

Scientific registration n° : 2178
Symposium n° : 26
Presentation : Poster

Mitigation of atmospheric concentrations by increased carbon sequestration in the soil

Diminution de la concentration atmosphérique en CO₂ par séquestration du carbone dans les sols

BATJES Niels H.

International Soil Reference and Information Centre (ISRIC), P.O. Box 353, 6700 AJ
Wageningen, The Netherlands

Introduction

Expanding use of fossil fuels and large-scale land-use changes have led to increased concentrations of radiatively-active trace gases in the atmosphere, affecting global climate (Watson *et al.*, 1996). Current international climate negotiations are aimed at deriving targets for the reduction of greenhouse gas emissions after the year 2000. The proposal of the European Union, for the third conference of the parties to the UN Climate Convention in Kyoto (December 1997), is that the industrialized countries should reduce their emissions of greenhouse gases to 15 per cent below 1990 levels by the year 2010. Consequently, many research institutes and industries have been developing technologies to this avail. How effective can such technological measures be in periods of economic growth, associated with higher uses of fuel by industry and the transport sector? And can these measures, alone, adequately reduce current atmospheric CO₂ levels as envisaged by the policy makers?

The average global releases of carbon to the atmosphere, in the 1980s, were 1.1 Pg C yr⁻¹ from land-use changes (1 Pg = 1 Gt = 10³ Tg = 10¹⁵ g), 5.5 Pg C yr⁻¹ from fossil fuel combustion, with the atmosphere gaining 3.2 Pg C yr⁻¹ and the oceans absorbing 2.0 Pg C yr⁻¹ (Schimel, 1995). Current budgets for human-induced perturbation of CO₂ point to a small inferred terrestrial uptake of about 1.4 Pg C yr⁻¹, part of which is due to the 'CO₂-fertilization effect' (1.0 Pg C yr⁻¹), forest regrowth in the Northern Hemisphere (0.5 Pg C yr⁻¹), and increased N deposition (0.6 Gt C yr⁻¹) (Schimel 1995).

Direct effects of elevated atmospheric CO₂ concentration on soil-C cycling are unlikely in view of high ambient CO₂ concentrations in the soil. Evidence exists, however, that plant growth and soil carbon sequestration are increasing due to the so-called physiological 'CO₂-fertilization' effect, associated with increased atmospheric CO₂-levels (Allen *et al.*, 1996; Bazzaz *et al.*, 1996), plus the associated improved water-use efficiency (Van de Geijn and Goudriaan, 1996) and more favourable temperatures and increased anthropogenic nitrogen

emissions (Hudson *et al.*, 1994; Mellilo, 1996). In this context, the possibility for enhanced and sustained carbon sequestration in standing vegetation and the soil should be considered as a possible option for atmospheric CO₂-mitigation.

Soil organic matter

Most carbon in the soil is associated with organic matter. Carbonate carbon can be significant in calcareous soils of semi-arid and arid regions, while charcoal may be an important constituent in ecosystems subject to frequent fires (Sanford *et al.*, 1985; Skjemstad *et al.*, 1990). Soil organic carbon mass in the upper 1 m of soil is about 1200-1550 Pg C (Batjes and Sombroek, 1997), and about 2376-2456 Pg C in the upper 2 m of soil (Batjes, 1996). On average, the soil contains about 2.5 times more organic carbon than the vegetation (\approx 650 Pg C) and about twice as much carbon than is present in the atmosphere (\approx 750 Pg C).

There is a great variation in the amount and vertical distribution of organic matter in temperate, tropical and subtropical soils. Soil organic matter stored in the topsoil contributes most actively in nutrient cycling in the soil-water-plant system and to gaseous exchanges with the atmosphere, but the subsoil is also important (Nepstad *et al.* 1991; Davidson *et al.*, 1993).

Major environmental controls of organic matter behaviour in soil are moisture status, soil temperature, oxygen supply (drainage), soil acidity, soil nutrient supply, clay content and mineralogy (see Batjes, 1992). Globally, the mean residence time of soil organic matter is about 22 years (Post *et al.*, 1992). The turnover time of organic matter increases with depth in the soil, ranging from several years for litter to 15-40 y in the upper 10 cm and over 100 y below a depth of about 25 cm (Lobo *et al.*, 1990; Harrison *et al.*, 1990).

