Soil management options to sequester carbon and mitigate the greenhouse effect

- by Niels H. Batjes

The imbalance between global sources and sinks in the global budget of atmospheric CO_2 is one of the most important problems in the study of global change. At present there is a 'missing sink' of about 1–2 Pg C yr^{-1}. It is likely that a major part of this sink for carbon is to be found in the functioning of terrestrial ecosystems. The Kyoto Protocol currently restricts the allowable terrestrial sequestration of carbon to strictly defined cases of "afforestation, reforestation and deforestation". Appropriate conservation and management of the terrestrial natural resources and especially of soils, however, can substantially reduce the buildup of atmospheric greenhouse gases over the next 25 to 50 years while new, "clean" technologies for energy production are being developed and overall anthropogenic emissions are being curtailed.

Three main anthropogenic sources of greenhouse gases are fossil fuel combustion and transport; the chemical industry, including cement production; and land use changes and system conversion. Agro(eco)systems can be managed to reduce carbon emissions and increase carbon sinks in vegetation and soil. It appears that this increased carbon uptake/storage can offset fossil fuel emissions temporarily (on a time scale from decades to a century), and partially, after which new equilibrium levels will be reached, provided the agro(eco)systems remain undisturbed.

About two thirds of the carbon in the terrestrial biosphere is stored below ground, in the soil. There is a great variation in the amount and vertical distribution of organic carbon in boreal, temperate and tropical soils (Table 1). Humification, aggregation, and translocation to the subsoil are the main processes of C sequestration in soils. Erosion, decomposition and leaching are important processes causing C concentrations to decrease in the soil.

Table 1. Total stocks and densities of soil organic carbon (SOC) by major Agro-Ecological Zone.

Agro-Ecological Zone	Spatially weighted SOC pools (Pg C to 1.0 m depth)	Mean SOC density (kg C m^{-2} to 1.0 m depth)
Tropics, warm humid	176.8 - 182.5	10.0 - 10.4
Tropics, warm seasonally dry	121.6 - 127.8	7.0 - 7.3
Tropics, cool	55.9 - 59.2	8.4 - 8.9
Arid	91.4 - 100.	3.7 - 4.1
Subtropics, with summer rains	64.4 - 68.2	8.6 - 9.1
Subtropics, with winter rains	37.1 - 40.8	7.2 - 8.0
Temperate, oceanic	39.7 - 43.7	11.7 - 12.9
Temperate, continental	233.3 - 243.0	10.8 - 11.3
Boreal	477.6 - 495.9	23.1 - 24.0
Polar & Alpine (excl. land ice)	166.9 - 188.5	20.6 - 23.2

Within a given agro-ecological region, the organic carbon content of most agricultural soils is lower than that of natural peatlands or forest soils. Soils can store carbon in "pools", or reservoirs, with different turnover times. With respect to carbon sequestration it is best to immobilize the atmospheric carbon dioxide in soil C pools having long turnover times. Detection of small increments in soil carbon storage over the relatively short time-frames of relevance for monitoring and verification of article 3.4 of the Kyoto Protocol will require sensitive techniques. Defining a baseline level for soil organic carbon stocks may be difficult in this respect.

The potential for carbon sequestration in a given soil, and agro-ecological zone, will be proportional to the original reserves present under undisturbed conditions. Options for carbon sequestration must be chosen on the basis of a knowledge of the nature and likely magnitude of C pools, whether organic or inorganic, in the soils of a given biome or major agro-ecological region and the responses of these soils to different land uses and management systems.

