the blue area of the chart contain insufficient carbon to enable avoided deforestation based on REDD funds alone. The need for additional resources to tackle deforestation within a national REDD scheme will vary depending on the carbon price, the carbon content of the ecosystem, and the cost of avoiding deforestation. As the cost of REDD and the carbon price vary, the ratio between the two shaded areas will change.
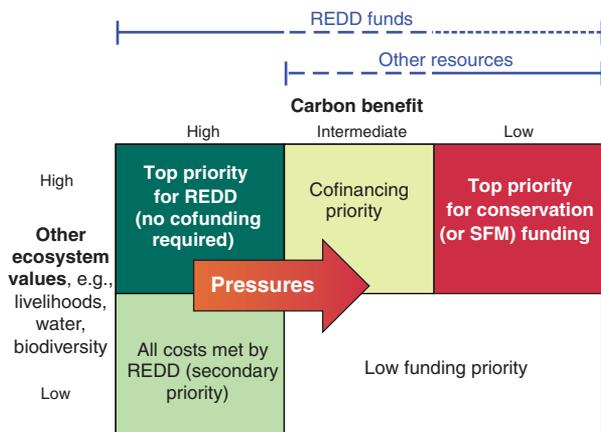

Fig. 2. Biodiversity value and carbon value are distributed differently among tropical ecosystems. Therefore funding from REDD would protect only some biodiversity values and could increase pressures on other ecosystems. Funds for other purposes such as sustainable forest management (SFM) and conservation will need to be targeted to fill the gap.

Another risk is that REDD implementation may be imperfect. Having planned for carbon savings and cobenefits from reduced deforestation, it is necessary to ensure that these are delivered. Considerable effort has been devoted to identifying the factors that influence the success of formally protected areas in limiting deforestation and in supporting and improving livelihoods, but it is often difficult to draw firm conclusions [e.g., (14, 15)]. Although protected areas are typically successful in reducing deforestation, other approaches, including sustainable forest management, will sometimes be more effective in delivering a full range of benefits. Management strategies need to be designed to address local needs and deforestation drivers.

To maximize the benefits of REDD and reduce any risks, it is important to prioritize investment, both among and within countries. Various global conservation priorities have already been identified, each favoring different aspects of biodiversity (16). A simple approach would be to identify areas of high value for carbon and for biodiversity at either scale. However, it is also essential that deforestation pressure and the cost of preventative action are taken into account, because the primary motivation is to reduce annual greenhouse gas emissions from this sector. Multicriteria analysis is therefore required, incorporating the degree of pressure and cost as well as the forest values (17). Some initial analysis using a national-scale biodiversity index has been undertaken (18), but data specific to forest biodiversity would yield more relevant results.

A more comprehensive analysis to produce an optimized allocation of REDD and conservation funds within or even among tropical forest countries is technically feasible. Such analysis would allow the placement of each land unit within a framework like that shown in Fig. 2. Depending on the carbon price and the baseline rate of deforestation, this would help to identify those areas naturally covered by the mechanism, those requiring additional resources if they are to benefit from the mechanism, and the "losers," sites that are most at risk of loss or degradation as the result of pressures displaced by the mechanism. These may become new priorities for conservation and sustainable forest management.

It is crucial that feasibility studies and efforts to ready tropical forest countries for REDD take account of the context (resources and pressures) for biodiversity conservation and other ecosystem values. Several internationally and bilaterally funded demonstration programs are now in development. Methods for assessing their effectiveness, including the degree of displacement (leakage) of land-use change within and between countries, are urgently needed. It is vital to develop robust monitoring and reporting methods for quantifying cobenefits and assessing the impacts on them of changes in forest management and of any leakage into nontarget ecosystems. These data would help identify REDD methods that were most successful in delivering cobenefits.

There is a further need to test the agreed emissions reporting guidelines. Under current Inter-governmental Panel on Climate Change (IPCC) guidance, parties do not need to report emissions from forest areas designated as undisturbed (13). This leads to a risk of unrecorded anthropogenic carbon losses, such as those resulting from illegal logging or land clearance. The guidance also offers default values for accounting of soil carbon to 30 cm depth, which will certainly underestimate the effects of clearing tropical swamp forests, where peat depth can reach 20 m (19), and losses from drainage and fire can have substantial impacts on carbon storage.

