CHAPTER 2

Soil Carbon Sequestration

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CONTENTS

2.1 INTRODUCTION

Concerns regarding global warming and increasing atmospheric greenhouse gas (GHG) concentrations (CO_2, CH_4, and N_2O) have led to questions about the role of soils as a carbon (C) source or sink (Houghton, 2003). Excluding the carbonated rocks, soils constitute the largest surface C pool, approximately 1500 Gt C, which is almost three times the quantity stored in the terrestrial biomass, and twice that in the atmosphere (Lal, 2003). Therefore, any modification of land use and management practices, even for the agricultural systems at the steady state, can change soil C stocks (Schuman et al., 2002). Locally, these stock variations concern mainly the topsoil horizon (between 0 and 30 cm depth) and occur because of different processes at the plot scale, such as modification of the organic matter rates and quality inputs (Jenkinson et al., 1992; Paustian et al., 1992; Trumbore et al., 1995), transfer (deposition, erosion, leaching, and run-off) in solid or soluble form (Chan, 2001; Lal, 2002), and losses by mineralization (CO_2, CH_4) of soil organic matter (Schimel, 1995; Shang and Tiessen, 1997). It is, therefore, apparent that soils play a significant role in the control of the C stocks and fluxes (King et al., 1997; Schlesinger, 2000). For tropical soils, these changes may represent up to 50% of the original C stock in the top 20-cm depth (Feller et al., 1991; Feller

Table 2.1 **Number of References Indexed in the ISI-Web of Science (1945 to 2003) for the Word Queries "Soil," "Carbon," and "Sequestration" (Query 1) and "Soil" and "Carbon" (Query 2), Respectively, in the Topics and in the Title (in parentheses)**

Years	Number of References Returned by the Queries: Query 1	Query 2	Query 1/Query 2 ‰
1945 to 1990	0	719	0
1991	1[a]	643	1.6
1992	5 (1)[b]	694	7.2
1993	14 (1)	816	17.2
1994	7	908	7.7
1995	21 (1)	985	21.3
1996	24	1220	19.7
1997	36 (2)	1398	25.7
1998	47 (3)	1520	30.9
1999	38 (3)	1565	24.3
2000	94 (9)	1616	58.2
2001	104 (18)	1725	60.3
2002	153 (15)	1850	82.7
2003	150 (13)	2133	70.3
Total (1945 to 2003)	694 (66)	17792	39.0

[a] Thornley et al., 1991.
[b] Dewar and Cannell, 1992.
Queries performed on January 6, 2004.

and Beare, 1997). Therefore, land-use management policies may significantly influence fluxes of C between continental ecosystems and the atmosphere (King et al., 1997; Schlesinger, 2000).

The world community has been preoccupied since the early 1990s with potential climatic change due to increasing atmospheric GHG concentrations. Two possible courses of action to alleviate climate change are: (1) limiting the GHG emissions, and (2) enhancing the removal (or uptake) of these gases from the atmosphere to stabilize the pools (for example, sediments, trees, soil organic matter). World soils are one such pool. Yet, some prefer to use other terms in relation to the capture and retention of GHGs from the atmosphere; thus the terms *sequester* and *sequestration* have gained importance not only because they represent innovative ideas but also because they have gained widespread publicity.

With regards to the potential of the soil to mitigate the greenhouse effect, and more generally with regards to land use, land-use change, and forestry (LULUCF), the correct term is *soil carbon sequestration*. Although the published literature dates back to 1945, scientific publications increasingly began to use "soil carbon sequestration" in the early 1990s (Table 2.1).

As shown in Table 2.1, these terms are increasingly being used, but a definition or at least the broad meaning of "soil carbon sequestration" is rarely given. This chapter reviews and discusses some current definitions, proposes an alternative one, and draws attention to some necessary cautions when referring to soil carbon sequestration.