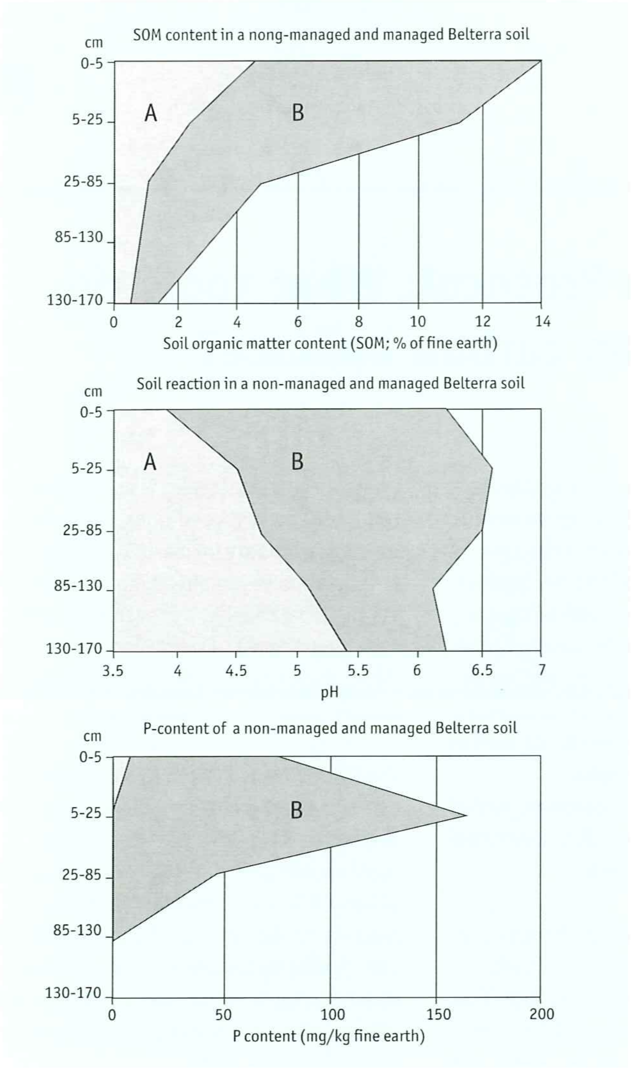
The greatest potential to increase current soil C stocks is probably through improved management of the agricultural land, particularly degraded cropland and grassland, as well as conservation/restoration of marginal lands and wetlands/peatlands. Recommended management practices to build up carbon stocks in the soil are basically those that increase the input of organic matter to the soil, and/or decrease the rates at which soil organic matter decomposes. These practices will generally include a combination of the following: tillage methods and residue management; soil fertility and nutrient management; erosion control; water management; and crop selection and rotation. Sustainable management of forests, notably those in the temperate and tropical regions, can significantly increase the biomass-C in standing forests and subsequently in the soil.

Improved information on the nature and dynamics of organo-mineral associations will lead to an enhanced understanding of soil structural dynamics, carbon cycling and sequestration in the soil, thus providing a better basis for developing improved approaches to soil management. The combined application of organic materials, mineral fertilizers and rock phosphates seems particularly important in this respect. This is demonstrated by the properties of soils that were historically

Table 2. Exploratory scenarios for increases in organic carbon sequestration in the soil over the next 25 years (first value is in Pg C yr^{-1}, second value in italics is given as Pg C).

Scenario	Inferred SOC increase		
	Low	Medium	High
A) Restoration of all degraded lands, irrespective of land use/cover	0.65	1.29	1.9
	16.1	*32.2*	*48.3*
B) Restoration of degraded lands, excl. those in Arid, Boreal, and Polar regions, irrespective of land cover/use	0.47	0.93	1.4
	11.8	*23.4*	*35.1*
C) Restoration of degraded, Agricultural Lands only	0.21	0.41	0.61
	5.1	*10.2*	*15.3*
D) Restoration of degraded Agricultural Lands, Extensive Grasslands, and Regrowth Forest	0.26	0.52	0.78
	6.5	*13.0*	*19.4*
E) Improved management of 'non-degraded' Agricultural Lands	0.09	0.17	0.26
	2.1	*4.3*	*6.4*
F) Improved management of 'non-degraded' Agricultural Lands, Extensive Grasslands, and Regrowth Forest	0.14	0.28	0.42
	3.5	*6.9*	*10.4*

enriched in stable soil organic matter, such as the "plaggen soils" of northwestern Europe and the "Terra-Preto do Indio" soils of the Amazon region (Figure 1).


