Biophysical considerations in forestry for climate protection

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Forestry – including afforestation (the planting of trees on land where they have not recently existed), reforestation, avoided deforestation, and forest management – can lead to increased sequestration of atmospheric carbon dioxide and has therefore been proposed as a strategy to mitigate climate change. However, forestry also influences land-surface properties, including albedo (the fraction of incident sunlight reflected back to space), surface roughness, and evapotranspiration, all of which affect the amount and forms of energy transfer to the atmosphere. In some circumstances, these biophysical feedbacks can result in local climate warming, thereby counteracting the effects of carbon sequestration on global mean temperature and reducing or eliminating the net value of climate-change mitigation projects. Here, we review published and emerging research that suggests ways in which forestry projects can counteract the consequences associated with biophysical interactions, and highlight knowledge gaps in managing forests for climate protection. We also outline several ways in which biophysical effects can be incorporated into frameworks that use the maintenance of forests as a climate protection strategy.

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Forestry – defined here and throughout this paper as practices such as afforestation (the planting of trees on land where they have not recently existed), reforestation, avoided deforestation, and forest management – is a potentially important climate-change mitigation strategy (Pacala and Socolow 2004; Canadell and Raupach 2008). Because forestry also has the potential to be a multibillion-dollar industry (Niles *et al*. 2002), trading institutions, such as the Chicago and European Climate Exchanges, and political entities, such as the State of California's Climate Action Registry, already contract with landowners for biological carbon (C) sequestration (Hamilton *et al*. 2009). In addition, the Clean Development Mechanism of the Kyoto Protocol allows governments and business organizations from industrialized countries to invest in forestry in developing countries to accrue C credits to offset industrialized emissions. The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) plan, which is part of the UN Framework Convention on Climate Change, is expected to provide credits for avoided deforestation not currently included in the Kyoto Protocol; globally, there are now dozens of projects intended to demonstrate the feasibility of REDD. Overall, there is strong interest in the role of forestry in climate mitigation agreements and legislation (Schlamadinger and Bird 2007).

In a nutshell:

- Forestry is becoming an important part of both voluntary carbon markets and government efforts to mitigate climate change
- Forests have biophysical effects that can enhance or counteract their potential for carbon sequestration to reduce climate warming
- These effects can differ greatly, depending on the spatial scale involved
- Consideration of both the biogeochemical and biophysical effects of forests is necessary when designing projects that maximize climate benefits; only broad best practices can be applied at this time, given that the science in support of such an integrated approach is still under development

Forests can sequester C, but this leads to other important biophysical changes (Figure 1). Forests often have a lower surface albedo (the fraction of incident sunlight reflected back to space) than that of the ecosystem they replace, and so absorb more solar radiation (Betts 2000). They can also affect other biophysical parameters, including surface roughness, which influences the exchange of energy and mass between the land surface and the atmosphere, and the amount of water recycled to the atmosphere through evapotranspiration (Bonan 1997). These changes affect climate at a variety of scales and can enhance or counteract the climate benefits from forest C sequestration (Marland *et al*. 2003). Resulting climate changes may themselves affect the permanence of stored forest C (Subak 2002).

Climate policies currently being established focus solely on greenhouse gases and do not reflect the net impact of biophysical changes that result from

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changes in land-use patterns. While research on the net effects of climate on forests is still in its early stages, current knowledge and scientific first principles can provide some guidance on the development of sound mitigation policies. Here, we review the relevant literature and make suggestions for maximizing the effectiveness of forest projects in climate protection. We also briefly address crucial non-climate aspects that are related to successful forestry, such as ecosystem services, human land-use needs, and the preservation of biodiversity.

