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Recovery of Soil Organic Carbon in Forest Restoration

Form international

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Definitions

Soil Organic Carbon (SOC): Carbon content in the soil, excluding carbon in living (roots) and dead (litter, dead roots) biomass, expressed in Mg C/ha.

1. Introduction

Forests are productive ecosystems that offer a variety of products and services; timber, fibers, non-timber forest products, water purification and carbon sequestration. In recent years, many forests have been converted from productive ecosystems to areas with low productivity.

The PBL-Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving PBL) commissioned the World Resources Institute (WRI) to map and quantify global forest degradation and the consequences of this process for carbon sequestration, carbon stock and wood stock. The total amount of land (in ha) in several states of degradation was calculated per biome, or 'major habitat type', as defined by the World Wide Fund for Nature (Olsen et al., 2001). This ecological classification system identifies 14 terrestrial biomes.

One of the findings of the WRI study was that the vast areas of degraded forest represent a huge amount of CO_2 emitted as a result of timber extraction and other forms of human use. Restoring the degraded forests will absorb similarly huge amounts of CO_2 and increase the production capacity of wood for timber, pulp and firewood. In order to quantify this, Form international calculated in a previous study the potential stock of the degraded forest ecosystems (Form international, 2013). That report presented an estimation of the current and potential carbon sequestration and storage in above- and below-ground biomass of forest ecosystems. This was done for six biomes, representing the biomes with (potential) forest cover:

- Boreal;
- Mediterranean[1];
- Temperate broadleaf;
- Temperate coniferous;
- Tropical dry broadleaf;
- Tropical moist broadleaf.

Based on that study, PBL has requested Form international to calculate the recovery potential of Soil Organic Carbon (SOC) in degraded forests. This report presents the potential SOC accumulation rates in deforested / degraded forests in the six biomes.

As this study (and report) is a follow-up of the study in 2013, more detailed background information can be found in that report. The following chapter describes the methodology and the third chapter describes the results: accumulation rates for the six biomes. A summary and some concluding remarks are given in the last chapter.

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[1] In this report the term Mediterranean is used as a shortage for 'Mediterranean forests, woodlands and scrubs'.

2. Methodology

To make a connection possible between the outcomes of the current study and the concepts developed by WRI and used by PBL, the same typology needs to be used for the scale of reforestation. Two terms are used: 'wide-scale reforestation' and 'mosaic reforestation'. The first type is related to regions with a low population pressure and much space for reforestation. The second type suits for densely populated regions where there is also a need for land for agricultural and other economic purposes. Form has developed three types of reforestation that suits these two typologies:

1. (Assisted) Natural Regeneration (ANR): the growing of (semi) natural forest by means of natural processes, potentially assisted by human interference;
2. Forest plantation (P): by means of active land preparation and intensive tree planting and forest management, a new forest is created consisting of one or several tree species;
3. Smallholder woodlots (SW): small scale land use system consisting partly or entirely of trees of one or several species.

Generally, the first management type suits 'widescale reforestation', and the last type suits 'mosaic reforestation. The second type is somewhere in between. It should be noted that at landscape level combinations of these management types are possible. This depends on biophysical, ecological and socio-economic conditions in the specific area. The choice for a specific management type should therefore be made with care.

The purpose of the study is to calculate the SOC accumulation rates per management type, based on available literature and study reports. Due to time limitations, Form's estimations were based on rough and general figures:

- Only the six forest biomes were included;
- A limited number of sources has been used to calculate the values;
- Peat forests are excluded, as they form a separate category;
- SOC values are based on technical limitations (such as soil depth) used in literature;
- Only SOC of the mineral soil is calculated, litter is excluded.

Although it is understood that SOC values also depend on soil characteristics, soil information is hard to find and the variety of potential soil types is high. Averages per eco-region, found in literature, are therefore used.

