The Role of Forests in Carbon Cycles, Sequestration, and Storage

Issue 4. Forest Management and Carbon Sequestration

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Foreword

The role of terrestrial ecosystems in the mitigation of climate change is an important component of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment. Foresters are aware that C sequestration in trees and soils represents only an intermediate solution, because sequestration potential is limited both in time and amount. However, it is nevertheless appealing to consider that the biosphere might immediately absorb CO_2 at low costs perhaps as a by-product of regular forest management. This issue of IUFRO e-notes on role of forests on carbon sequestration summarizes existing scientific information on potential C sequestration through active forest management.

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 introduce the fourth of a series of Task Force e-NOTES which together provide a suite of timely, readily accessible, concise, and informative state of science summaries.

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4.1 Executive Summary

The forest carbon (C) pool can actively be influenced by adapted forms of forest management that increase forest productivity and, thereby, increase the C input to the soil, and by decreasing soil disturbances, thereby avoiding high rates of decomposition of soil organic matter (SOM). This e-note gives an overview on the known or expected effect of silvicultural treatments and decisions that lead to additional C sequestration.

4.2 IUFRO and the global importance of forest carbon cycles

IUFRO's Vision is that of promoting "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 better decisions engendering greater public support and more societal benefit.
Forests play a major role in the natural global carbon cycle by capturing C from the atmosphere through photosynthesis, converting that photosynthate to forest biomass, and emitting C back into the atmosphere during respiration and decomposition. Globally, these exchanges of C between forests and the atmosphere are being influenced by human-caused and natural disturbances. This forest-atmosphere interaction leads to the view that controlling land use change practices involving forests might prevent some of the increase in atmospheric greenhouse gases, and additionally that some forest management activities might effectively reduce the rate of CO2 accumulation in the atmosphere.
The United Nations, through its Framework Convention on Climate Change and the Kyoto Protocol, are working at finding international agreement on incorporating forestry activities in the international response to this major environmental challenge. Ultimately it will be forest managers's role to put forestry-related components of international agreements on climate change into effect on the ground. These managers will require a sound scientific basis to be successful, so IUFRO is mobilizing to help them meet the challenge.

4.3 Forests as an effective option for C storage

Three factors are important consideration of forest management options for C storage. These are listed in no particular order of importance:

- **C pool size**: Forest ecosystems are the largest terrestrial C pool. They store more than 80% of all terrestrial aboveground C and more than 70% of all soil organic C.
- **C dynamics**: Net-growing forests cause sequestration of C. After harvesting the life-cycle of the wood products is decisive. Forest management and societal decisions both have significant influence on the carbon balance.
- **Chemical form of C**: Carbon is stabilized in terrestrial ecosystems to different degrees. The stable C form in biomass is wood, whereas many carbohydrates and proteins are quickly recycled. Soil C is comprised of a complex array of compounds. Stable forms are organic molecules that are chemically tied to the mineral soil. Stabilized soil C has a residence time of many decades. Carbon accumulated on the surface (forest floor material) has a much shorter residence time and is more vulnerable following disturbance.

The first and most significant option to enhance C sequestration potential of forests lies in the establishment of new forests (through afforestation or reforestation). A second option is to foster the slow formation of a stabilized soil C pool. The C sequestration potential in forest soils is large, although smaller than that of agricultural soils (Table 1).

Table 1:
The estimated carbon sequestration potential of the world's soils lies between 0.4 - 1.2 Giga tons C per year [1].

Land-use	Area	Annual C sequestration potential
	[ha]	[Giga tons C / yr]
Cropland soils	1.35×10^9	0.40 - 0.80
Rangeland, grass land	3.70×10^9	0.01.- 0.30
Irrigated soils	275×10^6	0.01 - 0.03
Degraded soils, forest soils	1.10×10^9	0.20 - 0.40

Importantly, the role of forest management in C sequestration is determined by factors that are under human control such as the following:

