Carbon Flows and Sustainable Agriculture

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The way we treat ecosystems influences the global flows of carbon. This is already well discussed when it comes to phosphorus and nitrogen. But also the flows of carbon, the major constituent of life on earth, are critically affected by land use and our way to conduct agriculture and forestry in particular. Besides the emissions caused by burning fossil fuels, land use and management has come up as a major concern in connection with climate change since global warming is caused by large-scale changes in the global carbon flows.

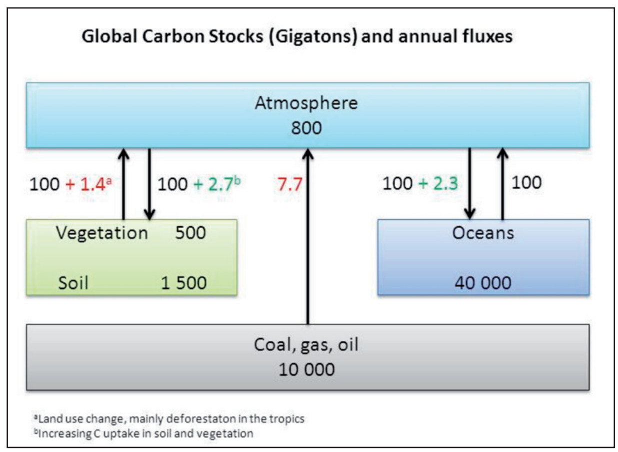

Figure 33.1. Global carbon stocks (Gigatonnes) and annual fluxes. (Based on Le Quéré et al., 2009).

Global Carbon Stocks and Flows

Figure 33.1 presents a simplified version of the global carbon cycle. Boxes represent carbon stocks as fossil fuels, in the oceans, terrestrial ecosystems and atomosphere. Arrows represent annual carbon exchange between these compartments.Stocks measured in billions of metric tons (Gigatonnes). Numbers are based on Le Quéré et al. (2009).

Large amounts of carbon are cycling between the atmosphere and ecosystems (about 200 Gigatonnes per year). Thus, natural carbon fluxes due to photosynthesis are about 25 times higher than those caused by the burning of fossil fuels and cement production (7.7 Gigatonnes per year). Clearing of mainly tropical forests for pastures, croplands and infrastructure, are also contributing to human induced carbon emissions (about 1.4 Gigatonnes per year) since carbon in the vegetation is released as carbon dioxide and often also soil carbon stocks are declining after this conversion. About 45% of total human induced carbon emissions (7.7 + 1.4 = 9.1 Gigatonnes) are accumulating in the atmosphere (4.1 Gigatonnes), whereas the remaing parts are adsorbed in the oceans (2.3 Gigatonnes) and terrestrial ecosystems, mainly temperate and boreal forests (2.7 Gigatonnes). All figures presented here are based on compilation from different data sources and modelling and are highly uncertain (Le Quéré et al., 2009). Between years, fluxes also vary due to natural climatic variation and disturbances such as forest fires and storms. However, relative magnitudes of the different carbon stocks and fluxes are much more certain. For examples, total amounts of carbon stored in soils down to 1 m depth are about three times higher than those in vegetation and about twice as high as those in the atmosphere. Thus, a change in land use and management that will change soil carbon stocks with 1% will result in a 2% change of atmospheric carbon dioxide. The soil carbon balance has therefore significant impact on our climate.

Carbon and Soil Fertility

In a typical soil profile, organic carbon concentrations are decreasing exponentially with depth. About the same amount of carbon is usually found in the upper 25 cm as in the subsoil between 25 and 100 cm depth. This can be visually observed when digging a soil pit where the darker upper horizon indicate a high carbon content compared to deeper horizons which are more greyish or reddish due to less amounts of minerals and oxides with organic material. Soil organic carbon content is a key-indicator for soil fertility since it affects soil structure and is positively correlated with aggregate stability, water infiltration, water holding capacity, nutrient delivery, nutrient use efficiency and soil erosion control. Therefore, keeping reasonable high levels of soil organic carbon is fundamental for sustainable management practices.