If a REDD mechanism comes into operation, a shift in funding policies may be indicated to ensure that conservation investment is spread over the range of ecosystems not covered by REDD funding. Although many of these issues have been raised within the UNFCCC-mediated discussions, their implications for conservation investment merit attention in the world outside these carbon-focused negotiations.

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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 activ-

ities: (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 bio-physical 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 trop-ics 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 avoid-ing 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 jeopar-dize the overall value of carbon mitigation pro-jects. 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, in-cluding additional income for rural development, prospects for conservation and other envi-ronmental services, and support for indigenous communities (*10, 25*). Principles of sustain-ability must govern the resolution of trade-offs that may arise from ancillary effects in order to simultaneously maximize climate change pro-tection and sustainable development.

The challenges facing sustainable mitiga-tion 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 interna-tional efforts. Currently, only 7% of all tropical timber trade comes from sustainably managed forests (*26*).

PHOTO: MICHAEL RYAN

The potential of carbon sequestration will depend on the degree to which climate pro-tection 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

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

of tropical regions is essential to take up the full global potential for climate change miti-gation through forestry.

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PERSPECTIVE

Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands

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Despite continued forest conversion and degradation, forest cover is increasing in countries across the globe. New forests are regenerating on former agricultural land, and forest plantations are being established for commercial and restoration purposes. Plantations and restored forests can improve ecosystem services and enhance biodiversity conservation, but will not match the composition and structure of the original forest cover. Approaches to restoring forest ecosystems depend strongly on levels of forest and soil degradation, residual vegetation, and desired restoration outcomes. Opportunities abound to combine ambitious forest restoration and regeneration goals with sustainable rural livelihoods and community participation. New forests will require adaptive management as dynamic, resilient systems that can withstand stresses of climate change, habitat fragmentation, and other anthropogenic effects.

Forest succession is a stochastic process resulting from the behavior of component populations and species. Yet, restoration ecologists tend to view forest communities as tightly integrated biological systems, using metaphors for organismal health and development to describe the state of forests throughout the world. Forests are "declining," exhibit "arrested development," are "infested" with invasive species, and may require active "rehabilitation." Although many principles of restoration ecology derive from insights into successional change, guided reconstruction of forests should be clearly distinguished from the natural processes of forest succession, which are not prescribed or directed by humans and often exhibit divergent and unpredictable pathways (1).

Both of these processes—assisted restoration and unassisted forest regeneration—are gaining momentum across the world. As a result, global assessments show a recent decline in the net rate of forest loss from 1990 to 2000 and from 2000 to 2005 (2). Although the global deforestation rate remains high, 13 million ha/year, forest cover in 18 countries has begun to increase, owing to both afforestation (tree planting on previously unforested land) and natural regeneration (2). Natural forests expanded in Bhutan, Cuba, Gambia, Puerto Rico, St. Vincent, and Vietnam from 1990 to 2005, following earlier forest transitions in six European nations and the USA during the 19th and early 20th centuries (3, 4). These increases, however,

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do not necessarily reflect increasing biomass or carbon sequestration (3). For developing countries, the Food and Agriculture Organization of the United Nations (FAO) requires a minimum of only 10% forest cover for land to be classified as forest (4), a criterion that would satisfy few forest-dwelling species. Moreover, forest assessment data provide no insights into the recovery of forest biodiversity or ecosystem services lost because of forest conversion or degradation. In many cases, these figures reflect the widespread establishment of plantations, which currently constitute about 4% of total forest area globally. Rates of planting of forests and trees are increasing by 2.8 million ha/year, for purposes of production, as well as for conservation and restoration (2). In China alone, 28 million ha of plantations were established from 2001 to 2007 (5). Commercial forest plantations can potentially play a role in landscape restoration and faunal conservation, if they are managed as components of a heterogeneous landscape mosaic (6, 7). Unfortunately, forest cover statistics do not clearly reveal changes in the status of degraded secondary and heavily logged forests, which will not recover on their own (8, 9). As classified by FAO, these forests constitute 60% of forest area globally (2).