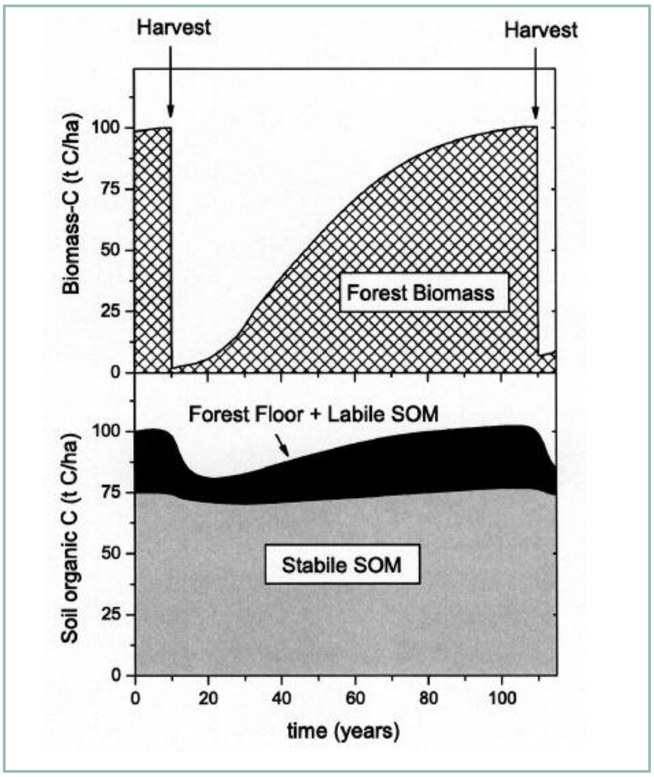
- silviculture practices such as selection of tree species, rotation period
- number of trees at planting (spacing)
- disturbances such as pest infestations, wind throw, wild fire
- air pollution
- water management, e.g. wetland restoration

Nevertheless, global warming will mobilize a certain, still unknown, quantity of soil C due to stimulation of the mineralization rate. At the landscape level, natural and non-natural disturbances are an integral part of ecosystem dynamics [2]. Natural disturbances per se cannot be controlled, but preventive measures can be taken to modify their extent and severity.

4.4 Silvicultural treatment options

- **Afforestation**: The storage of C in aboveground biomass is easily assessed by forest inventories. The rate of soil C sequestration is about 0.3 t C / ha / year but is highly variable [3]. This rate is slower than changes of the aboveground C and it takes decades until net gains occur in formerly arable soils. In temperate and boreal forests, the forest floor layer sequesters C quickly, but most of it exists in a labile form. The stabilization of the C is ensured when it is incorporated in the mineral soil. However, this process is much slower and continues over several decades. The effect of afforestation also depends on the previous land-use. Generally, rarely disturbed soils of rangelands and pastures have higher C densities than regularly ploughed croplands.
- **Tree species**: The effect on aboveground C depends on stand productivity, which is often already maximized in regions with a tradition of forest management, such as in the temperate zone. The effect of tree species on soil C depends on the chemical quality of litter, rooting depth, and rooting density. Some investigations on the influence of tree species on soil properties exist [4]. Due to the multiple interactions of tree species and site properties, comprehensive information is, unfortunately, unavailable. It is well known that tree species selection can quickly modify forest floor C stocks. Nitrogen fixing species can be especially effective at increasing soil C [5]. As to the permanence of C sequestration in the mineral soil, the evidence is scarce.
- **Thinning** provides a competitive advantage for the growth of some trees. The goal is to increase the economic value of the stand at the expense of the standing biomass. Thinning is, therefore, not primarily aimed at maximizing C sequestration. Opening the canopy at least temporarily stimulates the decomposition of the forest floor as soils become warmer and the rate of litterfall decreases. The consequence is a temporary decrease of the forest floor C pool. The effect of thinning on the mineral soil C pool is thought to be small. However, thinning increases the stand stability and greatly reduces the risk of storm damages.
- **Harvesting** removes biomass, disturbs the soil and changes the microclimate more than a thinning operation. In the years following harvesting and replanting, soil C losses may exceed C gains in the aboveground biomass. The long-term balance depends on the extent of soil disturbance and the stand productivity. Harvesting influences soil carbon in two contrasting ways: harvest residues left on the soil surface increase the C stock of the forest floor; disturbance of the soil structure leads to soil C loss because the soil respiration is stimulated. A schematic of C dynamics after harvest is given in Figure 1.