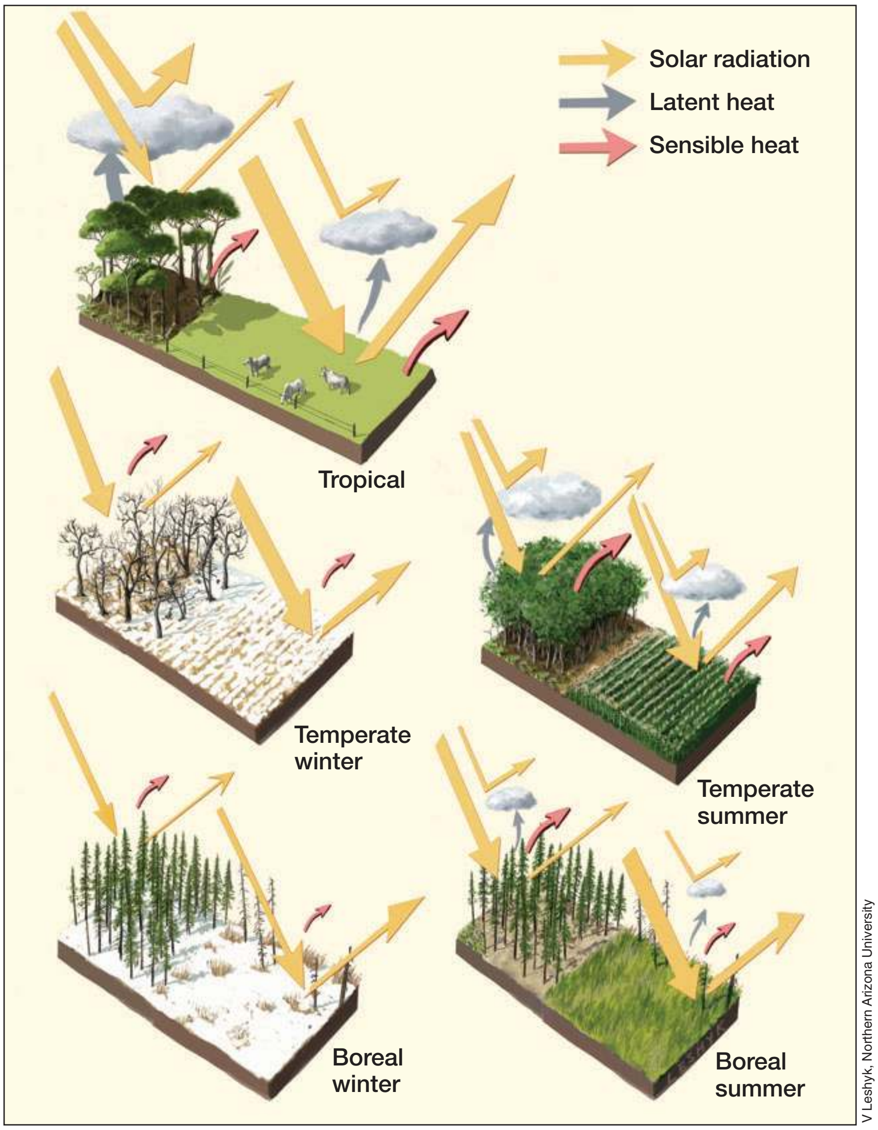


Figure 1. *Effects of forest and non-forest ecosystems on surface energy fluxes in tropical, temperate winter, temperate summer, boreal winter, and boreal summer scenarios. Forests have greater heat fluxes than non-forest ecosystems, resulting from their greater surface roughness. Tropical rainforests have large latent heat fluxes that result in the development of clouds, which reflect solar radiation back to space. Temperate and boreal forests have major seasonal variations in energy fluxes and can reduce seasonal cooling by masking snow.*

■ Considerations for maximizing the climate benefits of forestry

Complete C sequestration potential of an individual project

Afforestation leads to C accumulation in living biomass, coarse woody debris, and soil organic carbon (SOC), with the relative importance of accumulation in these pools varying considerably across different biomes. Potential rates of C accumulation in living biomass are generally highest in tropical forest regions and decrease toward the poles (Grace 2004). Large regional variations are possible, however; for example, old-growth temperate forests in the Pacific Northwest of the US can store the same amount of C in living biomass as similarly aged tropical forests (Hudiburg *et al.* 2009). SOC sequestration potential depends on the history of land use, soil texture, climate, and the species of trees used in forestry projects. Greater SOC gains are found in soils containing more clay, previous land use that involved greater soil disturbance (eg cropland), cooler climates (eg slowing decomposition losses), and the inclusion of deciduous trees; smaller increases occur when forests replace grasslands or pastures (Laganière *et al.* 2010). Large SOC accumulations are often found in older boreal forests (Harden *et al.* 2000). The variability in living biomass and SOC suggests that the rate and total C storage capacity above- and belowground should be estimated for any given forestry project.