Wherever actions are taken to promote forest restoration and regeneration, new forests emerging in human-impacted landscapes will not match the original old-growth forests in species composition (10). But forest restoration can restore many ecosystem functions and recover many components of the original biodiversity. Approaches to restoring functionality in forest ecosystems depend strongly on the

initial state of forest or land degradation and the desired outcome, time frame, and financial constraints (Fig. 1). Restoration approaches should take into account the spatial distribution, abundance, and quality of residual vegetation, a strong indicator of the potential for natural regeneration (11). Just as forest ecosystem processes decline in a stepwise fashion with increasing human impacts (12), restoration approaches can "elevate" a degraded or completely altered forest ecosystem to a higher level of the restoration staircase (Fig. 1). Reclamation may be the only viable option for restoring some levels of biodiversity and ecosystem services in former coal or bauxite mining operations, where abiotic factors, such as soil removal or toxic substrata, limit establishment and growth of native vegetation (13). In areas with degraded soils, rehabilitation through planting of carefully selected exotic or native trees can improve soil fertility and restore productive agricultural use, while offering little enhancement of biodiversity. Where agricultural land use has been less intensive and nearby forest patches and faunal dispersal agents can ensure diverse seed rain, the most rapid and least costly path toward restoring forests is through unhindered natural regeneration (11, 14). After 30 to 40 years, natural regeneration following abandonment of pasture and coffee plantations produced secondary forests in Puerto Rico with biomass, stem density, and species richness similar to the island's mature forests (15). Direct seeding and planting seedlings or saplings in regenerating forests can hasten recovery of species composition (14, 15). In sites at intermediate levels of degradation, where soils are intact but diverse seed sources are lacking, reforestation with native species, agroforestry, and assisted natural regeneration can augment biodiversity and ecosystem services, while also providing income for rural livelihoods. Such plantings can be incorporated—along with natural regeneration—into management of buffer zones and biological corridors to enhance landscape connectivity and landscape-level biodiversity (16).

In both developed and developing countries, forests are being restored by local communities, as well as through state and national programs. Forest rehabilitation projects in the Philippines, Peru, Indonesia, China, North Vietnam, and the Brazilian Amazon River basin promote community organization and improvement of rural livelihoods (17). Local knowledge of tree characteristics, planting of diverse species of ecological and economic importance, and integration of rehabilitation programs with regional development strategies are essential elements of restoration success (17). Communities from 12 villages in Phuc Sen in Northwestern Vietnam organized to restore limestone forests degraded in the 1960s

and 1970s by excessive fuelwood and timber extraction. Through planting indigenous tree species and fostering natural regeneration, forests are being restored, water is again flowing to lowland rice fields, and over 30 species of rare or endemic indigenous mammals are returning to the area (*18*). In the Shinyanga region of Tanzania, large areas of dense acacia and miombo woodland were cleared by 1985, transforming the landscape into semidesert. The HASHI program helped local people from 833 villages to restore 350,000 ha of acacia and miombo woodland through traditional pastoralist practices in only 18 years (*19*).

Experimental research is required to determine the most appropriate path toward restoration. In many cases, passive methods can achieve greater success than intensive interventions and are far less costly (*13*). In the northwest Czech Republic, unassisted succession led to more successful restoration of species richness in mine spoils after 20 to 30 years than in technically reclaimed treatments, where organic amendments stimulated the growth of weeds and inhibited establishment of target species (*13*). Restoration techniques involving plowing and mechanical planting may actually slow regeneration of seasonal deciduous forests in Brazilian Cerrado (*20*). There are few rigorous, replicated studies of the effects of different restoration treatments (including unassisted natural regeneration) that account for previous land use, soils, proximity to seed sources, and age since abandonment (*20*). At what position along a forest degradation gradient does "accelerating succession" through planting trees achieve faster recovery of forest structure and composition compared with unassisted regeneration? This question is challenging to address, as the effects of management will vary with the spatial scale of restoration, as well as with synergistic effects of biotic and abiotic stresses from climate change, invasive species, and altered plant-animal relationships (*10*, *13*).

