Foreword

Climate change, land use change and the world’s forests are inextricably linked. Man-made emissions of the greenhouse gas, carbon dioxide, into the earth’s atmosphere continue to escalate. Forests cover more than 4 billion hectares of the Earth’s land surface area and contain huge reservoirs of carbon in their vegetation and soils. Understanding the role of forests in carbon cycles and predicting whether they will be carbon sinks or sources in the future are important to ongoing international dialogue on the subject of climate change.

IUFRO is a non-profit, non-governmental international network of forest scientists whose objectives are to promote international cooperation in forestry and forest products research. Recognizing the duality of importance of forests in global carbon cycling and the uncertainty which exists around it, IUFRO in 2001 established a Task Force on the Role of Forests in Carbon Cycles, Sequestration and Storage. Its mandate is to report on the issues with a view towards improved decision making.

IUFRO is pleased to publish the Task Force e-NOTE series and provide a suite of timely, readily accessible, concise, and informative state of science summaries. This second issue brings focus to the very large and important roles that key natural and non-natural disturbances exert in determining the cycling of carbon within forest systems. It is authored by two international authorities in the fields of carbon modeling (Kurz) and forest fire behaviour (Conard).

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1.1 Executive summary

Forests play an important role in the annual exchange of carbon (C) between the terrestrial biosphere and the atmosphere. Currently, forests absorb some of the anthropogenic fossil C emissions, thus helping to buffer the impacts of human activities on the global environment and climate. Changes in the area of forest, or in the rate, type, and intensity of natural and human-induced disturbances can bring about net uptake (sink) or net release (source) of C in forested landscapes. The use and longevity of harvested wood products further affects the rate of C storage and release. Understanding and quantifying the impacts of disturbances are prerequisites to selecting forest management options aimed at enhancing C sinks and reducing C sources, while maintaining other ecological, social, and economic benefits of the forest.

1.2 IUFRO and the global importance of forest carbon cycles

IUFRO’s vision is to promote “science-based sustainable management of the world’s forest resources for economic, environmental, and social benefits.” IUFRO believes that public policy decisions supported by sound science produce decisions that have public support and yield societal benefit.

The United Nations, through the Framework Convention on Climate Change and the Kyoto Protocol, is developing international agreements to account for the impacts of forestry activities on the C balance. Forest managers are increasingly expected to understand and quantify the consequences of their land-management decisions on C sources and sinks. IUFRO scientists are providing new information and tools to help them meet this challenge.

1.3 Disturbance and carbon cycle interactions in forests

Forest ecosystems contain about 46% of the world’s terrestrial C. Conversion of forests to other land uses during the 1990s released 1.7 ± 0.8 gigatons (Gt) of C per year, equivalent to 27% of fossil-fuel emissions (6.3 Gt C yr⁻¹).

Global emissions from biomass burning (wildfire, biofuels, and other sources) are about 4 Gt C each year. About one third is from forests (including fuel-wood use). But unlike emissions from fossil sources, much of the C emitted from forests is released from the atmosphere as the forests re-grow following harvest or natural disturbance.

Carbon is continuously cycled between forests and the atmosphere. As trees grow, they remove C (as carbon dioxide, CO₂) from the atmosphere and store it in foliage, branches, and other woody biomass. As trees die and decompose, this C is gradually released back into the atmosphere as CO₂. Natural or human-induced disturbances contribute to this C cycle. Carbon in biomass and dead organic matter pools is oxidized during fires and released back into the atmosphere. Deforestation or other causes of failed forest regeneration interrupt the cycle of C uptake and release. Human activities can alter the rates or intensity of natural disturbances, such as through the suppression of fires or insect outbreaks, or through changes in forest structure that may increase the frequency or severity of these disturbances.

Disturbances have short and long-term effects on forest ecosystems: at the time of disturbance, C is released to the atmosphere and redistributed from live biomass to dead organic matter pools, such as standing dead trees. In the longer term, disturbances affect the release of C from forests as dead organic matter decomposes. Disturbances affect the rate of C uptake through their impacts on stand dynamics and succession. Some forms of disturbance, such as crown fire, are stand replacing and reset stand age; others merely reduce growth or kill some trees within the stand.

Some disturbances have large inter-annual variability: the rate of annual area burned can differ by one or two orders of magnitude between years, and the severity of fires can also vary greatly from year to year. Under certain climatic conditions, susceptible forests can succumb to insect attack over large areas; such infestations may last several years.