Soil Organic Matter

A typical mineral soil used for agriculture consists of about 45% minerals, 5% organic matter and 50% pores of different sizes, which partly are filled with water. Carbon concentration in soil organic matter is about 50%. Excluding plant roots, only about 2% of this carbon is in living soil organisms (about 90% thereof in archaea, bacteria and fungi and about 10% in eukaryotic organisms such as amoebas, nematodes and earthworms). The rest, about 98%, is a heterogeneous mixture of soil organic material deriving from vegetation and soil organisms at different stages of decomposition.

Soil Carbon Balance

The amount of carbon stored in the soil profile is determined by the balance between carbon inputs (crop residues, roots, root exudates and exogenous organic materials applied in fields such as farmyard manure, sewage sludge or other organic soil amendments) and outputs from decomposition (main part as carbon dioxide). Carbon input is controlled by the plant species and management. Since both choice of plant species and management such as crop residue treatments and manure addition are controlled in agricultural systems, the soil carbon balance is also under human control. All options like fertilization or irrigation that stimulate photosynthesis are likely to increase carbon inputs. Crop residue removal (e.g. for bioenergy) will result in less input, although this option may be favourable for reducing greenhouse gas emissions in a global perspective due to mitigation of emissions from fossil fuels. However, it is not only the quantity of organic inputs that matter for the soil carbon balance but also the quality of its organic constituents. Different organic substances are decomposed through different metabolic pathways and contribute differently to the built-up of soil organic matter. Whereas simple organic substances like sugars are almost instantly assimilated by the soil organism community, more complex molecules like cellulose or lignin are decomposing at a much lower rate. Thus, depending on its composition, the same amount of carbon input will contribute differently to the soil organic matter. It has been shown that for example the same amount of roots from agricultural crops or farmyard manure contribute more than twice as much to soil organic matter compared with above-ground crop residues (Kätterer et al., 2011).

Both input and decomposition are under climatic control. Due to long winters, the length of the vegetation period is decreasing with latitude. This is constraining photosynthesis and decomposition. The activity of decomposers in soil is very low during winter but they are responding fast when temperatures rise in spring. In general, decomposer activity increases exponentially with temperature. Heterotrophic organisms which are adapted to aerobic conditions need both water and oxygen. Decomposer activity is generally highest when 50-80% of the soil pore system is filled with water. Due to the interaction between temperature and soil moisture, decomposition rates are highest under relatively moist and warm conditions and are lowest under either cold or dry conditions. Therefore, the same organic material will decompose almost 5 times as fast in the same soil type at Brazzaville (Congo) compared to Uppsala (Sweden) but at about the same rate as in Uppsala at a hot and dry site in Chad (Andrén et al., 2007). Apart from temperature and moisture, also the soil chemical conditions like salinity and acidity are affecting soil microbes. Low salinity and acidity are generally favourable for decomposition.

Depending on soil type, a large proportion of soil pores are at the sub-micron scale and thus too small for any organism to enter. Soil organic molecules in these tiny pores are therefore more protected from decomposition than those in larger pores. Moreover, organic molecules interact with mineral surfaces through chemical binding to form organo-mineral complexes, which are not easily accessible to soil microorganisms. These interactions differ between soil types and are more pronounced in fine textured soils (clay) than in course textured soils (sand). Soil aggregation is favoured in fine textured soils where soil organic matter is gluing together mineral particles. Both the affinity of clay particles binding to organic substances and the large amount of narrow pores leads to stabilization of soil organic matter in clay soils. According to a Swedish inventory of agricultural soils, soils classified as clay contain about twice as much carbon as those classified as sand (Kätterer et al., 2006). Thus, carbon in soil is stabilized due to physical, chemical and biological reasons and is therefore not readily decomposed. This also implies that all management options affecting carbon input to soil have long-lasting consequences.