Large-scale forest restoration presents complex and poorly understood implications for the structure and composition of future forests, landscapes, and fauna. Will widespread plantations of a small number of native species—an increasingly popular form of forest restoration in tropical regions—increase biotic homogenization and decrease genetic diversity of planted species (Fig. 2)? Monoculture tree plantations may also facilitate establishment of invasive species and increase susceptibility to species-

specific pathogens (*10*). Interventions to promote rapid carbon sequestration through tree plantations will increase the regional abundance of fast-growing, disturbance-tolerant species, which can impact forest dynamics in mature forest fragments (*21*). Emerging forests provide breeding grounds for invasive exotic

Fig. 1. The restoration staircase. Depending on the state of degradation of an initially forested ecosystem, a range of management approaches can at least partially restore levels of biodiversity and ecosystem services given adequate time (years) and financial investment (capital, infrastructure, and labor). Outcomes of particular restoration approaches are (1) restoration of soil fertility for agricultural or forestry use; (2) production of timber and nontimber forest products; or (3) recovery of biodiversity and ecosystem services.

species, which can rapidly colonize established forests in protected areas (*10*) (Fig. 2). Population explosions of the white-tailed deer (*Odocoileus virginianus*) in recovering forests of the eastern United States provide a sobering example of synergistic effects of widespread forest expansion, reduced predator populations, and spread of invasive species and human disease agents (*22*).

Effects of different restoration approaches on recovery of ecosystem services are also poorly studied, despite wide recognition of the links between biodiversity, functional traits, and ecosystem services (*23*). Incentives for increasing carbon stocks in vegetation provide a major impetus for a wide range of forest restoration interventions, as well as conservation of existing forests. An aggressive global program of reforestation and natural regeneration could potentially restore forests on 700 million ha over the next 50 years (*24*). Fast-growing, short-lived species with low-density wood are favored by many reforestation projects designed to provide carbon offsets, but long-term carbon sequestration is promoted by growth of long-lived, slow-growing tree species with dense wood and slow turnover of woody tissues. These species increase in abundance and biomass throughout the course of
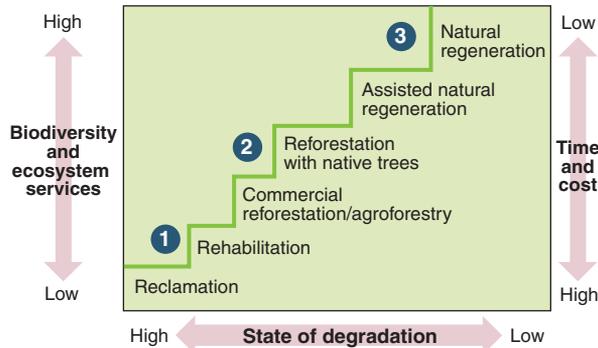
Fig. 2. A commercial restoration plantation in northeastern Costa Rica. In the foreground are planted individuals of *Acacia mangium*, a fast-growing tree species native to Asia and Australia, which tolerates poor soils. A fast-growing native species, *Vochysia guatemalensis* is also planted here among the *A. mangium* trees. In the background is a fragment of 25-year-old secondary forest. *Euterpe oleracea*, an exotic palm species from Brazil that was cultivated in a nearby plantation has colonized the restoration site (upper right quadrant) and is now invading secondary forests in this area. [Photograph by R. L. Chazdon]

natural forest regeneration (*23*). Short-term solutions are attractive, but forest regeneration and restoration are long-term processes that can take a century or more. Plantations have a high rate of failure if few tree species are planted and they are not well suited to site conditions. Of 98 publicly funded reforested areas in Brazil, only 2 were successful (*25*). It is essential to plan for long-term returns on restoration investments if future forests are to support the wide range of species, species interactions, and ecosystem services present in current forests.

Ambitious efforts are being mounted to restore forests, ecosystem services, and biodiversity throughout the world. The Riparian Forest Restoration Project hopes to reforest 1 million ha of riparian rainforest in the Atlantic Rainforest in São Paulo, Brazil, with up to 800 native species (*25*). Forest restoration efforts, whether at national, regional, or local scales, will take many decades, long-term financing, political will, labor, and personal commitment. In the process, these efforts will also restore new relationships between people and forests. As so clearly stated by William R. Jordan III, a founder of the field of restoration ecology, "Ultimately, the future of a natural ecosystem depends not on protection from humans but on its relationship with the people who inhabit it or share the landscape with it" (*26*).