2.2 AVAILABLE DEFINITIONS AND CONCEPTS

A list of available definitions in publication or on Web pages is given below:

- U.S. Department of Energy: "Carbon sequestration in terrestrial ecosystems is either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from the terrestrial ecosystems into the atmosphere." (U.S. Department of Energy, 1999)

- U.S. Department of Agriculture (USDA): "What is soil carbon sequestration? Atmospheric concentrations of carbon dioxide can be lowered either by reducing emissions or by taking carbon dioxide out of the atmosphere and storing it in terrestrial, oceanic, or freshwater aquatic ecosystems." (USDA — FAQ, www.usda.gov/oce/gcpo/sequeste.htm)
- Oak Ridge National Laboratory (ORNL): "From the viewpoint of terrestrial ecosystems, carbon sequestration is the removal of carbon dioxide from the atmosphere by enhancing natural absorption processes and storing the carbon for a long time in vegetation and soils. Carbon sequestration may be accomplished by fixing more carbon in plants by photosynthesis, increasing plant biomass per unit land area, reducing decomposition of soil organic matter, and increasing the area of land covered by ecosystems that store [carbon]." (Jacobs, 1999)
- Soil Science Society of America (SSSA): "Carbon sequestration refers to the storage of carbon in a stable solid form … . The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms." (Position of the SSSA, dated October 25, 2001: www.soils.org/carbseq.html)

Intensive speculations are being made about a future C market. Moreover, LULUCF has been accepted as a credit-earning climate change mitigation option for the first five-year commitment period. International negotiations also recognize afforestation and reforestation as viable LULUCF sink activities (Bernoux et al., 2002) for the clean development mechanism (CDM), which is based on specific projects undertaken by an Annex I country in a non-Annex I country. Therefore, reported below are definitions given by the potential entities that formulate theses projects and are C traders:

- Ecoenergy International Corporation (EIC): "Carbon sequestration is a strategy to slow the accumulation of atmospheric carbon dioxide by absorbing carbon into soil and perennial vegetation. This can be achieved through reforestation, agroforestry, or forest management activities that preserve or increase an existing carbon 'sink.' Carbon sinks include forests and other ecosystems, as well as sustainable agriculture crops that sequester carbon in the soil and in long-lived harvested products." (www.eic-co.com/sequestration.htm)
- CO2e.com (www.CO2e.com): "Carbon Sequestration is a Category on the CO2e Trading Floor. It refers to projects that capture and store carbon in a manner that prevents it from being released into the atmosphere for a specified period of time, the storage area is commonly referred to as a carbon sink (A carbon sink is a reservoir that can absorb or "sequester" carbon dioxide from the atmosphere. Forests are the most common form of sink, as well as soils, peat, permafrost, ocean water and carbonate deposits in the deep ocean.). Carbon Sequestration projects include: Forest Sequestration; Land Conservation; Soil Conservation and Land Use; Waste CO_2 Recovery/Deep Injection." (www.co2e.com/common/glossary.asp)

In the Kyoto Protocol (UNFCCC 1998) the word "sequestration" appears only once in its Article 2.1: "Each Party included in Annex I, in achieving its quantified emission limitation and reduction commitments under Article 3, in order to promote sustainable development, shall: (a) Implement and/or further elaborate policies and measures in accordance with its national circumstances, such as: … (iv) Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound … " Moreover, it is cited within a section that has no direct relation with the LULUCF sector that is treated by the points a-ii and a-iii of the same article.

Another important document that deals with soils and their management is the International Panel on Climate Change (IPCC) special report on LULUCF. This report defines sequestration as "the process of increasing the carbon content of a carbon pool other than the atmosphere."

2.3 DISCUSSION

Most of these definitions (soil specific or not) are based on CO_2 removal from the atmosphere and storage in an organic form in the soil or plant pools. Only the SSSA and IPCC (in its Special

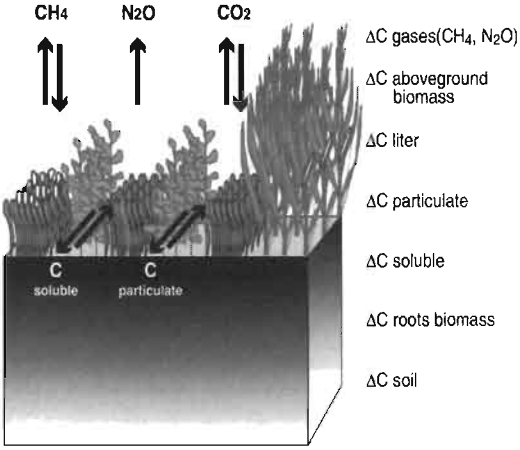

Figure 2.1 Fluxes (arrows) and changes (Δ) that need to be accounted, at the plot level, for a complete comparison of the C and GWP balances for a given agrosystem.