Figure 33.2. shows the remaining mass of decomposing crop residues during 10 years in the field. Decomposition is fast during the first year whereafter it slows down.

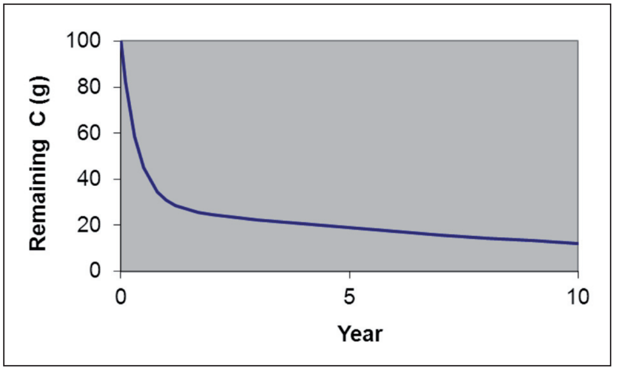

Figure 33.2. Decomposition of crop residues.

After 10 years there is still more than 10% of the original added carbon present in the soil.

Inputs of fresh organic materials (crop residues, roots, manure etc.) are stimulating the decomposer community to breathe and to grow. Organic carbon is transformed into microbial biomass and carbon dioxide. Decomposition rates are high in the beginning but are decreasing with time when sugars, proteins and other easily decomposable substances are depleted. A part of the decomposition products (mostly dead microbial cells en exudates) are entering small pores or are chemically interacting with mineral surfaces. Their further decomposition is very slow, governed by different processes and limited by diffusion and their solubility in water.

Carbon inputs in agricultural systems occur mainly through roots and also a higher proportion of root input compared to above-ground crop residues contributes to the build-up of soil carbon stocks. Cereals like wheat and barley have been breeded for thousands of years for optimizing grain yields. Therefore, a lower proportion of assimilated carbon ends in roots and straw and a higher proportion is exported compared with many grassland species. This is the main reasons at many sites for higher carbon stocks under grassland or forests compared to cultivated soils. Intensive tillage methods like mouldboard ploughing may also stimulate decomposition since parts of organic material that not were accessible to microbes maybe exposed through breaking up of soil aggregates. In some regions, soil tillage has been shown to result in decreasing soil carbon stocks although earlier studies

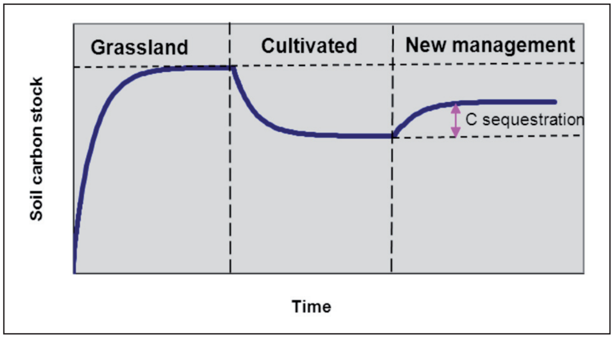

Figure 33.3. Evolution of soil carbon over time.

were overestimating this effect. This effect seems to be more pronounced in semi-arid areas like the prairies in the US and Canada. Under more humid conditions, in the eastern part of Canada or in the Baltic region, this effect is probably much smaller or even negligible. However, reduced tillage has many other positive effects. Generally it decreases risks for water and wind erosion and it also reduces cost for labour and diesel and thus, emissions of carbon dioxide. On the other hand, no-till systems favour weeds and the survival of plant pathogenic fungi under certain conditions. Therefore, the need for both herbicides and fungicides increases when reducing tillage intensity.

Figure 33.3. shows a hypothetical evoluton of soil carbon over time, from mineral sediments almost free from organic matter to natural grassland or forest vegetation. At a certain time, land use is changed to agricultural usage which results in lower carbon stocks. Thereafter, agricultural management is changed in order to sequester carbon in soil. The time scale in this example maybe more than 1000 years since it takes hundreds of years until the soil system has adjusted to new conditions, i.e., carbon stocks have reached a dynamic equilibrium (carbon input = carbon output), after the change of land use or management.