Large-scale tropical forestry likely has the greatest climate benefits

Tropical forestry has the clearest climate benefits of any such projects, because tropical forests exhibit high globally averaged C storage and uptake per unit area, cover the greatest amount of land, and are responsible for the highest level of net cooling of any biome (Grace 2004; Bala *et al.* 2007; Table 1). Further-more, tropical deforestation currently accounts for over 90% of net C emissions resulting from global land-use change (Houghton 2003); therefore, avoided tropical deforestation reduces anthropogenic C emissions from land-use change (Gullison *et al.* 2007).

The value of tropical forests for atmospheric cooling at local and regional scales (relative to that of grasslands) has long been recognized (eg Shukla *et al.* 1990). Tropical forests have high rates of transpiration that contribute to cloud formation, considerably reducing both surface tem-

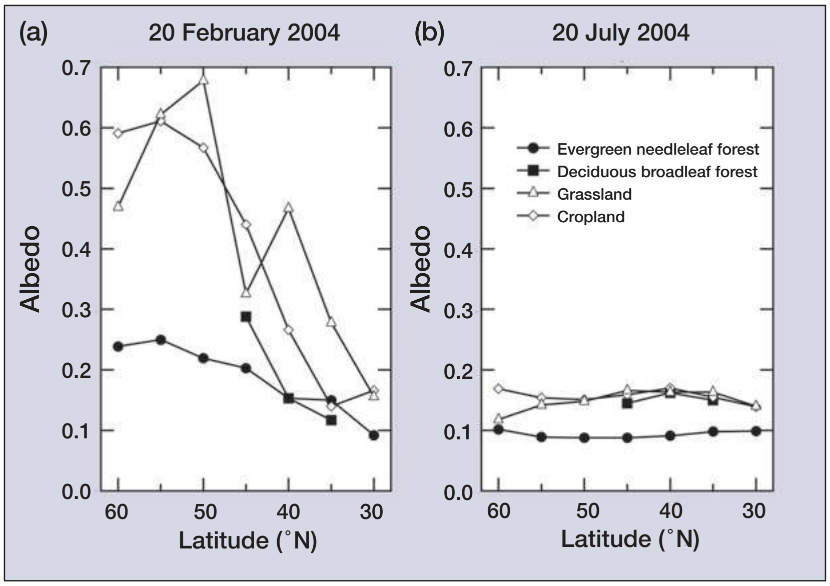


Figure 2. *Satellite observations of zonally averaged, shortwave, surface albedo for select land-cover types and latitudes for (a) winter and (b) summer in 2004. The albedo data were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements of black sky albedo (MCD43C3 version 5; Schaaf* et al. *2002) and span 16-day intervals. The albedo observations were averaged within International Geosphere-Biosphere Program (IGBP) land-cover classes (MOD12C1 version 4), developed through concurrent MODIS surface reflectance observations (Friedl* et al. *2002). Only grid cells at 0.05° resolution were sampled; these were composed of > 80% of a single IGBP vegetation class. These data were zonally averaged within 5° bins of latitude for zones with more than 10 pixels of a vegetation class.*

peratures and the amount of sunlight reaching the Earth's surface. Modeling experiments have consistently shown that tropical deforestation increases surface radiation, reduces evapotranspiration and surface roughness, and raises surface temperatures (Zeng *et al.* 1996; Werth and Avissar 2002; Bala *et al.* 2007). In an extreme, idealized case, Bala *et al.* (2007) showed that complete tropical deforestation could increase global land temperatures by 0.9 °C, while complete temperate deforestation and complete boreal deforestation had a near zero effect, and boreal deforestation actually had a cooling effect on global temperatures. Reforesting tropical areas and preventing the destruction of existing tropical forests may have the greatest global climate impact of any forestry project because of the high level of emissions currently generated by tropical deforestation, the size of the tropical forest C pool, and the dual cooling nature of tropical forests.