Figure 1:
Model for C in the aboveground biomass and the soil after harvesting. - Assumptions: Biomass-C stock typical for Central European Norway spruce forest; rotation period ? 100 years; 25% of Soil Organic Matter (SOM) are labile, total SOM loss from literature [6].



A literature review on harvesting suggests that the effect on soil C is rather small and depends on the harvest type. Whole-tree harvesting caused a small decrease in A-horizon C stocks, whereas conventional harvesting, leaving the harvest residues on the soil, resulted in a small increase. Although soil C changes were noted after harvesting, they diminished over time without a lasting effect. In general, harvesting method had its greatest effect on ecosystem C because of its effects on regeneration biomass rather than soil C change [5].

- **Rotation period**: Increasing the length of the rotation period ensures a longer time for undisturbed soil development. Even very old unmanaged forests can sequester large amounts of C [7,8]. A limit on the feasible rotation period is imposed by market mechanisms, when the timber industry responds to the inevitable temporary shortage of wood [9].
- **Nitrogen fertilization:** Many forest ecosystems are N-limited and numerous fertilization experiments have shown that N fertilization can have impressive consequences for stand productivity. Thereby, more C is stored in the aboveground biomass. The effect on soils is complex. The stimulated tree growth increases C inputs into soils through litterfall and root decomposition. Nutrient rich litter material can both stimulate the decomposition rate of labile organic material and support the formation of stabilized

organic matter [10] or increase the soil biological activity to the effect of soil C losses.
Nitrogen fertilization, however, has a serious drawback. Inefficient use of the applied N by the plants leads to the formation of nitrous oxide (N2O). In this case, the effect of C sequestration is offset by the production of an especially persistent green-house gas. Until the trade-off between C sequestration and N2O release in forest ecosystems is quantified, N fertilization should be treated with caution.

- **Liming**: In Central and Northern Europe many forest soils have been limed in the past in order to regulate soil and surface water chemistry, to prevent the ecosystem from irreversible acidification and to mobilize recalcitrant layers of forest floor material. The target of mobilizing the forest floor is in conflict with the objective of C sequestration and leads indeed to C losses from soils [11].

4.5 Offsetting disturbances from wild fire and storms

Disturbances consistently lead to the mobilization of C and represent a large C source. Preservation of ecosystems and adapted management for maximum stability is of primary importance, because it takes decades (biomass) to centuries (soil) to restore the pre-disturbance C levels of ecosystems.

- **Fire** has always played an integral role in the structure and function of forest ecosystems, especially seasonally dry forests. The policy of fire suppression can delay, but cannot over the long term prevent wildfires. Instead, it leads to an apparent net C accumulation that in fact represents a time bomb in terms of C release during catastrophic fires. In boreal and Mediterranean forests, wildfires impose natural limits on the rotation period. Wildfires in tropical forests are not common, but can have serious impacts on the global C cycle. Burning of forested peatlands of Indonesia in 2002 has released an amount equivalent to 13 to 40% of the annual C emissions from fossil fuels. No management options exist to affect the size of the C pool in tropical peatlands, but the protection of these swamp-forest-ecosystems is required [12]. In some cases, fire can have unexpected long-term benefits on soil C by stimulating the invasion of N-fixing species, which have the capacity to greatly enrich soils in both C and N [5].
- **Storm damage** may result in strongly increased amounts of coarse woody debris on the forest floor. The C dynamics after the disturbance are strongly affected by management practices, which will include clear-cuts and salvaging of damaged timber. Uprooting of windthrown trees destroys soil structure, which in turn makes protected C accessible for decomposers.