Report on LULUCF) give a definition based only on C storage, and that this should be a stable pool. Other definitions consider different pools, such as fresh water, oceans, and carbonated sediments.

A major flaw in these definitions is considering only the CO_2 fluxes. In addition to CO_2, soils are also characterized with methane (CH_4) and nitrous oxide (N_2O) fluxes. Furthermore, the Kyoto protocol covers all sources and sinks of those gases. The net emission calculations of the signatories of the United Nations Framework Convention on the Climate Change (UNFCCC) are expressed in equivalents of CO_2, by taking into account the global warming potential (GWP) of each gas: the Third Assessment Report of the IPCC (IPCC, 2001) expressed GWP at the secular horizon values (100 yr-GWP) of 23 for CH_4 and 296 for N_2O. GWPs are measurements of the relative radiative effect of a given substance (CO_2 here) compared to another and integrated over a specific time period. This means that 1 kg of CH_4 is as effective, in terms of radiative forcing, as 23 kg of CO_2. On a C or N mass base, 1 kg of C-CH_4 is equivalent to 8.36 kg of C-CO_2, and 1 kg of N-N_2O to 126.86 kg C-CO_2.

A recent review by Six et al. (2002) illustrates the importance of those considerations. They reported that in both tropical and temperate soils, a general increase in C pool (≈325 ± 113 kg C ha^{-1} yr^{-1}) was observed under no-till (NT) systems compared with conventional till (CT). But that, on average, in temperate soils under no-till, compared with conventional till, CH_4 uptake (0.42 ± 0.10 kg C-CH_4 ha^{-1} yr^{-1}) and N_2O emissions increased (≈2.91 ± 0.78 kg N-N_2O ha^{-1} yr^{-1}). The increased N_2O emissions led to a negative GWP when expressed on a C-CO_2 equivalent basis. Other changes in soil induced by NT showed that "from an agronomic standpoint NT is beneficial, but from a global change standpoint more research is needed to investigate the interactive effects of tillage, fertilizer application methodology, and crop rotation as they affect C-sequestration, CH_4-uptake, and N_2O-fluxes, especially in tropical soils, where data on this matter is still lacking." This is particularly true for the N_2O fluxes when leguminous crops are used as cover crops or green manure, because some studies show that N_2O emissions may be enhanced (Giller et al., 2002; Flessa et al., 2002; Millar et al., 2004). Figure 2.1 is a schematic of different C pools and fluxes among them at the plot level.

A holistic comparison of NT vs. CT must involve the computation of all contributors to the net GWP of these systems (Robertson et al., 2000; Flessa et al., 2002). Some potential contributors depend on the crop production cycle: GHG emissions from agricultural machines, direct and indirect GHG emission following liming (Bernoux et al., 2003), and direct and indirect GHG emission associated with pesticides and herbicides use.

Based on all these considerations, it appears that a concept of "soil carbon sequestration" must not be limited to C storage consideration or CO_2 balance. All GHG fluxes must be computed at the plot level in C-CO_2 or CO_2 equivalent, incorporating as many emission sources and sinks as possible for the entire soil-plant system. Moreover, the term soil appears to be too restrictive; and, the whole agronomic system must be considered. Finally, there is no absolute "soil carbon sequestration" potential for a given agronomic system. This raises different problems that need to be taken into account at the plot level, or at the national level, when drawing a national inventory. For the national inventory assessments, calculations are made by sectors. For instance, the emissions associated with fertilizers or lime manufacture is computed in CO_2 equivalent (Bernoux et al., 2002). These emissions, to avoid double accounting, cannot be taken into account in the balance of direct and indirect fluxes at the plot scale that would be extrapolated to the national scale. If, however, for a same fertilizer quantity, different emission fluxes are observed according to the plot management (e.g., no-till vs. conventional till), those differences must be computed during the national scale extrapolation. But, at the plot scale, it is only all the direct and indirect fluxes that need to be computed to enable an absolute comparison even for different agroecosystems (pasture against agroforestry, for instance) among them.