Table 1. Area and C storage in vegetation of select biomes

Ecosystem	*Area (millions km^2)*	*Total C (gigatons)*	*C per unit area (kg*m^{-2})*
Tropical forests	17.5	553	31.6
Temperate forests	10.4	292	28.1
Boreal forests	13.7	395	28.8
Crops	13.5	15	1.1
Tropical grasslands	27.6	326	11.8
Temperate grasslands	15.0	182	12.3

Notes: Area and total C storage data are from Grace (2004). Total C storage includes vegetation and soil organic matter.

Limited water availability may reduce the biophysical cooling effect of trees

Afforestation is another tool for sequestering C. Some afforestation projects will probably occur in water-limited regions (ie locations where potential evapotranspiration is greater than precipitation). Conifers have been planted in locations with as little as ~300 mm precipitation per year, thereby opening up large regions of the Earth to potential afforestation (Grunzweig *et al.* 2003; Law *et al.* 2003). However, these forests may reduce surface albedo (Field *et al.* 2007; Figure 2) and increase surface roughness as compared with the ecosystems they replace, thus absorbing more solar radiation and more effectively transferring energy from the land surface to the atmosphere through convection. A disproportionate amount of available energy in water-limited forests is partitioned into sensible heat (energy transferred by convection of warmer air from the surface; Baldocchi *et al.* 2004); this results in warmer local, and possibly regional, air temperatures.

Cooling biophysical effects will probably increase along a gradient of little to ample water availability. Model simulations (eg Werth and Avissar 2002) indicate that in tropical environments with plenty of water, afforestation cools the Earth through low-altitude cloud formation. Increased evaporation in temperate and tropical environments with ample water is likely to result in a net cooling effect, when considered from both regional and global perspectives. The net effect of afforestation on climate in water-limited regions is unclear.

Afforestation in snow-covered regions may counter the C sequestration

As compared with other natural surfaces, snow has a high albedo and reduces the amount of energy absorbed at the surface. Figure 3 shows an example of the seasonal impact of snow on albedo, as found in British Columbia, Canada. Short canopy ecosystems, such as grasses and crops, in northern latitudes have albedos that approach 0.6 when covered by snow in winter (Figure 2a); this exceeds summer albedo by a factor of 2–3 (Figure 2b). In contrast, forests in the same region have winter albedos that are substantially lower, because darker tree canopies obscure snow and absorb radiation. Not surprisingly, during winter, deciduous forests tend to reduce albedo less than coniferous forests (Jackson *et al.* 2008; Liu and Randerson 2008; McMillan and Goulden 2008), probably as a result of both increased stem reflectance and greater exposure of surface snow below leafless canopies. The albedo effect of forests is amplified in boreal regions and at elevations where snow persists into spring (eg Montenegro *et al.* 2009). Modeling studies on boreal deforestation have suggested that considerable cooling would occur when both C and biophysical climate interactions are included in the simulations (Betts 2000; Bala *et al.* 2007). Fire has also been shown to have a net cooling effect in boreal forest ecosystems, resulting from a similar increase in mean, long-term albedo that counters C losses (Randerson *et al.* 2006). The net effect of afforestation on regions with intermediate snow cover, such as the northern half of the continental US, is unclear at this time (Jackson *et al.* 2008). The uncertainty arises, in part, from counteracting effects of forestry on rates of evapotranspiration and albedo, and the difficulty of parameterizing the processes that regulate this net balance in climate models. Modeling results indicate that the net effect in mid-latitude regions may be negligible (Bala *et al.* 2007).