Where forests regenerate after disturbances, periods with above-average disturbance emissions are often followed by periods of above-average C uptake. Cohorts of forest created in years of high disturbance rates become cohorts of forests with high C uptake rates in the decades following disturbances.

Human activities have expanded the forest C cycle: in unmanaged forests, C is stored in live biomass and various dead organic matter pools, but harvest transfers ecosystem C to new pools outside the forest. Whereas one third to one half of the harvested C is quickly released to the atmosphere during various manufacturing steps, the remainder is stored for years to decades in manufactured wood products, buildings, or landfills.
1.4 Disturbance regimes and the net carbon balance of forests

Depending on the time since last disturbance, a forest stand can be a C source or a sink. For some years after a disturbance, the net C balance of a stand is negative (C stocks are declining) as C release from decomposition exceeds C uptake by new tree growth. Eventually the stand-level C balance will become positive (C stocks increasing) as trees remove more C from the atmosphere than is released from decay. As trees age and grow more slowly, and as dead organic matter accumulates and decomposition releases increase, the net C balance declines toward zero.

Forested landscapes typically comprise stands in many stages of growth and development and the landscape-level net C balance is the sum of the contributions of the stands contained in the landscape. A forest landscape that has been subjected to a “constant” disturbance regime for a long time can have a net C balance of zero, or close to it. The annual C release from disturbances and from the decay of debris left after disturbance is offset by the C uptake by the re-growing forest. In such cases, the forest age-class structure is stable, and the average age of the forest landscape does not change.

Alterations to the C balance of a forested landscape result from changes in the disturbance regimes that affect one or more of (1) the annual rate of disturbance, (2) the type of disturbance, or (3) the intensity of disturbance.

Changes in the rate of stand-replacing disturbance impact the proportion of the area in a landscape in different age classes (time since disturbance). Increasing the rate of stand-replacing disturbances increases the proportion of the forest area in younger age classes and lowers the average age in the landscape. Transition to a younger average age is usually associated with a decrease in landscape-level C stocks (a landscape-level source). Conversely, lowering the rate of stand-replacing disturbance increases the average age of the landscape and this transition results in a C sink.

Changes in the type of disturbance affect landscape-level C stocks in two ways. First, disturbances vary in the amount and type of C that they remove from or redistribute within ecosystems. For example, harvesting removes large stemwood, but leaves behind slash composed of branches, tree tops, and foliage, whereas fire consumes fine material and leaves behind charred stemwood. The disturbance type affects the amount and composition of the dead organic matter left after a disturbance. Second, disturbances differ in the type of stands they affect. Wildfires tend to burn stands of a wide range of ages whereas harvesting occurs in stands of commercial-size timber, and some insects are more likely to affect high-density or older stands. These differences in the dependence of disturbance on forest structure and age affect the landscape-level age-class distribution.

Changes in the intensity of disturbances can also bring about landscape-level C stock changes by affecting the C released per unit area. For example, if the severity of wildfires increases (but the area annually burned stays the same) landscape-level C stocks...
will decline because more severe fires can consume 3 to 4 times as much of the live biomass and dead organic matter as less severe fires.

When considering disturbance impacts on landscape-level C dynamics, interactions with disturbances and vegetation dynamics must also be evaluated. For example, a small increase in the area annually burned may result in a small decrease in C stocks, but a large increase in area burned may cause a change in vegetation type and bring about much larger changes in C stocks. When stand-replacing fires return more frequently, trees may not be able to reach the seed-producing age, forests could fail to regenerate, and the landscape could switch from forest to shrub or grass-land vegetation cover.

The impacts of disturbances on the net C balance of a forested landscape are complex. Alterations to the disturbance regime that result in changes in the rate, type, or intensity of disturbances usually cause periods of C sources or sinks. The resulting changes in forest structure may then affect the frequency, types or severity of future disturbances.

1.5 Disturbance agents

Globally, land-use change involving deforestation is the human-induced forest disturbance with the greatest impact on the global carbon balance. The FAO’s Forest Resource Assessment 2000 reports an estimated net loss in forest area of 9.4 Mha per year in the 1990s. Not only does deforestation cause annual emissions as forests are cleared and converted to other uses but, more importantly, the change in land use typically prevents the re-growth of forest, thus reducing the forest area that acts as a C sink. Forest fires caused by lightning or humans are the single biggest source of annual disturbance-related emissions, but they are balanced by the C uptake in forests that are re-growing after disturbance in prior years. Insect outbreaks, extreme weather events (windstorms, drought, flooding, and ice), forest harvesting, and the impacts of air pollutants are other important disturbance agents. Disturbance agents can also interact by pre-disposing forests to other disturbances.