Therefore, a new definition is proposed that could be applied only to the soil pool, but that is more appropriate for the entire soil-plant pools of agroecosystems. This definition takes into account all the fluxes, in gaseous form, of GHG at the soil-plant-atmosphere interfaces expressed in equivalent CO_2 or equivalent C-CO_2 exchanges. These fluxes may originate from different ecosystem pools: solid or dissolved, organic or mineral.

"Soil carbon sequestration" or "Soil-plant carbon sequestration" for a specific agroecosystem, in comparison with a reference, should be considered as the result for a given period of time and portion of space of the net balance of all GHG expressed in C-CO_2 equivalent or CO_2 equivalent computing all emissions sources at the soil–plant–atmosphere interface.

In addition to that general definition, it is important to emphasize some other different aspects:

- What is the form and mean residence time of the sequestered C at the plot level?
- Which time scales have to be considered?
- How is the C (or equivalent C) transferred off-site?
- How is C sequestration determined at the plot scale for the emissions balances at the national level?

2.3.1 What Is the Form and Mean Residence Time of the Sequestered C at the Plot Level?

C sequestration is more effective when the mean residence time (MRT) of new C stored is long. It is, thus, absolutely necessary to evaluate the different C pools and to have an estimate of their respective turnover time. As it is not possible to undertake such determinations systematically, two approximations are possible based on the results of the literature:

- Measuring, by simple methods, variations in the soil organic C pools and their MRT. Different approaches of fractionation, chemical or physical, are possible; in particular granulometric separations that allow an adequate segregation of organic compartment with contrasted biostability: organic matter of the sand, silt, and clay fractions (Feller and Beare, 1997; Balesdent et al., 1998).
- Using simulation models of organic matter dynamics that incorporate conceptual pools defined by their biostability (e.g., active, slowly decomposable, refractory) like the Century (Parton et al. 1987), RothC (Jenkinson and Rayner, 1977) or Morgane Models (Arrouays et al., 1999).

2.3.2 Time Scales

Several issues with regards to time and space scales must be addressed. The desirable time scale has to be sufficient to cover the entire vegetation successions and husbandries for a specific agroecosystem (for example fallow-culture successions), and must be considered on multidecadal scales. In the context of the Kyoto protocol, the first evaluation will be made in 2010