Deciduous broadleaf trees may be more effective at cooling than evergreen conifers

Deciduous tree species have two properties that may make them more effective for cooling. First, deciduous forests have a summer albedo of up to 0.1 (reflectivity scale from 0 to 1) higher than coniferous forests, depending on the region (Eugster *et al.* 2000; Breuer *et al.* 2003; Jackson *et al.* 2008; Figure 2). Second, studies of deciduous broadleaf forests have shown that, during mid-summer, they have canopy conductances (the ease with which plants transpire water) and an evaporative fraction (the fraction of available radiation that is used to evaporate water) that is approximately twice that of coniferous forests (Eugster *et al.* 2000; Breuer *et al.* 2003). This additional transpiration from deciduous canopies results in local cooling and possible cloud formation that could increase albedo and reduce temperatures when incoming solar radiation is near its maximum annual value. The effect of deciduous cover on evaporation and energy exchange also depends on the length and timing of leaf cover (Wilson and Baldocchi 2000). Coniferous species tend to sequester slightly more (< 5–10%) C than deciduous species in the same region, but this difference is less important than inter-regional differences or differences resulting from management practices (Bateman and Lovett 2000). When appropriate for the region, deciduous species may offer additional biophysical cooling as compared with coniferous species.

Consider effects of forests on regional climate

Forest removal or addition alters (1) surface roughness, temperature, and albedo, (2) planetary boundary layer height, and (3) soil–atmosphere coupling, all of which can affect local and regional climate in various ways. For example, models of afforestation in the Mediterranean region show an increase in winter evaporation, winter precipitation, and summer temperature with afforestation (Gates and Liess 2001). Deforestation data and modeling in Australia show that both evaporation and precipitation decline, but temperatures increase (Pitman *et al.* 2004). In contrast, models of land-use change in temperate Europe show that forest-to-crop conversions decrease mid-day temperatures and increase summer evaporation as a result of higher crop stomatal conductance and albedo (Zhao and Pitman 2002). In addition to mean climate conditions, modeling studies have shown that afforestation alters diurnal climate variability, including a reduction in the diurnal temperature range and an increase in the dew-point temperature range (Wichansky *et al.* 2008).

Canadian Forest Service, Natural Resources Canada

Figure 3. *Impact of differing forest cover on effective albedo during winter. Denser forest cover reduces snow exposure and absorbs more solar radiation. These forests are part of the Montane Alternative Silviculture Systems Study in British Columbia, Canada, which was designed to assess the ecological impact of different logging regimes (Mitchell* et al. *2004).*

Forestry may enhance or dampen the regional effects of climate change. Decreases in runoff as a result of afforestation, for example, could further stress regional water resources (Jackson *et al.* 2005). However, accompanying increases in precipitation in drier regions, such as Western Australia, would be very beneficial to society (Pitman *et al.* 2004). Thus, when designing large-scale afforestation programs, considering regional climate effects is crucial. These examples show that forestry practices can affect the hydrological cycle in important ways, and that temperature should not be the only metric considered. Investments in regional climate modeling studies and field measurements during the design of forestry projects may help to quantify region-specific responses to land-surface changes.

Less intensive management may reduce the risk of warming climate effects

Forest management practices, such as fertilizer use, monoculture planting, and thinning, can reduce the benefits of C sinks in multiple ways. First, applying fertilizers can boost both the rate and capacity of C sequestration, but substantially increases soil emissions of nitrous oxide (N_2O; Smith and Conen 2004). Given that N_2O has a 100-year greenhouse warming potential (GWP) about 300 times that of carbon dioxide (CO_2), and methane has a GWP of 20 to 25 times that of CO_2, practices that result in slightly more N_2O or methane emissions could disproportionately offset the cooling effects from forest C sequestration (eg Schulze *et al.* 2009). Second, conversion of native forests to plantations can increase runoff and reduce evapotranspiration, especially in the early stages of plantation growth (Fahey and Jackson 1997), thereby reducing biophysical cooling (see above) in comparison with the native forest.

Finally, C emissions from energy used to manage forests, including tailpipe emissions from trucks and tractors, are typically greater in intensively managed forests. However, energy production from forestry products might indirectly mitigate climate change by reducing C emissions from the burning of fossil fuels. It is crucial to extend cost–benefit analyses to include net greenhouse-gas emissions from management activities over the entire life cycle of the proposed project.