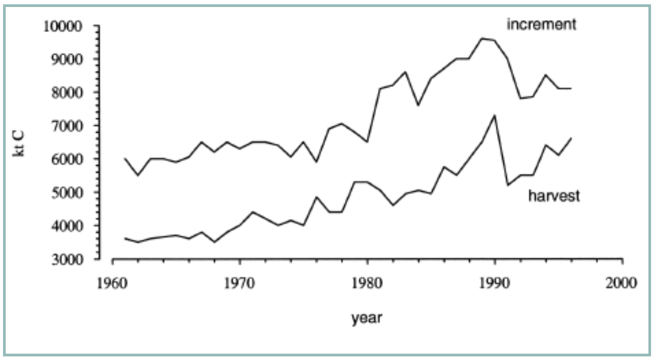
4.6 Carbon sequestration potential of peatlands

In peat soils, excess water suppresses the rate of decomposition of SOM and leads to C accumulation. Drainage stimulates the productivity of forested peatlands and enables the establishment of a forest in otherwise treeless peatlands. The soil aeration stimulates decomposition and reduces the soil C pool. Upon global warming and drainage, peatlands will become drier and the increased microbial activity turns the boreal region into a C source. In the Nordic countries, approximately 15 million ha of peatland have been drained for forestry. Direct measurements of soil C balances in peatlands are rare. Mostly, forest drainage decreases CH4 emissions, increases N2O and CO2 emissions from peat, and increases C sequestration to the ecosystem as a consequence of the increased productivity.

4.7 Accounting of forest management for C sequestration in C trading

The economics of C trading is the subject of Issue 3 in this series of e-notes [13]. Based on Article 3.4 of the Kyoto Protocol, and according to the rules of the IPCC (Good Practice Guidance for Land Use and Land-Use Change and Forestry), the direct impact of specific silvicultural strategies on C sequestration needs to be transparent. Such strategies are accountable when the management action has taken place after 1990, the base-line of the Kyoto Protocol. However, a part of the current C sink strength of forests of the Northern hemisphere is driven by elevated rates of nitrogen deposition and the regeneration of forests on abandoned agricultural land. The on-set of the related C

Figure 2:
The persistent difference between increment and harvest leads to C sequestration – Example: Austrian forests. Source: Austrian National Forest Inventory.



sequestration is ill defined and not accountable for national greenhouse gas balances. Some activities are accountable, although their intended action is different from C sequestration:

- in many European countries the annual biological growth exceeds the harvest rate; reasons are manifold, the traditional land-use of forest owners plays a role; cf figure 2
- conversion of marginal land to forests
- declaration of forests to protected zones, according to conservation treaties (Natura 2000)

4.8 Implications

In regions where exploitative historic land-use practices have reduced the soil C pool, one option for enhancement of C sequestration and storage is to restore the previous forest type. The restoration can be either due to active management or due to other actions such as aggradation caused by increased N deposition and climate change. Carbon credits under Article 3.4 of the Kyoto protocol are restricted to effects of active management after the year 1990, whereas indirectly-induced human effects on C sequestration are not accountable.

- The increase of the stable soil C pool is a much slower process than the accumulation of C in the litter layer and depends on physico-chemical soil properties
- Adapted forms of forest management for C sequestration aim at forests with a high productivity and a low vulnerability to disturbance
- Adapted forms of forest management for C sequestration does not necessarily ensure the highest revenue from timber production

Refined methods of adapted forest management for the maintenance of a high C pool in the soil and the biomass are still to be evaluated with respect to their suitability on different site types. The challenge for forestry is to find a viable compromise between potentially conflicting demands of the society such as supplying wood and non-wood products simultaneously with sequestering large quantities of C in forest ecosystems.

4.9 Glossary

- **Soil organic matter:** Organic constituents in the soil, including undecayed plant and animal tissues, their partial decomposition products, and the soil biomass.
- **Nitrogen fixer**: Nitrogen fixers are plants whose roots are colonized by certain bacteria and cyanobacteria that extract nitrogen from the air and convert or "fix" it into a form required for their growth.
- **Labile soil C pool**: The amount of C that is readily mineralized by soil biological processes.
- **Stable soil C pool**: The amount of soil C that is resistant to rapid degradation.
- **Liming**: soil amelioration by the application of solid carbonate
- **Teragram**: Teragrams of C; (1 Tg = 1012 g)

4.10 Further Reading

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