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PERSPECTIVE

Changing Governance of the World's Forests

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Major features of contemporary forest governance include decentralization of forest management, logging concessions in publicly owned commercially valuable forests, and timber certification, primarily in temperate forests. Although a majority of forests continue to be owned formally by governments, the effectiveness of forest governance is increasingly independent of formal ownership. Growing and competing demands for food, biofuels, timber, and environmental services will pose severe challenges to effective forest governance in the future, especially in conjunction with the direct and indirect impacts of climate change. A greater role for community and market actors in forest governance and deeper attention to the factors that lead to effective governance, beyond ownership patterns, is necessary to address future forest governance challenges.

Central governments own by far the greater proportion—about 86%—of the 5.4 billion hectares of the world's forests and wooded areas. Private and "other" (mostly communal) forms of ownership constitute just over 10% and below 4% of global forests, respectively (*1*). There are important regional variations around these averages [Fig. 1, based on (*1*)]. Official statistics on forest ownership, however, misrepresent the extent of and changes in forest cover (*2*). They also misrepresent the nature and changing forms of global forest governance.

Effective governance is central to improved forest cover and change outcomes. Changing forest governance today is for the most part a move away from centrally administered, top-down regulatory policies that characterized much of the 19th and 20th centuries. Many government-owned forests are managed as common property for multiple uses by local communities and community-based organizations (*3*). Many other forests classified under public ownership are effectively governed as private timber concessions by logging companies (*4*). Civil society organizations and market incentives increasingly play a role in forest governance through certification processes and changing consumer preferences (*5*). At the same time, the growth in the number and size of strict protected areas in the latter half of the 20th century has also meant that ~6.4 million km^2 of publicly owned forests are now under governance regimes that involve greater restrictions on human use and habitation (*6*, *7*) (fig. S1).

In the 21st century, three important forest governance trends stand out: (i) decentralization

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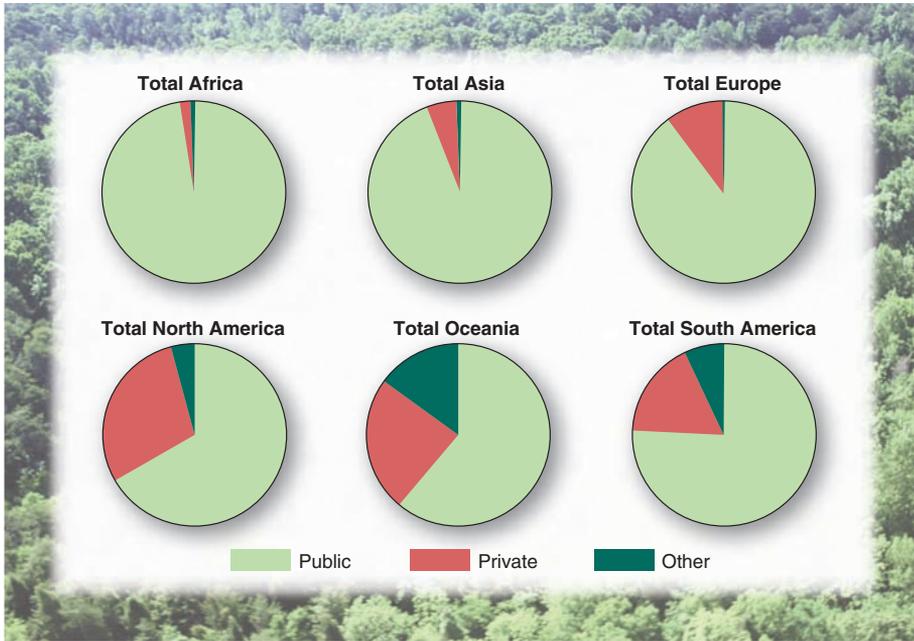*To whom correspondence should be addressed. E-mail: arunagra@umich.edu

Fig. 1. Distribution of forest ownership by world regions.