Land-use and Land-cover Change

Land-use changes, such as the conversion of forests to cropland, break the natural cycle of disturbance and forest re-growth. Forests generally store more biomass C per hectare than other land-cover types, and the conversion of forests to other vegetation types usually is associated with large declines in biomass C. In temperate and boreal forest ecosystems, dead organic matter pools (woody debris, litter, and soil) store much more C than the biomass pools. Carbon losses from dead organic matter pools can continue for one or more decades after the biomass pools have been removed, and these losses occur at higher rates if the land is tilled. These changes can be reversed in areas where agricultural land is abandoned and either reforested or allowed to regenerate to forest.

Table 1: Estimates of forest area and annual rate of forest area net change (1990–2000). Source: FAO 2001a based on country reports.

<table>
<thead>
<tr>
<th>Region</th>
<th>Land Area Mha</th>
<th>Forest Area Mha</th>
<th>Net Change 1990-2000 Mha yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>2978</td>
<td>650</td>
<td>-5.3</td>
</tr>
<tr>
<td>Asia</td>
<td>3085</td>
<td>548</td>
<td>-0.4</td>
</tr>
<tr>
<td>Europe</td>
<td>2260</td>
<td>1039</td>
<td>0.9</td>
</tr>
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<td>North and Central America</td>
<td>2137</td>
<td>549</td>
<td>-0.6</td>
</tr>
<tr>
<td>Oceania</td>
<td>849</td>
<td>198</td>
<td>-0.4</td>
</tr>
<tr>
<td>South America</td>
<td>1755</td>
<td>886</td>
<td>-3.7</td>
</tr>
<tr>
<td>WORLD TOTAL</td>
<td>13064</td>
<td>3869</td>
<td>-9.4</td>
</tr>
</tbody>
</table>

Figure 2: Annual Burned Areas in Northern Hemisphere

Fire

Estimates of the forest area burned annually are highly uncertain, and burned areas vary greatly between years, both regionally and globally. The area burnt in the temperate and boreal zones of the Northern Hemisphere can exceed 15–20 Mha in severe fire years. Unfortunately, current statistics do not allow separation of forest from non-forest types in many countries, but at least two thirds of this burned area is likely to be forest. Data are

Figure 2: Burned area statistics for boreal and temperate regions of the Northern Hemisphere and Malaysia, as reported by the FAO of the UN (ECE 1999, FAO 2000). These totals include non-forest areas. Statistics in a number of countries, including the US and Russia, do not cover all lands, and may significantly under-report burned areas (see, for example, Conard et al. 2002).
less consistently available for tropical regions, South America, and Africa, but existing statistics suggest that several million hectares of forest and woodland burn annually in the southern Hemisphere as well.

Depending on the forest type, some burns are low-severity surface fires that release small quantities of C per hectare and have little impact on stand dynamics, whereas others are stand-replacing crown fires that can cause direct emissions of 15–25 t/ha of C from biomass, litter, and woody debris, and additional post-fire emissions as fire-killed biomass decomposes.

**Insects and disease**

Periodic insect and disease infestations have always been part of the natural cycles of growth, thinning, death, and rejuvenation of forest stands. Alterations to the disturbance regime can occur where stands are stressed by factors such as drought or high tree densities (e.g., resulting from fire suppression), or where non-native invasive insects or diseases are introduced. Examples include the chestnut blight of the early 1900s, which led to regional changes in forest structure in the eastern US; gypsy moth and Siberian silk moth, which have defoliated or killed trees over large areas in eastern North America, Siberia, and the Russian Far East; recent infestations in Alaska by the spruce beetle, which responds to climate warming with a shortened growth cycle; or the ongoing outbreak of Mountain pine beetle in western Canada.