The resilience of forest projects to future climate change

Future climate change is expected to have substantial and varying effects on temperature and precipitation across the globe, and there is considerable uncertainty regarding the magnitude of these effects at regional and local scales. Climate change has the potential to alter forest structure and C storage (eg Dale *et al.* 2001). Climate change may also reduce C storage via increased disturbance associated with more intense hurricanes (Juarez *et al.* 2006), fires (Westerling *et al.* 2006), insect attacks (Seidl *et al.* 2008), or droughts (van Mantgem *et al.* 2009). To diminish the chance that climate-induced physiological stress or disturbance reduces C storage, afforestation projects should use species and practices that recognize and adapt to future climate and disturbances (Millar *et al.* 2007; Galik and Jackson 2009). For example, project managers could plant species that are currently outside their optimal climate range, but that would likely succeed in a region's future climate. C accounting rules may also need to be revised, to encourage practices that result in stable, long-term growth and minimize disturbances (Law and Harmon 2011).

Urban forests can provide local cooling and reduce anthropogenic energy use

In addition to sequestering C, planting trees around and within urban areas can reduce building energy use and associated C emissions. Deciduous trees that shade a building during the summer reduce the incoming radiation absorbed by the building, thus reducing energy use for air conditioning, while allowing passive heating during winter (Akbari 2002). In winter, evergreen trees that act as windbreaks can decrease air infiltration, reducing the energy needed for heating (Liu and Harris 2008). Liu and Harris (2008) found an energy reduction of ~20% for winter heating in Scotland when trees acted as windbreaks, whereas Akbari (2002) found a reduction in energy-related C emissions of 18 kg of C per tree per year in Los Angeles, California, resulting from direct shading and cooling of buildings, which was 3 to 5 times the C sequestration within each planted tree.

In addition to direct shading effects, widespread planting of trees in urban areas can result in lower air temperatures by changing regional-scale land-surface energy fluxes. Model results indicate that if tree planting were adopted across an entire urban area, enhanced latent heat fluxes would decrease surface air temperatures near the urban center by 1–3°C, thus leading to additional reductions in energy use (Akbari *et al.* 2002). However, urban trees often require irrigation, which can increase greenhouse-gas emissions associated with water transport and regional water management.

Social, economic, and biological sustainability criteria are crucial factors

Forestry, like any land transformation, may lead to unintended environmental and socioeconomic consequences, which could jeopardize the long-term success of projects (Canadell and Raupach 2008). Frameworks and standards have been proposed to assess the social, economic, and biological sustainability of afforestation projects and their compliance with international agreements (Madlener *et al.* 2006; Merger 2008). Biological sustainability includes factors such as ecosystem services (eg water and air purification) and biodiversity conservation or enhancement. Forestry's impact on water availability and soil salinity should also be considered, because forest projects in semiarid regions can transpire more water than is provided by precipitation and infiltration, thus resulting in unsustainable use of groundwater and salinization (Jobbágy and Jackson 2004). Cannell (1999) showed that both ecosystem services and biodiversity would suffer if monoculture forest plantations replaced various natural ecosystems; however, the impact would be less if afforestation replaced other highly managed ecosystems, such as marginal cropland. Social sustainability factors include ensuring that local forests improve the livelihoods of nearby residents without reducing services provided by the previous land uses (eg crop or grazing land for affordable food). Gaining support and involvement from local populations is important; for example, Hunter *et al.* (1998) provided a case study in India where failure to ensure social sustainability resulted in eventual deforestation of afforested "marginal" land. Forest projects are likely to be unsuccessful for climate mitigation if they fail to promote economic, social, and environmental sustainability.

Future directions

The issues of C storage, forest permanence and resilience, social, environmental, and economic sustainability, and urban forestry intersect with a critical set of additional considerations related to the impacts of forestry activities on landscape properties that affect climate. Key challenges include:

(1) How can the biophysical climate impacts of forestry be compared with the climate impacts of C sequestration? Should existing metrics that convert the radiative impact of a surface change into a C equivalent (eg Betts *et al.* 2000) be used, knowing that these metrics cannot capture non-radiative effects, such as changes in precipitation? Or should both radiative and non-radiative climate effects be considered in terms of their impacts on ecosystem services?