tems, and changing forest policy frameworks (*15*). Under concessionary forest governance, central governments or forest departments provide logging companies with long-term resource extraction rights in commercially valuable forests in exchange for a stream of revenues. Although a variety of logging concessions arrangements also exist in the developed world, they are a dominant form of forest governance in tropical forests in Southeast Asia, parts of the Amazon, and especially in Central and West Africa, where at least 75 million hectares of forests are under concession to logging companies (*4*). Contemporary governance through forest concessions is prompted by demand for logs and timber—often in distant markets—and governments' need for revenues. The limited enforcement of concession agreements in most countries in Southeast Asia and Africa has also meant that legal logging in concessions exists side by side with costly and unsustainable levels of illegal logging (*16*). The World Bank estimates U.S. $15 billion to be lost to developing countries every year as a result of illegal logging.

Forest certification initiatives emerged in the early 1990s as market instruments in which an independent certification body provides an assurance to consumers that forest product suppliers have conformed to some predetermined criteria of sustainable forest management (*17*). Certification efforts were launched as a way to improve the sustainability of tropical forest management. Yet they have been used far more broadly in temperate forests—
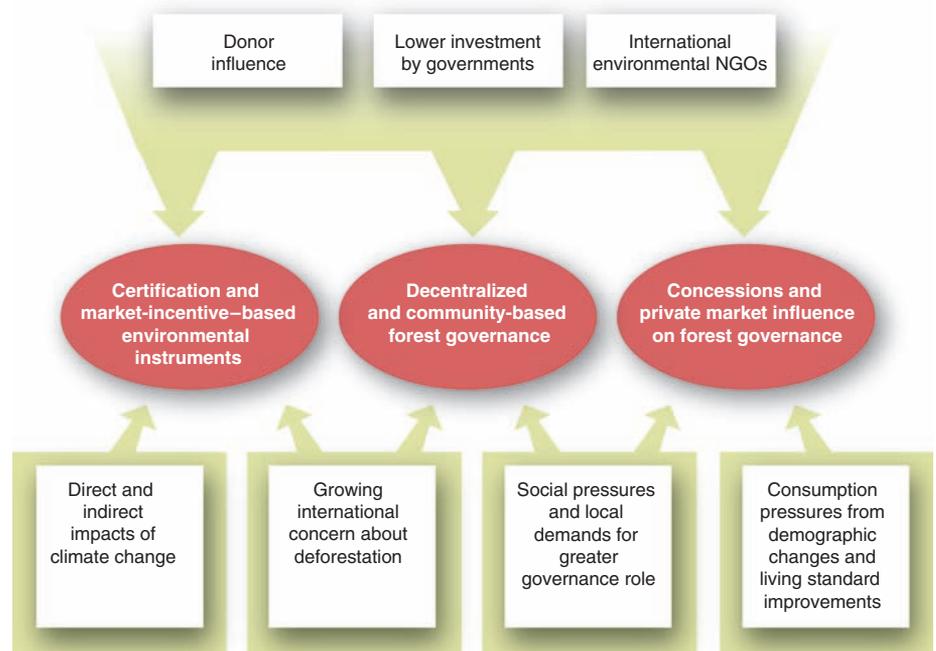
of management, especially for commercially low-value forests that nonetheless play an important role in the livelihoods of hundreds of millions of rural households in developing countries; (ii) the substantial role of logging companies in forest concessions, typically for selective logging in tropical forests; and (iii) the growing importance of market-oriented certification efforts, mainly in temperate forests in the developed world.

Decentralization of forestry policies began in the mid- to late 1980s and had become a prominent feature of forest governance by the mid-1990s (*8*, *9*). It was impelled in part by infusions of material and technical support from bilateral, multilateral, and private donors who sought better forest governance from recipient countries. These external pressures coincided with domestic demands for a greater recognition of local communities' needs for forest products and their role in managing local forests for multiple purposes (*10*). They also worked in the same direction as the desire of many governments to reduce the financial burden of forest governance in an economic context characterized by substantial fiscal and budgetary pressures. An emerging body of scholarly work on local participation, resource institutions, governance, and accountability helped provide some justification for decentralization reforms (*11*, *12*). Decentralization reforms in the past two decades have often promoted local, more democratic participation in governance. In tandem with policy advocacy and social movements, such reforms have fostered new practices of forest use, sometimes provoking social tensions revolving around

claims of indigenous peoples within forest zones (*10*). Overall, local communities and organizations have come to govern close to an additional 200 million hectares of forests compared to the 1980s (*13*, *14*).