Organic Soils

Soils with high content of soil organic matter have been formed under water-logged conditions. Under low oxygen conditions, organic material is accumulating as peat since decomposition is strongly limited. A typical organic soil used for agriculture in the Baltic area is derived from drained wetlands around lakes that were reclaimed for agriculture by lowering water tables, thus allowing oxygen to enter the soil profile. This lowering of the water table is resulting in soil subsidence, i.e., the sinking of the soil surface, due to physical compaction caused by gravimetric forces and increased decomposition. During the years, water tables have to be lowered from time to time due to this subsidence and the organic layer, up to several meter thick from the beginning, is decreasing. Finally, the remains from this organic layer are mixed with the mineral sediment below and what is left is a mineral soil with a high soil organic carbon content. Around the Baltic sea around 5-10% (depending on classification criteria) of the agricultural soils share this history and are today at different stages along the way from organic to mineral soils. The oxidation of organic material caused huge emissions of carbon dioxide. Moreover, decomposition of organic material is also resulting in nitrogen mineralization and nitrification. Since nitrate can be transformed to nitrous oxide, these soils also contribute to significant emissions of this greenhouse gas, which is about 300 times as effective as a greenhouse gas as carbon dioxide. Organic soils are therefore a major source for greenhouse gas emission and management options for mitigation of emissions are presently under discussion. Raising the water table and reconverting them into wetlands may be only an effective mitigation strategy for some of these soils since emissions of methane, another potent greenhouse gas, will probably not be totally compensated for by decreased emissions of the other gases. Research is presently conducted for optimal management strategies for minimizing climate impact from different kinds of organic soils.

Climate Negotiations

Soil carbon dynamics have received much attention in recent years due to the demand for national reporting of changes of soil C stocks in national Greenhouse Gas Inventories according to IPCC guidelines (IPCC, 1997). Further, Article 3.4 of the Kyoto Protocol of the United

Nations Framework Convention on Climate Change (UNFCCC) indicates that C sequestration in agricultural soils can be accountable for national budgets, and thus of value for balancing out emissions from fossil fuels.

Ways to Increase Soil Carbon

Carbon Sequestration in Agricultural Soils.
Since grasslands and forests generally lose carbon upon conversion to agriculture, prevention of land use change in this direction is an effective measure for reducing greenhouse gas emissions. Increasing demand for food, fibres and bioenergy are setting natural ecosystems under pressure and will probably result in changes in land use towards more agriculture in the future. More intensive (higher production per unit area), more efficient and sustainable agricultural and aquacultural production systems have to be developed for minimizing the impact on natural ecosystems. Carbon sequestration as a mitigation strategy for reducing greenhouse gas emissions can be a win-win strategy, since increased soil carbon is also crucial for soil fertility. Many agricultural practices have the potential to mitigate greenhouse gas emissions. At global level, this potential was estimated to about 1.5 Gigatonnes per year (Smith et al., 2008) excluding potential fossil fuel offsets due to bio-energy production in agricultural systems. If all these potential changes in agronomic practices were included in the carbon trading market, a certain portion of these potentials could be realised depending on the price of carbon dioxide equivalents. Carbon sequestration in soil is one of these options. Carbon inputs are the more controllable part of the soil carbon balance since decomposition is mainly governed by climatic conditions. The most prominent carbon sequestration strategies are therefore practices that result in higher carbon inputs to soil. However, optimizing a system only in one dimension (e.g. carbon sequestration) may under certain circumstances lead to unwanted consequences like higher nitrous oxide emissions or higher nitrate leaching. Therefore, agricultural systems have to be optimized in many dimensions at the same time for providing enough food, fibers and other ecosystem services for a growing population with less negative impact on climate and nature.

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