This is particularly difficult, given that climate impacts due to changes in surface biophysics may change from warming to cooling or vice versa depending if one is examining local, regional, or global climate. Furthermore, biophysical and biogeochemical changes have a very different temporal character; for example, CO_2 emissions produce long-lasting effects on atmospheric concentrations and thus have lasting effects on climate, whereas climate effects of albedo changes diminish quickly if the albedo reverts to its previous value. Thus, a judgment must be made on how best to compare the value of changes at different times and places. Simple metrics, such as effect on global mean temperature, may not capture key issues that matter most to humans.

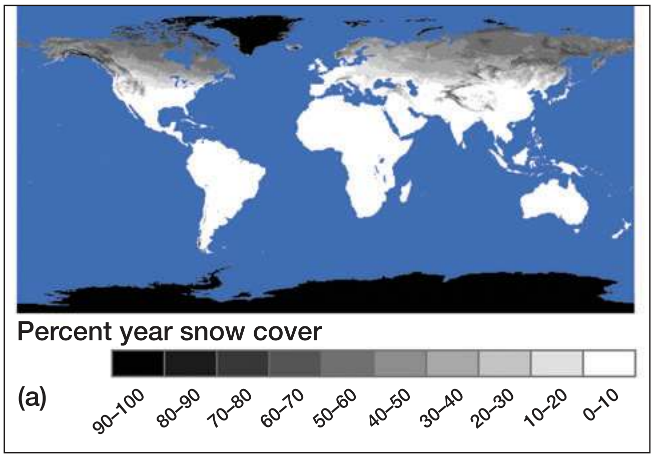
(2) How can the biophysical impacts of forestry be incorporated into climate-change mitigation strategies? Should the biophysical impacts of forests be viewed as a separate criterion for crediting forest projects (ie accredited mitigation projects need to demonstrate the occurrence of biophysical climate cooling effects, in the same way current projects need to demonstrate C sequestration)? Or should the biophysical impacts be viewed as an additional credit/discount to sequestration credits and management practices (eg Thompson *et al.* 2009)?

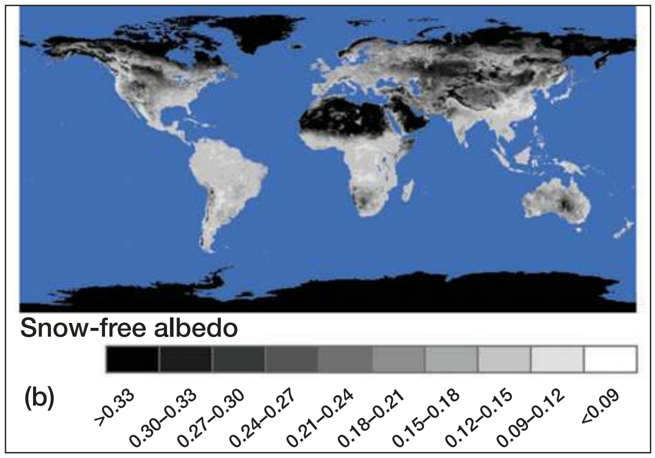
For example, if the project causes biophysical cooling, it could be allowed additional credits, equal to the C value of its physical benefits, whereas if it causes warming, a discount rate could be applied to the project, proportional to the resulting physical warming.

These questions require further research to comprehensively assess forestry's impact on climate and to account for biophysical effects in further development of climate-change policies. However, because forest projects are already being certified for C credits, there is an immediate need for an understanding of the potential biophysical impacts of forestry.

To illustrate the possible effects of biophysical changes on the suitability of land coverted to forest for climate protection, we have constructed maps showing three factors known to affect the climate impacts of forests: background albedo, snow cover, and water availability (Figure 4). All of these maps are at a resolution of 0.5°, because this is the highest resolution dataset existing for water availability. Furthermore, the snow-free surface-albedo map (Figure 4b) shows a considerable amount of subgrid variability that could mask locations that have different albedo. For example, a pixel could contain mostly dark forests or could be depicting a deforested area with a higher albedo. Afforestation in these deforested locations would then reduce albedo, because the forest would absorb more radiation. It is important for project planners to consider the pre-project surface albedo relative to the albedo of the planned forest.