**Weather and Climate**

Changes in the frequency, duration, or intensity of extreme weather events, as well as long-term changes in climate, can greatly affect disturbance patterns and C stocks. Extreme weather events, such as droughts, severe cold weather, or hurricanes can impact forest C over large regions. During extended drought periods, tree growth and C uptake can be greatly reduced but severe droughts also decrease C releases from decomposition. The impacts on the net C balance are still poorly understood. Changing climate is expected to significantly affect forest C storage through a complex set of interactions that include impacts on growth and decomposition, drought-induced mortality, changes in susceptibility to insect and disease, changes in fire regimes, and changes in snow cover and permafrost depth.

**Forest Harvesting**

Harvesting removes C from forests and provides timber and fiber to meet human needs. Where forests are managed in a sustainable manner, forest re-growth balances the C losses from harvesting, and landscape-level C stocks can be stable. Some of the world’s forests are still in transition from a natural to a managed disturbance regime, and these transitions are usually associated with C stock decreases. In other forests, C uptake from re-growth exceeds harvest losses and the forests act as a C sink. Assessing the impacts of harvesting on atmospheric C concentrations requires analyses that consider the fate of the harvested wood products, the rate of forest regrowth, and the C cost of alternative ways of providing the services offered by wood products and energy derived from forest biomass.

**Air Pollution**

One of the emerging human-induced disturbances is air pollution. Ground-level ozone (O$_3$) is the most pervasive, and one of the most damaging air pollutants to forests worldwide. With the expansion of cities, many formerly rural forests are being exposed to the photochemical products of urban emissions, and almost 50% (17 million km$^2$) of the world’s forests are predicted to be exposed to potentially damaging levels of O$_3$ between 2050–2100. Ozone can reduce tree growth, decrease soil C storage, and make trees more susceptible to insect attack. In the United States, ozone has reduced net primary productivity in forests and other crops by up to 13%. Other forms of air pollution, such as nitrogen deposition in Europe, are adding nutrients that, at low deposition rates, may be beneficial to forest growth, but at high rates are detrimental.

**1.6 Policy Implications**

The C balance of forested landscapes is affected by the rate, type, and intensity of the disturbances that operate in that landscape. Changes in one or more of these factors can bring about changes in C stocks, associated with either a net uptake or net release of C from the atmosphere. The extent of human control over disturbances differs greatly among the different forests of the world. Protecting forests against one disturbance type, such as fire, can bring about other changes, such as forest succession, aging of the forest, or accumulation of woody biomass, that can lead to increased risk of other disturbance types (e.g., insects) or to more intensive disturbances (e.g., crown fire). Global change will increase the stresses on many forests, which in turn will diminish the ability to suppress natural disturbances. Where land-use change reduces the area of forest, C stocks will decline and the potential for future C uptake will be reduced. Afforestation, the conversion of non-forest to forest, has the potential to contribute C sinks by increasing the area of forest that removes C from the atmosphere.

Forest C accounting models will empower forest managers and policy analysts to quantify the impacts...
of natural and human-induced disturbances on forest C stocks and stock changes over both short- and long-term time horizons. Research indicates that management regimes can be developed and implemented that enhance C sinks and reduce C sources, while maintaining other ecological, social, and economic benefits of the forest.

1.7 Glossary

decomposition: degradation of organic matter by biological and non-biological processes

Gt: Gigatonnes of carbon (1 Gt = 1,000,000,000 tonnes)

IPCC: Intergovernmental Panel on Climate Change; http://www.ipcc.ch/

M: mega = one million (2 Mha = two million hectares)

pool: a reservoir that can accumulate or release carbon

sequestration: removal and storage; carbon dioxide removed from the atmosphere by photosynthesis

sink: a process or mechanism that removes carbon or other greenhouse gases from the atmosphere

source: opposite of a sink

stand-replacing disturbance: an event that kills the majority of the trees in a stand and allows a new cohort of trees to establish

1.8 Further reading


Acknowledgments

We thank the Task Force Coordinators Drs. Percy and Jandl, as well as the external reviewers for their comments and contributions.

Further publications in this series

Issue 1: Forests and the Global Carbon Cycle: Sources and Sinks
Issue 2: Influences of Natural/Non-Natural Disturbances on Forest Carbon Sequestration and Storage
Issue 3: The Economics of Carbon Sequestration in Forests
Issue 4: Increasing CO₂, Forest Composition, Structure and Adaptive Ability
Issue 5: Operational Strategies to Enhance Adaptation and Mitigation
Issue 6: Product Strategies to Enhance Mitigation
Issue 7: Approaches to Forest Carbon Accounting
Issue 8: A Summary Report

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