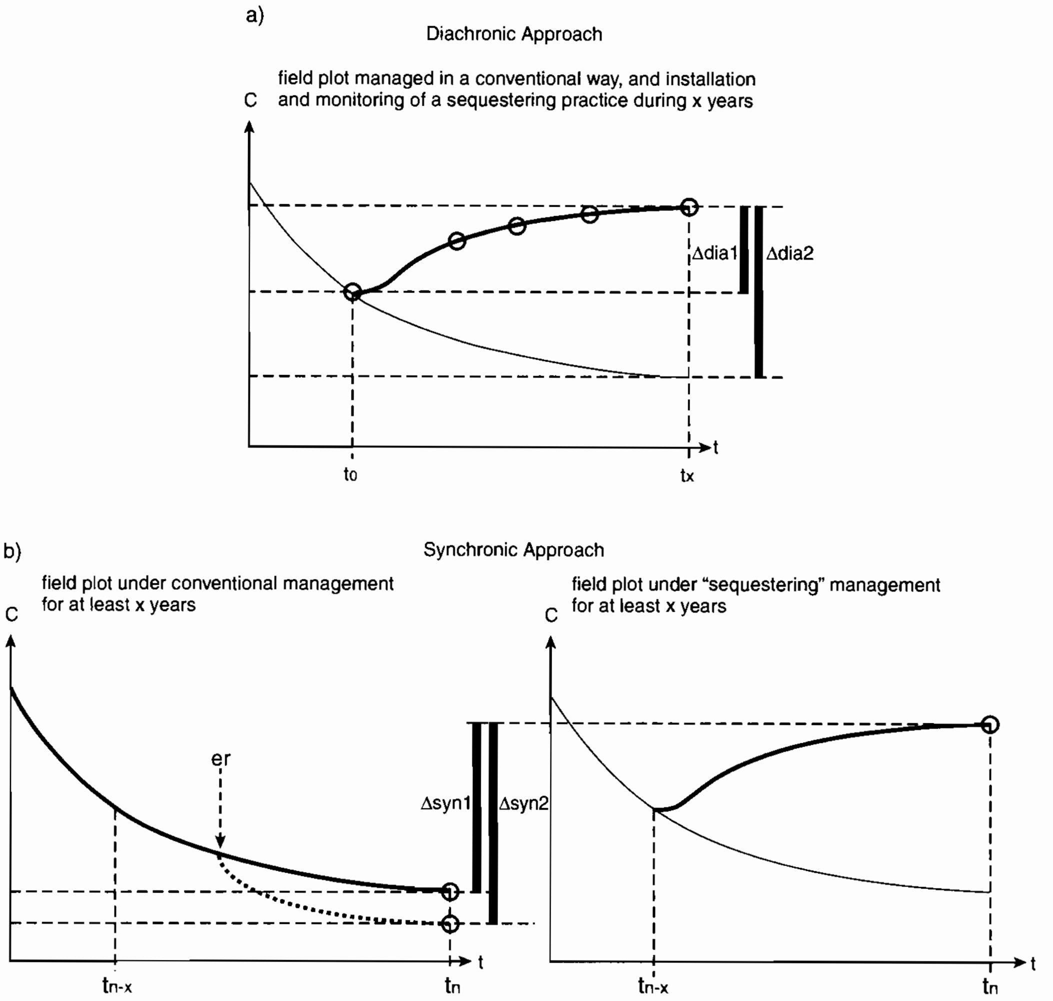

Figure 2.2 Comparison of the diachronic (a) and synchronic (b) approaches. Black circles correspond to C stocks determination; "er" stands for erosion.

using the year 1990 as reference or baseline. In other words, the corresponding time considered here is 21 years.

In addition, as the net balance for a given agroecosystem is always given compared to a reference system, this raises the problem of the choice for the year 0, or its equivalent, referring back to when the sequestering agroecosystem was established. Two approaches are possible: diachronic and synchronic (Figure 2.2).

The diachronic approach consists of measuring, Δt on the same field plot, soil C sequestration between time 0 (installation of the new system) and time x. C sequestered is then represented (Figure 2.2a) by Δdia1. This value is accurate only if soil C under the previous agrosystem of reference was at steady-state. If it was not the case, and the dynamics of C went toward an additional loss by mineralization during Δt ($t_x - t_0$), it would then be necessary to consider not Δdia1 but rather Δdia2. The measurement of Δdia1 is thus an approximation of C stored. It is then necessary to be able to evaluate the additional loss by mineralization (Δdia2 – Δdia1) that would have occurred during Δt for the original agrosystem without change of the practices.

The major disadvantage of the diachronic approach is that one must wait and measure over long periods of time before being able to evaluate the quantity of C sequestered. Therefore, research is generally based on a synchronic approach.

The synchronic approach consists, at a given time tn, of comparing the C stock of a field plot corresponding to the sequestering practice tested during x years to that of a field (control or conventional practices) under traditional management to represent t0 state or the reference point (Figure 2.2b). C sequestered is then represented by Δ_{syn1} (equivalent to Δdia2 in Figure 2.2a). However, it may be that the referenced plot was subjected to drastic alterations in its C stocks by accelerated erosion ("er" in Figure 2.2b). Losses of C occurred (in the reference field plot) in the form of solid transfer of C out of the field, and the difference of soil C between the two fields, is an apparent sequestration Δ_{syn2}. This difference is allotted to the only process of sequestration, where it is the sum of the net sequestration process Δ_{syn1} (capture of C-CO_2) and of a transfer process (deposition of C eroded: $\Delta_{syn2} - \Delta_{syn1}$), which, a priori, does not have to be considered as a sequestration or desequestration (see next section). In this case, Δ_{syn2} overestimates the C sequestration. Thus, it is necessary to be very careful in this type of approach with the existing risks of erosion for the reference plot. In addition, it is known that the quantities of C likely to be lost by erosion at field scale (from 0 to 1tC $ha^{-1}yr^{-1}$) are of the same order of magnitude as those susceptible to be gained by sequestration (conclusions of the conference Erosion and Sequestration of Carbon, Montpellier, September 2002).