The private concession model in forest governance has been in existence at least since the imperial trades of the early 1700s, enduring shifts in commodity values, political sys-

Fig. 2. Changes in forest governance and their social, economic, and political drivers.

Forests in Flux

less than 10% of 80 million hectares of certified forests in 2000 were in the humid tropics (*18*). Certification processes and performance standards are expanding into new regions and niches as a market and civil society response to public concern about deforestation, the organizational strength of international environmental nongovernmental organizations (NGOs), and continuing economic globalization (*5*).

Decentralization, concession, and certification-related trends in forest governance are the result of important social, economic, and political drivers (Fig. 2).

The role of drivers mentioned in Fig. 2 is likely to be reinforced and made more complex by climate change. Existing trends around conversion of forests to biofuel plantations, for example, are likely to affect both biodiversity and the livelihoods of the poor adversely.

In conjunction with competing demands for food and forest products from a growing, and on the average wealthier, global population, climate change impacts will strengthen governance trends (especially in the direction of concessions and certification), increase the involvement of market actors in forest governance, and create pressures toward greater formalization as governments seek to take advantage of emerging carbon funds. The intersection of production strategies for food, fuel, and forest products as competition grows for scarce land will inevitably lead to new experiments with governance arrangements at all levels, from the local to the international. It can potentially reverse contemporary trends in favor of the involvement of civil society actors and communities, instead promoting greater privatization. The need for making careful choices in this regard will become especially critical after the next two decades as the joint effects of changes in climate, demographic patterns, and living standards begin to be felt more acutely (*19*).

The effectiveness of forest governance is only partly explained by who owns forests. At the local level, existing research finds only a limited association between whether forests are under private, public, or common ownership and changes in forest cover or sustainability of forest management (*11*). National-level association between forest area under different forms of ownership and changes in forest cover is also relatively weak, especially for public ownership [Spearman's rho for proportion of forests under public ownership and forest cover change = 0.017, $P > |t| = 0.98$, based on data in (*1*)]. At the regional level, the greatest net declines in forests have occurred in tropical countries. Conversely, net increases in forest cover have occurred primarily in North America and Europe (see figs. S2 and S3 for illustration). However, the relationship between this pattern and forest ownership is limited. Moreover, there is only partial knowledge about the relationships between the condition of forests, different forms of forest ownership, and the multiple objectives of forest governance—improvements in income, livelihoods, biodiversity, carbon sequestration, and ecosystem service provision.

The need to look deeper, therefore, into how governance arrangements work is paramount if forest dwellers, users, managers, and policy-makers are to make better choices about forest governance at a variety of scales. A very large number of factors influences the effectiveness and outcomes of forest governance (*20*, *21*). Among these, careful definition of user rights and responsibilities in forests, greater participation by those who use and depend on forests, downward and horizontal accountability of decision-makers, better monitoring of forest outcomes, stronger enforcement of property rights and governance arrangements, and investments in institutional capacities at local, regional, and national levels have been identified as critically important for more effective forest governance in tropical country contexts.

Broadly speaking, the goal of forest conservation has historically not been met when in conflict with land use changes driven by the demand for food, fuel, and profit. It is necessary to recognize and advocate for better governance of forests more strongly given the importance of forests in meeting basic human needs in the future, making resources available for livelihoods and development, maintaining ecosystems and biodiversity, and addressing climate change mitigation and adaptation goals. Such advocacy must be coupled with financial incentives for governments of developing countries and a greater governance role for civil society and market actors if forests are to continue to provide benefits to humans well into the future.

Many scholars recognize the central importance of governance in influencing forest outcomes, but a review also shows major gaps in existing knowledge about the history and distribution of forest governance arrangements and in the understanding of how different features of governance affect outcomes. The challenge of understanding the coupled social and ecological systems (*22*) that all forest governance represents urgently needs more emphasis and attention than it has received until now.

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