3. Results

3.1. General findings

The amount of SOC inputs depend on the release of organic compounds by plant roots in their surrounding environment (rhizodeposition), litter fall, additions (fertilization) and biomass left after harvest. Biotic and abiotic decomposition largely controls output levels of SOC. The SOC of mineral forest soils (to 1 m depth) typically varies between 20 to over 300 Mg C/ha depending on the forest type and climate. SOC furthermore tends to concentrate in the upper soil layers: roughly half of the SOC is found in the upper 30 cm. Human activities, especially soil disturbance (e.g. tillage) can strongly influence the SOC pool in mineral soils: 20-40% of the carbon stocks can be emitted from the soil conversion from native forest land to cropland (Eggleston et al. 2006, comparable figures are found by Guo and Gifford 2002).

Soil studies show that SOC is a complex phenomenon depending on a number of factors, especially in the case of accumulation (or release) of carbon in the soil in the case of land use change (Fonseca et al. 2011a, Singh 2000). Some authors even conclude that very little is known yet on SOC and the factors influencing these values (Vesterdal and Leifeld 2010, Johnson and Curtis 2001). Nevertheless, some conclusions can be drawn from literature. With regards to planted forests and natural forest regeneration, there seems to be a correlation between soil carbon and forest age, but this correlation is poor, likely because of the slow incorporation of carbon into the soil (Fonseca et al. 2011a, Feldpausch et al. 2004, Kotto-Same et al. 2002). According to other studies, this is also strongly influenced by factors such as previous land use, the number of years under the previous land use, the stage of the succession, distance from seed sources and intervention or management (Fonseca et al. 2011a, Post and Kwon 2000). A comparative study from Post and Kwon (2000) furthermore shows that reforestation and afforestation projects in some cases lead to SOC increase, while in other cases it leads to a decrease in SOC. This might sometimes be the result of the carbon distribution between forest floor and mineral soils, in which the distribution rather than total carbon stock tends to differ among tree species in temperate zones, suggesting that some species may be better engineers for sequestration of carbon in the mineral soil (Vesterdal et al. 2013). It is concluded that all the factors mentioned above (individually or in a combination) determine the amount of carbon found in the soil (Fonseca et al. 2011a) and contribute to the complexity of SOC and land use change.

3.2. SOC accumulation rates

Post and Kwon (2000) compared a range of studies investigating the rates of soil carbon accumulating during forest establishment after agricultural use. They calculated an average rate of soil C sequestration of 0.3 Mg C/ha/yr following afforestation across different climatic zones. They found that there is a tendency for rates of SOC accumulation to increase from temperate regions to subtropical regions. They conclude from this trend that major factors determining the rate of accumulation are amounts of organic matter inputs which increase with temperature and moisture. They furthermore found that maximum rates of C accumulation during the early growth stage of perennial vegetation are usually much less than 1 Mg C/ha/yr (see also Lal 2004). Average rates of accumulation are similar for forest or grassland regeneration: 0.338 Mg C/ha/yr and 0.332 Mg C/ha/yr respectively. However, they also found that growth of woody plants in a subtropical thorn steppe system, where the vegetation was shifted from a grazed grassland to an ungrazed woodland, resulted in a decrease in SOC, despite the fact that woody plants produced a greater amount of more recalcitrant material than perennial grasses. Apparently woody plants may be less effective than perennial grasses in some environments at storing carbon in soil. Comparable differences (increasing vs. decreasing SOC values) between afforestation projects are found by Lal (2004). Although it is likely that forest plantations cause accumulation of SOC, there is too little evidence and references to calculate the additionality of forest plantations in carbon accumulation.

Several studies show that the SOC growth does not necessarily follow a linear growth, and might even start with a decrease, and only increasing after a couple of years (Chen and Shreshta 2012, Vesterdal and Leifeld 2010). Nevertheless, because of the variation in growth patterns, and the complexity of SOC growth (which is still hardly understood), it is decided to follow the IPCC approach, assuming that the sequestration or release during the transition to a new equilibrium SOC occurs in a linear fashion (Eggleston et al. 2006). As a result, fixed growth values are calculated that are assumed to apply for the whole transition period.

Next, it is concluded that SOC accumulation rates in small-scale woodlots systems can either be negative, neutral or positive, depending on the system chosen (combination of trees, crops and grassland), soil treatments applied (tillage, fertilizing) and the species used. It is therefore unreliable to calculate an average SOC accumulation rate for this management type.

