Biophysical considerations in forestry for climate protection


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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 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.

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

**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 (e.g., cropland), cooler climates (e.g., 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.

**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.

**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). Furthermore, 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 (e.g., Shukla et al. 1990). Tropical forests have high rates of transpiration that contribute to
cloud of available energy in water-limited forests is par-

amount of available energy in water-limited forests is par-

The net effect of afforestation on climate in

perspectives. The net effect of afforestation on climate in

Increased evaporation in temperate and tropical environ-

ments (eg Werth and Avissar 2002) indicate that in

tropical environments with plenty of water, afforestation

cools the Earth through low-altitude cloud formation.

The net effect of afforestation on climate in

Limited water availability may reduce

the biophysical cooling effect of trees

Afforestation is another tool for sequester-
ing C. Some afforestation projects will probably occur in

water-limited regions (ie locations where potential evap-

otranspiration 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 par-
tioned into sensible heat (energy transferred by convec-
tion 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 sim-

ulations (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 environ-

ments 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

northem latitudes have albedos that approach 0.6 when

covered by snow in winter (Figure 2a); this exceeds sum-

mer albedo by a factor of 2–3 (Figure 2b). In contrast,

forests in the same region have winter albedos that are

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

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Area (millions km^2)</th>
<th>Total C (gigatons)</th>
<th>C per unit area (kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forests</td>
<td>17.5</td>
<td>553</td>
<td>31.6</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>10.4</td>
<td>292</td>
<td>28.1</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>13.7</td>
<td>395</td>
<td>28.8</td>
</tr>
<tr>
<td>Crops</td>
<td>13.5</td>
<td>15</td>
<td>1.1</td>
</tr>
<tr>
<td>Tropical grasslands</td>
<td>27.6</td>
<td>326</td>
<td>11.8</td>
</tr>
<tr>
<td>Temperate grasslands</td>
<td>15.0</td>
<td>182</td>
<td>12.3</td>
</tr>
</tbody>
</table>

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

**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).

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 (N₂O; Smith and Conen 2004). Given that N₂O has a 100-year greenhouse warming potential (GWP) about 300 times that of CO₂, and methane has a GWP of 20 to 25 times that of CO₂, practices that result in slightly more N₂O 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.

**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
(1) How can the biophysical climate 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 converted 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,

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 on if one is examining local, regional, or global climate. Furthermore, biophysical and biogeochemical changes have a very different temporal character; for example, carbon dioxide 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)?
regions that have high surface albedo and low water availability (Figure 4b, c) or high snow cover (Figure 4a) 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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References

Akbari H. 2002. Shade trees reduce building energy use and CO

carbon-cycle effects of large-scale deforestation. P Natl Acad Sci
USA 104: 6550–55.

Baldocchi DD, Xu L, and Kiang N. 2004. How plant functional-
type, weather, seasonal drought, and soil physical properties
alter water and energy fluxes of an oak–grass savanna and an

Bateman IJ and Lovett AA. 2000. Estimating and valuing the car-
bon sequestered in softwood and hardwood trees, timber prod-

Bets RA. 2000. Offset of the potential carbon sink from boreal

Bonan GB. 1997. Effects of land use on the climate of the United

Breuer L, Eckhardt K, and Frede HG. 2003. Plant parameter values

Canadell JG and Raupach MR. 2008. Managing forests for climate

Cannell MGR. 1999. Environmental impacts of forest monocl-
uations: water use, acidification, wildlife conservation, and car-

Dale VH, Joyce LA, McNulty S, et al. 2001. Climate change and

energy exchange in Arctic tundra and boreal forest: available

Fahey BD and Jackson RJ. 1997. Hydrological impacts of convert-
ing native forests and grasslands to pine plantations, South


mapping from MODIS: algorithms and early results. Remote

Galik CS and Jackson RB. 2009. Risks to forest carbon offset pro-

Gates LD and Liess S. 2001. Impacts of deforestation and afforesta-
tion in the Mediterranean region as simulated by the MPI

Grace J. 2004. Understanding and managing the global carbon

Grunzeig JM, Lin T, Rotenberg E, et al. 2003. Carbon sequestra-

forests and climate change. Science 316: 985–86.

Hamilton K, Sjardin M, Marcello T, et al. 2009. Fortifying the foun-
dation: state of the voluntary carbon markets 2008. Ecosystems
marketplace and new carbon finance report. Ecosystem
com/documents/cms_documents/2008_StateofVoluntaryCarbon

Harden JW, Trumbore SE, Stocks BI, et al. 2000. The role of fire in

Houghton RA. 2003. Revised estimates of the annual net flux of
carbon to the atmosphere from changes in land use and land

Oregon and Northern California forests and potential land-

Hunter IR, Hobley M, and Smale P. 1998. Afforestation of
degraded land – pyrrhic victory over economic, social, and eco-


Jackson RB, Randerson JT, Canadell JG, et al. 2008. Protecting cli-

Jobbágy EG and Jackson RB. 2004. Groundwater use and saliniza-

changes in land cover create biogeophysical climate feedbacks.

in agricultural soils after afforestation: a meta-analysis. Glob

and fluxes in a chronosequence of ponderosa pine. Glob Change

Liu Y and Harris DJ. 2008. Effects of shelterbelt trees on reducing
heat-energy consumption of office buildings in Scotland.
Appl Energ 85: 115–27.

Liu H and Randerson JT. 2008. Interannual variability of surface
energy exchange depends on stand age in a boreal forest
fire chronosequence. J Geophys Res-Biogeosci 113: G01006,

Madlener R, Robledo C, Muys B, et al. 2006. A sustainability frame-
work for enhancing the long-term success of LULUCF projects.

land surface change and carbon management, and the implic-

McCullum AMS and Goulden ML. 2008. Age-dependent variation
in the biophysical properties of boreal forests. Global

Merger E. 2008. Forestry carbon standards 2008: a comparison of
the leading standards in the voluntary carbon market and the
state of climate forestation projects. Carbon Positive. www.car-
bonpositive.net. Viewed 15 Sep 2009.

Millar CI, Stephenson NL, and Stephens SL. 2007. Climate change
and forests of the future: managing in the face of uncer-

Mitchell AK, Dunsworth BG, Arnott JT, et al. 2004. Growth limi-
tations of planted conifers regenerating under Montane
Forest Chron 80: 241–50.

down of small scale afforestation from satellite observations.
Global Planet Change 69: 195–204.

tion and income in developing countries from changes in use
and management of agricultural and forest lands. Philos T Roy

Pacala S and Socolow R. 2004. Stabilization wedges: solving the
climate-change and forests of the future: managing in the face of uncer-

Mitchell AK, Dunsworth BG, Arnott JT, et al. 2004. Growth limi-
tations of planted conifers regenerating under Montane
Forest Chron 80: 241–50.

down of small scale afforestation from satellite observations.
Global Planet Change 69: 195–204.

tion and income in developing countries from changes in use
and management of agricultural and forest lands. Philos T Roy

Pacala S and Socolow R. 2004. Stabilization wedges: solving the
climate problem for the next 50 years with current technolo-

cover change on the climate of southwest Western Australia. J

Randerson JT, Liu H, Flanner MG, et al. 2006. The impact of
boreal forest fire on climate warming. Science 314: 1130–32.

Schaaf CB, Gao F, Strahler AH, et al. 2002. First operational BRDF,
albedo–nadir reflectance products. Remote Sens Environ

Schlamadinger B and Bird DN. 2007. Carbon accounting beyond
Wilson KB and Baldocchi DD. 2000. Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. Agr Forest Meteorol 100: 1–18.

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