The favourable effects of soil organic matter on the physical, chemical and thermal properties of the soil and on biological activity, and thus in sustaining soil productivity and biodiversity, are well known. These aspects may be seen as an 'added-benefit' over direct carbon mitigation techniques that would only physically store carbon in the deeper subsoil (e.g., old gasfields, mines and aquifers).

Possible effects of human-induced changes on carbon sequestration

The soil forming factors, notably climate as well the local biological activity in which man is often a predominating factor, control the amount of soil organic matter that corresponds with equilibrium conditions in a certain natural ecosystem or agro-ecosystem. After each disturbance, a period of constant management is required in order to reach a new steady state. It may take from 10-50 y for soil organic C and between 15-20 y for N, depending on climate. Upon the introduction of adapted management practices on present and newly cultivated soils or reforestation, whereby litter inputs exceed decomposition, the organic carbon content in the soil will gradually increase towards a new steady state. This new equilibrium may be lower, similar or higher than the original climax level.

Historic examples of enhanced carbon sequestration through adapted management include: agricultural soils to which large amounts of farm-refuse, rich in phosphorus, have been added over prolonged periods; agricultural soils supplied with large amounts of farmyard manure annually for over 100 y; and, soils under maize supplied annually with NPK-fertilizers for 30 y

(Gregorich *et al.*, 1996). Some of these increases are of a long-lasting nature, as is the case for "Terra Preta-do-Indio" found throughout the Amazon Basin and "Plaggen" soils in North-Western Europe (Sombroek, 1995). Others are not once the beneficial land management practices are stopped because, apparently, most of the soil carbon was still present in a labile form.

The potential effects of changing climate and higher atmospheric CO₂ levels on soil carbon sequestration are highly interactive and complex. Both net primary productivity (NPP) and organic-matter decomposition, being (micro)biologically mediated, are likely to be enhanced by increasing temperature, provided water and nutrient supply are not limiting. According to Kirschbaum (1995) organic-matter decomposition is likely to be stimulated more than NPP. This then would imply that while global NPP is likely to increase with global warming, soil carbon storage is likely to decrease at the same time, which would release more CO₂ to the atmosphere (e.g., Schimel *et al.*, 1990; Kirschbaum, 1995). However, few of these studies consider interactive effects of temperature and moisture limitations on plant responses and decomposition rates, as extensively reviewed by Bazzaz *et al.* (1996). Model studies by Klein Goldewijk *et al.* (1994), suggest the effects of increased temperature and water availability on soil respiration - implying CO₂ release - are smaller than those associated with the CO₂-fertilization effect. Similarly, Post *et al.* (1996), reported an increase in soil organic carbon content in their transient and equilibrium climate change scenarios in which NPP was varied as a function of "climate and atmospheric CO₂ concentration", as opposed to a decrease for scenarios which considered solely "climate change" respectively "climate change and concomitant NPP change".

Basically, it is still uncertain in which direction soil carbon pools will actually evolve (Körner, 1996). Under elevated CO₂-levels, most plants are found to produce tissues that contain more carbon and less nitrogen. The assumption then is that this CO₂-induced increase in C/N ratio, and possibly increased lignin content, will lead to reduced rates of decomposition (Ball, 1997), and thereby facilitate carbon sequestration in the soil. Körner (1996), however, illustrated there is another pathway by which CO₂-fertilization may influence the soil environment. That is, through priming-effects of increased rates of turnover of fine roots and higher exudation of low molecular-weight organic compounds to the rhizosphere (Paterson *et al.*, 1997); quantitatively, root exudation may be much less important in forests than in grasslands. Only a small portion of the exuded labile carbon can be stabilized in soil organic matter through interactions with clay minerals, contrary to other more recalcitrant plant constituents such as lignin and cellulose (Hungate *et al.*, 1997). Soil mineralogy is a strong control of passive carbon pools. According to Torn *et al.* (1997), the effect of mineralogy on soil carbon storage is of the same magnitude as that attributed to climate or vegetation.