2.3.3 Taking into Account the C (or Equivalent C) Transferred Off-Site

A significant problem rarely taken into account is the transfer of C in solid or soluble form among two adjacent ecosystems as is the case erosion/deposition cycle represented in Figure 2.3 along a toposequence. During the timeframe corresponding to the variations of C stocks on various situation of the toposequence, it may be that part of the observed variations (reduction or increase) that are due to a loss of solid or soluble C by erosion and run-off upstream and by an accumulation downstream. Determination of the sole variations of C stocks at plot level for a specific period does not reflect only variations of C-CO_2 fluxes. The variations due to the transfers of solid or soluble C should not then be considered in the assessment of GHG fluxes. This problem is particularly important for Mediterranean and tropical regions where erosion processes are very frequent, even on very gentle slopes. The conference Erosion and Sequestration of Carbon (Montpellier, September 2002) concluded that the quantities of solid C transferred by water erosion could be of the same order of magnitude, between 0 and 1tC $ha^{-1}yr^{-1}$, and that the amount is likely to be sequestered under the effect of an improving management. Therefore, the real level of C sequestration can be under- or overestimated in absence of measurements or at least estimates of the transfers of solid or soluble C.

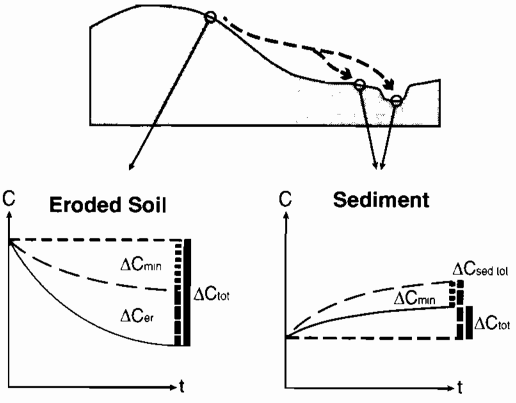

Figure 2.3 Soil C stock variations resulting from lateral transfers (solid or soluble) during Δt. Eroded soil: the decrease ΔCtot corresponds to the sum of the erosion (ΔCer) and mineralization (ΔCmin) processes. Deposit: the increase (ΔCtot) is issued from the difference between the overall sedimentation (ΔCsed.tot) and the mineralization during or after the transportation (ΔCmin).

Another aspect rarely documented is the change, or lack thereof, of the mean residence time (MRT) of the C transferred and deposited. For instance, in the case of eroded and redeposited C (ΔCsed.tot), the changes in term of C MRT throughout the transfer process are: soil aggregate breakdown, detachment of the soil particles from the initial site, transfer by water erosion, and deposition at the bottom of slope or sedimentation in fresh or marine waters. It is known that the breakdown of the soil aggregates tends to increase the potential of mineralization of soil organic C initially protected within the aggregates. Lal reports, in this volume, values of about 30% of additional C mineralized. Those values are to be taken into account in GHG inventories. Furthermore, is the C deposited in the solid form in the alluvium or sediments as stable as that in the original material? There are few data available on this subject.

Considering the scarcity of information relative to the MRT modification of C induced by and during detachment, transport, and deposition, it is prudent not to use C transferred in solid or soluble forms in computing C sequestration balance.

2.3.4 Assessing C Sequestration of the Soil–Plant System for the Emissions Balances at the National Level

The establishment of the GHG inventories, for both industry and agriculture sectors on a national scale, is an important step for the GHG fluxes management at the global scale. Several countries are establishing these inventories according to the guidelines provided by the IPCC (IPCC/UNEP/OECD/IEA, 1997).