Due to the ambiguity found in literature Form decided not to differentiate SOC climax values or recovery rates for the different management types (ANR, P, SW). Figures presented in this chapter therefore present those found for natural regeneration and/or forest plantations, as well as small woodlots.

3.2.1. Boreal biome

Luca and Boisvenue (2012) studied the succession of boreal forests on sites that were deforested as a result of harvesting and as a result of forest fires. They found that carbon content increases in primary succession linearly and stabilizes in later stages of succession, after which SOC values even decrease as coniferous species (producing less litter) are replacing the broadleaf species. This was confirmed by Chen and Shrestha (2012), although such a change in forest structure was observed at a forest age of more than 200 years. Their figures were used to calculate the SOC growth and it seemed that the SOC increases with 11 Mg C/ha in the first 27 years, after which the growth is approximately zero, which counts for a SOC growth of approximately 0.3 Mg C/ha/yr (soil depth 0.15 m).

3.2.2. Mediterranean biome

Munoz et al. (2007) indicate that restoration activities can have a large impact on restoring SOC values in Mediterranean forests. However, no SOC growth values were found for Mediterranean forests. The above-ground biomass growth seems to correlate with SOC, this relationship is however not easily calculated (as concluded when comparing e.g. Vesterdal and Leifeld 2010, Johnson and Curtis 2001, Lal 2004 and Post and Kwon 2000). Nevertheless, it is decided to use an interpolation function to calculate the SOC accumulation rate for the Mediterranean biome. The calculations are explained in Paragraph 3.3.

3.2.3. Temperate broadleaf and coniferous biome

According to Lorenz and Lal (2010), the long-term SOC accumulation rates in temperate forests range from 0.07 – 0.12 Mg C/ha/yr (soil depth unknown), but reaches an average SOC sequestration rate of 0.8 – 1.0 Mg C/ha/yr in an experiment in Minnesota (Vesterdal and Leifeld 2010). Afforestation, however, may not always enhance the SOC pool. In New Zealand afforestation of pastures with *Pinus radiata* resulted in a 15 % decrease of SOC concentration. Rates of soil C sequestration from studies of Vesterdal and Leifeld (2010) ranged from being negligible to 1.3 Mg C/ha/yr (soil depth 0.25 m). The SOC sequestration in the mineral soil varies tremendously among the studies, in some cases mineral soils even lost C after afforestation. Again, the distribution of C between the forest floor and mineral soil seems to be important. Foote and Grogan (2010, soil depth 0.20 m) found an average of 0.1 Mg C/ha/yr. No distinction in these studies is made between broadleaf and coniferous forests.

3.2.4. Tropical dry broadleaf biome

Post and Kwon (2000) cited two studies on secondary and plantation forests with SOC sequestration rates of respectively 0.8 and 0.4 Mg C/ha/yr (soil depth 0.25 m). Silver et al. (2000) found an accumulation rate of 1.02 Mg C/ha/yr (soil depth 0.25 m), which was a slightly higher rate than found in tropical moist forests in their study.

3.2.5. Tropical moist broadleaf biome

In a study from Fonseca et al. (2011a) in the succession of secondary forest, a SOC sequestration rate of 1.09 Mg C/ha/yr is found and 1.3 – 1.7 Mg C/ha/yr for plantation forests (Fonseca et al. 2011b; soil depths 0.30 m). According to these authors, other studies reported average increase rates of 0.5 – 2.0 Mg C/ha/yr for primary and secondary tropical forests. Silver et al. (2000) found an accumulation rate of 0.51 Mg C/ha/yr (soil depth 0.25 m). Reforestation of a deforested area with teak (*Tectona grandis*) in Ghana showed an average SOC sequestration rate in the first 8 years of 1.07 Mg C/ha/year (Form international 2009, soil depth 0.20 m).

3.3. Summary SOC accumulation rates

The SOC accumulation rates per biome found in literature are summarized in Table 1 (third column). These values are found at different soil depths (second column). To calculate the accumulation rate for a soil depth of 1.0 m, the following assumptions are made:

- Based on Eggleston et al. (2006) it is assumed that 50% of the SOC concentrates in the upper 0.3 m of the soil;
- For practical reasons it is assumed that the SOC accumulates evenly in the upper 0.3 m of the soil;
- Esteban and Jackson calculated the SOC values for soil depths up to 3.0 m, with intervals of 1.0 m. For practical reasons it is assumed that 100% of SOC is found in this 3.0 m. In that case the percentage of SOC in the first 1.0 m could be calculated for most of the biomes: 54-76% of total SOC is found in 0.0-1.0 m. The rates per biome are presented in Table 1 (fourth column).