The complexity of terrestrial ecosystem response to increased atmospheric CO₂ concentrations and climate, illustrates the need for modelling approaches. Possible impacts of increased atmospheric deposition of nitrogen on soil physical, chemical and biotic processes and ultimately carbon-sequestration will need to be considered also in conjunction with impacts caused by changing land-management practices and possible shifts in species diversity

and functions (Brinkman and Sombroek, 1996; Betts *et al.*, 1997; Jefferies and Maron, 1997; Norby, 1997).

Management options for enhanced soil carbon sequestration

Differences in soil type, their suitability for different uses and the factors of soil formation must be considered when identifying management options for enhanced C-sequestration. Organic carbon contents in artificially drained peat soils are unlikely to increase, unless they are reverted to wetlands. As a result, possibilities for increased C-sequestration are largely limited to the so-called 'upland soils'.

The role of agriculture in sequestering organic carbon remains ambiguous. The overall picture is complicated by technological, social, economic and cultural factors. These must be addressed specifically in management of fragile and ecologically sensitive ecosystems. Watson *et al.* (1996) estimated that 0.4-0.8 Pg C yr⁻¹ could be sequestered in agricultural soils globally by implementation of appropriate management practices. This is about 10% of the global anthropogenic production of CO₂ for the year 1990 [≈ 6 Pg C y⁻¹].

Management practices should be aimed at optimizing CO₂-utilization in photosynthesis to increase crop productivity and yields, and at increasing especially the passive or stable fraction of the soil organic matter pool. Available options include: high residue production; mulching; reduction of bare fallow; tillage practices that limit depth and intensity of disturbances (i.e., minimum tillage); and fertilization, notably with (rock)phosphates. Manipulation of the quality and quantity of organic inputs, for example by cultivar selection and introduction of leguminous crops, and of the soil fauna are options worthy of further research (Fernandes *et al.*, 1997).

The degree to which various management techniques will be effective depends on several environmental controls, some of which may be altered by climate change. Management implications of elevated CO₂ concentrations and increased temperatures need consideration. Increased atmospheric CO₂ concentrations may stimulate crop growth until nutrient or water limitations are reached, which means the potential for additional fertilizer application must be evaluated by soil and crop type (e.g., C₃, C₄ or CAM). Land-users will only adopt adapted management techniques if they improve profitability within several years (Izac, 1997).

Energy crops or 'biofuels' have a considerable potential for mitigation of atmospheric CO₂ emissions by countervailing the use of fossil fuels. Biofuel production on 10-15% of the land currently in agricultural use or in agricultural set-asides could substitute for 0.3-1.3 Pg C yr⁻¹ of fossil fuel, while recovery and conversion of crop residues could substitute for an additional 0.1-0.2 Pg C fossil fuel per year (Cole, 1996). These figures do not include the indirect CO₂-offsets of biofuel production through increasing carbon storage in the standing (woody) vegetation, and possibly by increased carbon sequestration in the soil. Inherently, only part of the residues of biofuel crops can be removed without affecting future soil productivity.

Management of forests and reducing tropical and subtropical deforestation are viable options for C-mitigation (see review by Brown, 1996). Such actions will also reverse

processes of land degradation, thus contributing to sustained food productivity and security for the people in the regions concerned.

Evidence of enhanced soil carbon sequestration

Historical decreases in soil carbon content upon cultivation, as reported for the 'US dust bowl' and the 'Virgin Land Scheme' in the former USSR, were often associated to low production levels, inadequate fertilizer application, removal of crop residues and intensive tillage (e.g., Papendick, 1994). Historical examples of sustainable doubling of the organic matter component of soils under century-long human occupation exist also, albeit for smaller areas. Encouraging reports have become available also on enhanced C-sequestration under improved grasslands both for the tropics and subtropics, as well as on the positive effects of agroforestry (see Batjes and Sombroek, 1997; Fernandes *et al.*, 1997).