The definition of the soil C sequestration, given above, implies all the GHG sources and sinks at plot level. This is, for instance, the case of GHG fluxes from N fertilizers use. It is estimated (IPCC/UNEP/OECD/IEA, 1997) that the application of 100 kg ha^{-1} of N-manure led to the emission of N_2O (a GHG with very high GWP), at an average rate of 1.25 kg ha^{-1} N-N_2O; that is an equivalent of 158 kg ha^{-1} C-CO_2. This 1.25 (±1)% emission rate applied to mineral and organic fertilizers, as suggested by IPCC/UNEP/OECD/IEA (1997), was established from the observation of a relation of proportionality established on a reduced dataset between the intensity of the N_2O emissions and the quantities of N applied to the soil (Bouwman, 1996).

At the plot scale, the GHG balance must consider those fluxes. However, if the results obtained at plot scale are used in national assessments, it is necessary to ascertain that these N_2O emissions are not accounted twice by (1) using only the national fertilizer consumption, and (2) using the extrapolation and generalization of the plot data at national scale. The examples may be extended to other types of contributions (lime, pesticides, etc.). However, any change in the contribution of N fertilizers induced by specific farming practices can result in variations of N_2O emissions by simple modification of the soil properties or modification of quality and quantities of the organic input. That is the case of potential sequestering practices in term of C-CO_2 like no-till practices associated with cover crop plants or agroforestry with leguminous plant integration. In these two cases, there is a significant risk of increased emissions of N-N_2O for this system compared to conventional tillage (Six et al., 2002; Choudhary et al., 2002; Millar et al., 2004), which can completely cancel the beneficial effect of the C-CO_2 capture by the soil. These emissions induced by specific management are not entered elsewhere than at the plot level, and therefore must be generalized at the national scale for a complete balance.

2.4 CONCLUSION

Soil carbon storage is only half of the story: land-use management is not a long-term solution for the global warming in terms of C storage but rather in terms of N_2O and CH_4 mitigation options. Therefore, a definition of soil carbon sequestration or of a sequestrating agroecosystem must address these issues. Due to its large 100-yr GWP, N_2O is perhaps the key point of the C sequestration concept! Most success of agricultural mitigation strategies would be linked to a careful management of the N cycle on the top of the crop cycle. In some cases, N fertilizer may have a positive effect on soil C storage by increasing plant productivity and organic matter restoration. In other situations, N fertilizer may lead to drastic N_2O emissions. If food security has to be insured, the maintenance of yield levels have to be achieved through improved N fertilizer use, and probably a careful management of cover crops. Moreover, the recommended land-use management must be beneficial from a global change standpoint, but also for the agronomic standpoint (erosion control, biodiversity, environmental, etc.), which is commonly achieved with increasing C stocks.