Regions subject to multiple factors that would result in forest-induced cooling, such as the southeastern US, southern China, and other coastal regions (Figure 4), could gain the most from biophysical cooling effects due to afforestation. These areas have low existing surface albedo, high availability of water, and little snow cover; afforestation will result in less additional radiation being absorbed and a greater potential for evaporative and cloud feedback cooling as a result of increased transpiration. Most of these regions have or had substantial forest cover, which suggests that avoided deforestation or reforestation may be more successful at protecting climate than afforestation elsewhere. However, even in these areas, modeling results do not agree regarding whether forests would have a warming or cooling effect. There is an urgent need to resolve this question. In contrast, regions that have high surface albedo and low water availability (Figure 4b, c) or high snow cover (Figure 4a)





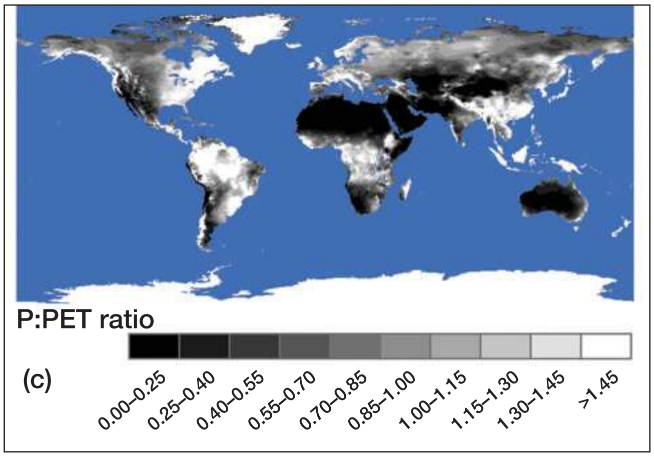


Figure 4. *Annually averaged values for snow cover, snow-free background albedo, and water availability. Color scale provides qualitative evaluation of temperature changes with forestry for each variable. Light colors indicate areas that are more suitable for afforestation than dark colored areas. (a) Map of average snow cover for calendar years 2001–2008. Snow cover was obtained from MODIS (MCD43C3 version 5). All data grids from MCD43C3 are 0.05-degree resolution resampled to 0.5-degree resolution. Snow measurements were average over 2001–2008 to determine the average fraction of the year with surface snow cover. (b) Snow-free surface albedo. Snow-free pixels from the MODIS MCD43C3 version 5 black sky, shortwave albedo were annually averaged to obtain albedo. (c) Map of water availability determined from the ratio of precipitation over potential evapotranspiration (P:PET). Precipitation and PET data are for 1950–1999 from Willmott and Matsuura (2001).*

might be less suitable for forestry aimed at counteracting climate change.

Conclusions

To be effective in mitigating climate change, forests need to sequester C or allow for reduced fossil-fuel burning through bioenergy production, while avoiding biophysical effects that would jeopardize the net climate benefits and long-term sustainability. Successful forest projects will likely have three characteristics: (1) they will have a net greenhouse-gas balance that is more favorable than that of the ecosystems they replace, and their C storage will be resilient under future climate and forest disturbance regimes; (2) they will have biophysical effects that cool the Earth relative to those of the ecosystems they replace; and (3) they will provide ecosystem services, biodiversity, economic livelihoods, and other benefits that enhance the quality of life for humans, thus ensuring that landowners and users have an incentive to maintain the forests. They may also buffer human settlements from local climate change by reducing heating and cooling requirements in dwellings, thus reducing energy use and associated C emissions.

Regional experiments and modeling that assess all of the climate effects associated with forest manipulations are a useful approach for assessing the full climate effect of forestry, but they require a considerable degree of additional investment. Research into forestry's effects on climate is still relatively new and requires a major expansion to support policy development; sound science-based policy would help optimize the climatic benefits of forestry, while mitigating its costs.

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