Based on these assumptions the SOC accumulation rates found in literature are extrapolated to accumulation rates for a soil depth of 1.0 m. The results are presented in the last column of Table 1.

Table 1 SOC accumulation rates

Biome	Literature references of SOC accumulation rates at specific soil depths		Calculated SOC accumulation rates at 1.0 m soil depth	
	Depth (m)	Rate (Mg C/ha/yr)	% of SOC in first meter	Rate (Mg C/ha/yr)
Boreal	0.15	0.3	74%	0.89
Mediterranean	-[*1]	-[*1]	-[*1]	0.20-0.55[*2]
Temperate broadleaf	Unknown 0.25 0.20	0.07-0.12 0.8-1.3 0.1	76%	0.23-2.38
Temperate coniferous	Unknown 0.25 0.20	0.07-0.12 0.8-1.3 0.1	71%	0.21-2.22
Tropical dry broadleaf	0.25 0.25	0.4-0.8 1.02	54%	0.52-1.33
Tropical moist broadleaf	0.30 0.30 0.25 0.20	1.09-1.7 0.5-2.0 0.51 1.07	67%	0.67-2.67

[*1] No values found

[*2] Range calculated with interpolation function

As no references of accumulation rates for the Mediterranean biome are found in literature, several interpolation calculations are applied to calculate rates for this biome. Per biome the percentage of SOC growth as a function of aboveground biomass is calculated (see Table 2, last column). Next, the average range for all biomes is calculated (Calculation 1 in the table) and used for the Mediterranean biome (results in a range of 28-78%). By multiplying this range with the aboveground biomass growth of the Mediterranean biome (0.71 tC/ha/yr), the SOC accumulation rates for this biome are calculated (Calculation 2 in the table). This results in a range of 0.20-0.55 tC/ha/yr.

Table 2 Figures used to calculate the SOC growth for the Mediterranean biome.

	Aboveground biomass growth (study 2013)		SOC accumulation rates found in literature	SOC growth / aboveground biomass growth
	tDW/ha/yr	tC/ha/yr*1	tC/ha/yr	%
Boreal	2.30	1.08	0.89	83%
Mediterranean	1.50	0.71	Calculation 2	Calculation 1
Temperate broadleaf	4.00	1.88	0.23-2.38	12-127%
Temperate coniferous	10.20	4.79	0.21-2.22	4-46%
Tropical dry broadleaf	4.40	2.07	0.52-1.33	25-64%
Tropical moist broadleaf	7.90	3.71	0.67-2.67	18-72%

*1 Calculated using a carbon fraction of 0.47.

4. Conclusions & Recommendations

A summary of the SOC accumulation rates is presented in Table 3. It is concluded that there is still little known of SOC values, especially in relation to changes in SOC values due to human disturbances and restoration activities. Next, literature on SOC values use different soil depths, which makes comparison relatively difficult. Figures are therefore to be used with care.

As just one or a few SOC accumulation rates per biome were found, it is not reliable to calculate an average value per biome. However, for modelling purposes the mid values could be used (last column in Table 3), which represent a potential little over- or underestimation, although these values do seem relatively logic.

Table 3 SOC accumulation rates (Mg C/ha at soil depth 1.0 m)

Biome	SOC accumulation rate (Mg C/ha/yr)	Mid value of SOC accumulation rate (Mg C/ha/yr)
Boreal	0.89	0.89
Mediterranean	0.20-0.55*	0.38
Temperate broadleaf	0.23-2.38	1.31
Temperate coniferous	0.21-2.22	1.22
Tropical dry broadleaf	0.52-1.33	0.93
Tropical moist broadleaf	0.67-2.67	1.67

* As explained in the previous paragraph, these are calculated, whereas the values of the other biomes are based on values found in literature.

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