ACKNOWLEDGMENTS

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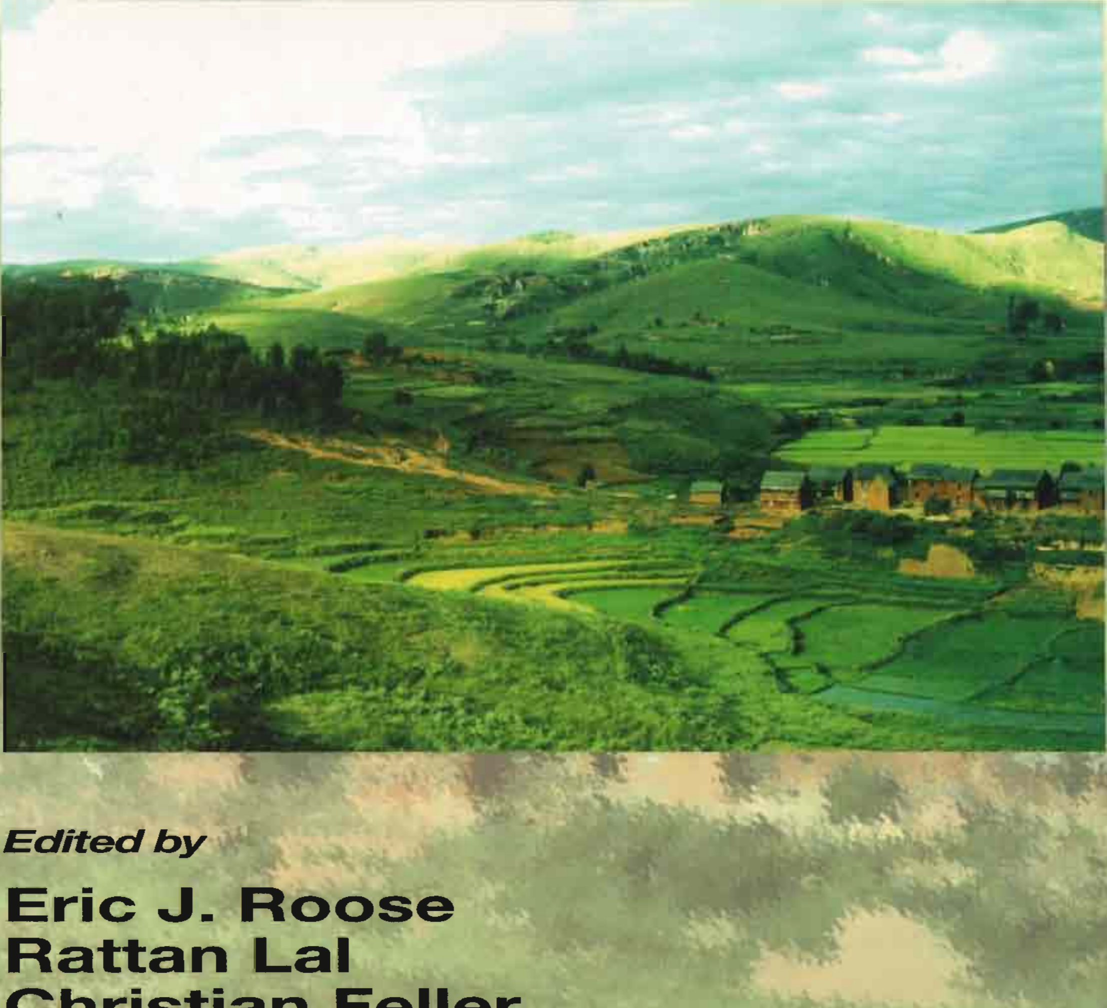

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On the cover: A typical landscape of red ferrallitic soils on the high plateau of central Madagascar near Antananarivo during the rainy season. The hilltop is covered by overgrazed grassland deeply eroded around the cattle trails which join the village and the springs in the valley. The hills lose carbon, nutrients, soil, and water, but might be nourishing the rice paddies below.

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SOIL EROSION AND CARBON DYNAMICS

In addition to depleting nutrients necessary for healthy crops, soil erosion processes can affect the carbon balance of agroecosystems, and thus influence global warming. While the magnitude and severity of soil erosion are well documented, fluxes of eroded carbon are rarely quantified. **Soil Erosion and Carbon Dynamics** brings together a diverse group of papers and data from the perspectives of world-renowned soil scientists, agronomists, and sedimentologists to resolve whether soil erosion on carbon is a beneficial or destructive process.

This book collects quantitative data on eroded organic carbon fluxes from the scale of the agricultural plot to that of large basins and oceans. It quantifies the magnitude of eroded carbon for different soil management practices as compared to normal carbon sequestration and discusses the fate of the eroded carbon and whether or not it is a source or sink for atmospheric CO_2. Finally, the book offers data reflecting the impact of soil erosion on soil, water, and air quality. Other important topics include solubilization, carbon transfer, and sediment deposition, as well as carbon dioxide emissions, global warming potential, and the implications of soil erosion on the global carbon cycle and carbon budget.

Features

- Defines basic concepts and general approaches to the global carbon cycle, carbon sequestration, erosion, and eroded carbon
- Addresses the great debate on "missing" or "fugitive" carbon
- Includes arguments and data that support contrasting viewpoints on the effects of the carbon cycle
- Offers a meaningful look at the impact of soil erosion on the global carbon cycle and the global carbon budget
- Covers solubilization and carbon transfers in rivers and deposition in sediments
- Addresses the impact of soil erosion on crop production systems
- Elucidates the CO_2-to-carbon relationship and organic carbon fluxes

Based on the first symposium of the international colloquium *Land Uses, Erosion and Carbon Sequestration* held in Montpellier, France, **Soil Erosion and Carbon Dynamics** provides data that link soil erosion to the global carbon cycle and elucidates the fate of eroded carbon at scales ranging from plot to watershed.

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