The root-system of tropical pastures can be used effectively to sequester and redistribute carbon deeper in the soil profile (Nepstad *et al.*, 1991) where it tends to be better protected and less susceptible to decomposition. Carbon sequestration in many grasslands in semi-arid areas can be increased by reduction of biomass burning, by raising the nutrient status of the soil and by introducing improved grasses and legumes in combination with controlled stocking rates (Fisher *et al.*, 1994).

Lal *et al.* (1995) estimated that with improved land-use, cultivated and (resilient) degraded soils can sequester 0.1 to 1 Pg C y^{-1} , depending on management. Assuming a recovery of 50 to 66 per cent of historic C-losses since 1860, Cole (1996) estimated that (improved) cultivated soils globally could sequester 20-30 Pg C over the next 50 years, and that this could be in the order of 23-44 Pg C if permanent set-asides and restoration of degraded lands is also included. Sampson *et al.* (1993) found that, globally, agro-ecosystems may be converted to a net carbon sink of up to 7 Pg C during the next 50 y by use of appropriate soil management practices. This would require increased production and major improvements in management on much of the world's cultivated areas, notably in the economically less-developed regions.

In the European Union there is some potential to increase soil carbon stocks over the next decades through changes in agricultural practices, notably in the context of the 'set-aside' policies associated with current agricultural overproduction. Regression studies by Smith *et al.* (1997), based on data for 14 long-term experiments, showed the increase in soil carbon over the next 100 y by addition of animal manure, sewage sludge or straw would be less than 15 Tg C y^{-1} . However, these increases would be obtained in combination with annual cropping, implying a concomitant removal of carbon-containing agricultural produce! Greater potential exists through afforestation of surplus arable land (≈ 50 Tg C y^{-1}), and conversion of current arable land to a ley-arable system (≈ 40 Tg C y^{-1}), i.e. extensification, in which organic residues are re-worked into the soil.

The scenarios of Smith *et al.* (1997) did not consider the potential for increased carbon sequestration in the soil of new set-aside lands, under grass or legumes together with application of lime and (rock)phosphates. Such scenarios are worthy of further research as up to 20-30% of the European Union's cropland may be comprised of 'set-aside' land by the year

2010. However, this mitigation option may no longer be available if policies change, for example due to new environmental concerns or changing demands for food and fibre crops.

Adverse environmental side effects

Some measures that enhance C-sequestration in the biomass and soil, such as N-fertilizer application, increase emissions of greenhouse gases such as N₂O. In wetland rice soils, incorporation of fresh organic materials may lead to methane formation and emission, another radiatively active gas. Possible (adverse) environmental side-effects of widespread additions of manure and sludges to soil, through increased heavy metal and organic pollutant concentrations, should be taken into consideration also.

Land-use and management practices which could reduce emissions of greenhouse gases such as CH₄ and N₂O include, sustaining existing forest cover; slowing deforestation; regenerating natural forests; establishing tree plantations; promoting agroforestry; altering management of agricultural soils and rangelands; improving efficiency of fertilizer use; restoring degraded agricultural lands and rangelands; recovering CH₄ from stored manure; and, improving the diet quality of ruminants (Watson *et al.*, 1996).

Conclusions

Several management practices are available for increasing the carbon content in the soil. These options deserve more attention in programmes aimed at reducing national and global CO₂-budgets, similar to re- or afforestation and biofuel programmes.

There is a need for better integration of long-term monitoring, experimental and modelling programmes at different scales, both in space and time, coupled with development of spatially explicit databases of climate, vegetation, topography, soils and land use (Oldeman and Van Engelen 1993; Cole 1996; Ingram and Gregory 1996; Cramer and Fischer 1997). Attention should be paid also to a comparative assessment of the cost-effectiveness — i.e. social and economic dimensions — of the available technical options, both in terms of enhanced carbon sequestration in the soil and increased sustainability, for example in terms of improved water management, soil fertility and productivity.

Acknowledgements

The author thanks Wim Sombroek for useful comments on an earlier version of the manuscript.

Keywords : soil organic matter, carbon sequestration, climate change, CO₂, carbon dioxide
Mots clés : matière organique du sol, séquestration du carbone, changement climatique, CO₂, gaz carbonique