SOM content in a nong-managed and managed Belterra soil

Soil reaction in a non-managed and managed Belterra soil

P-content of a non-managed and managed Belterra soil

There are about 1964 x 10^6 ha of degraded soils in the world. Exploratory scenarios have shown that 14 ±7 Pg C may be sequestered over the next 25 years – with even higher potentials over a 50 year period – if the "degraded" and "stable" (i.e., non-degraded) Agricultural Lands are restored and/or submitted to appropriate management (Table 2; see Medium SOC increase for scenario C + E). When the areas of Extensive Grasslands and Forest Regrowth are also considered, this would be 20 ± 10 Pg C (scenario D + F). The scenarios show that, on average, from 0.58 to 0.80 Pg C yr^{-1} can be sequestered in the soils of the regions under consideration; this would correspond with about 9–12% of the anthropogenic CO_2-C produced annually. These estimates are within the range of historic C losses from cultivated soils over the last 100 years, under the assumption that about 50 % of these losses can be re-sequestered via improved management of mainly croplands and rehabilitation of degraded lands (15–45 Pg C).

The above scenarios assume that "best" management and/or manipulation of a large portion of the globe's soils is technically possible. Whether it will always be economically and environmentally feasible to increase the soil carbon content above the natural, "historic levels", however, still needs to be assessed. In addition, possible implications of the "CO_2 fertilization effect" and the "improved water use efficiency" (WUE) – associated with elevated atmospheric CO_2 levels – as well as those of increased air temperature on biomass growth and quality, and the subsequent build-up and decomposition of organic matter in the soil remain open to scientific debate.

Fig. 1. Positive effects of prolonged application of 'farmyard' manure, rich in Ca-phosphates, on the organic matter content, pH and P content of a non-managed forest (A) versus a managed (B) Belterra soil from the Amazon region of Brazil. The properties of the managed soil are the lasting result of early Amerindian occupation (credits: Otto Spaargaren and Wim Sombroek).

Three main anthropogenic sources of greenhouse gases are fossil fuel combustion, chemical industry and land use changes and system conversion - like burning clear a field for planting. *Photo: EPA/ANP*

Mitigation of atmospheric CO_2 concentrations by increased carbon sequestration in the soil, appears particularly useful when addressed in combination with other global challenges, such as combatting land degradation, improving soil quality and productivity, and preserving biodiversity – while simultaneously reducing greenhouse gas emissions associated with fossil fuel combustion and industry – thus creating "win-win" scenarios. Besides being technically sound, these "best" management practices should be socially and politically acceptable, as well as economically and environmentally viable.

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Biospheric sinks in the Kyoto Protocol: What tools do we need to monitor a European carbon balance?

• by Han Dolman, Pavel Kabat and Ronald Hutjes

Han Dolman

The rate at which carbon is accumulating in parts of the terrestrial biosphere is uncertain and is the subject of intense scientific and political debate. Studies using global inversion models indicate that a significant fraction of the net uptake of the terrestrial biosphere occurs in northern mid-latitudes. Direct measurement of the ecosystem carbon balance of forest in Europe indicates that most forests are currently acting as sinks, sequestering CO_2. There is considerable scientific controversy about what is causing this great uptake by the mid-latitude forests, as well as about the precise reasons why some of the forests appear to lose carbon. Furthermore, we do not know whether the uptake is a transient phenomenon, not of and when the terrestrial sink will be saturated. A workshop on this subject was held last year (see box). This article presents some of the topics and results.

These uncertainties and scientific controversies are in the spotlight due to the current efforts by the 174 nations who negotiated the Kyoto Protocol to develop a set of consistent regulations to monitor the reductions in CO_2 emissions due to afforestation and land use change, leaving additional management practices out of account. Even under (near) steady-state conditions, the determination of the carbon balance at continental and global scales is no trivial matter. Under present conditions, where CO_2 concentrations are increasing and terrestrial vegetation seems already to be responding to global change, it is even more difficult. nevertheless, a substantial amount of information has recently been gathered for specific temporal and spatial scales.

The Kyoto Protocol seeks to reduce the overall emission of greenhouse gases by an average of 7% below 1990 levels in the commitment period of 2008–2012. Articles 3.3 and 3.4 include the possibility to account for the removal of atmospheric carbon dioxide by biospheric sinks, limited to direct human-induced land-use change and afforestation, reforestation and deforestation (ARD) since 1990.