ELSEVIER

Agriculture, Ecosystems and Environment 87 (2001) 111–117

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Short communication

Managing carbon sequestration in soils: concepts and terminology

J.S.I. Ingram [a,*], E.C.M. Fernandes [b]

[a] *Global Change and Terrestrial Ecosystems (GCTE) Focus 3 Office, NERC Centre for Ecology and Hydrology, Crowmarsh Gifford, Maclean Building, Wallingford, Oxon. OX10 8BB, UK*

[b] *Department of Crop and Soil Sciences, Cornell University, 624 Bradfield Hall, Ithaca, NY 14853, USA*

Received 28 March 2000; received in revised form 24 October 2000; accepted 22 November 2000

Abstract

The rapidly growing scientific literature on various aspects of carbon storage in soils has given rise to the introduction of several terms when discussing the amounts of carbon that are, or could be, stored in soils. The term “carbon sequestration potential”, in particular, is used with different meanings, sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage. An attempt is made to clarify some of the main issues by adopting terminology developed in plant physiology and crop modelling research. This, together with examples from the tropics, is used to clarify some of the issues as relating to mineral soils. The term “$\text{Attainable}_{\text{max}}$” is defined and is suggested as the preferred term for carbon sequestration in mineral soils, being more relevant to management than “potential” and thereby of greater practical value.

Keywords: Carbon sequestration; Soil management

1. Introduction

The rapid increase of atmospheric CO_2 in recent decades is well documented and there is now growing concern as this leads to changes in the earth’s climate due to the “enhanced greenhouse effect”. There is consequently a growing demand to reduce atmospheric CO_2 levels by (i) reducing anthropogenic emissions to the atmosphere, and (ii) removing carbon from the atmosphere by sequestration in the biosphere. Paustian et al. (2000) estimate that crop-based agriculture occupies 1.7 billion hectares, globally, with a soil C stock of approximately 170 Pg. The oxidation of soil organic matter in cultivated soils is estimated to have contributed approximately 50 Pg C to the atmosphere. Returning the lost soil carbon via increasing C storage in soils is a clear sequestration possibility (Lal et al., 1998), and the potential increases in soil carbon associated with land-use changes and managed agroecosystems should logically be included in National Greenhouse Gas Inventories under the terms of the UN Framework Convention of Climate Change (IGBP, 1998).

---

[*] Corresponding author. Tel.: +44-1491-692410; fax: +44-1491-692313.
E-mail addresses: jsii@ceh.ac.uk (J.S.I. Ingram), ecf3@cornell.edu (E.C.M. Fernandes).

0167-8809/01/$ – see front matter
PII: S0167-8809(01)00145-1

The conversion of native vegetation to crops or pasture almost invariably results in a depletion of native soil carbon stocks. For example, estimates of the average loss of soil organic carbon (SOC) in the top 1 m within 2–8 years following conversion of native tropical vegetation to agriculture vary from 15 to 40% (Sanchez et al., 1989; Detwiler, 1986; Davidson and Ackerman, 1993; Paustian et al., 2000). For example, in the early 1980s, land use changes were estimated to have resulted in the transfer of between 1 and 2 Pg C yr^{-1} from terrestrial ecosystems to the atmosphere. Between 15 and 17% of this C came from the oxidation of SOC (Houghton et al., 1991; Houghton and Hackler, 1994). The regrowth of vegetation following cropping or the use of no-till systems, and the use of deep rooted, fast-growing tree and grass species (particularly in the tropics) can result in a recovery of SOC to levels approaching and often exceeding that of the forest soil. In temperate systems, simulations indicate that the recovery of SOC levels to near that of pre-cultivation period can be achieved by a combination of reduce tillage and greater inputs of organic matter into the soil system due to use of improved management (Paustian et al., 1998). Estimates of the capacity for C sequestration in agricultural soils globally are in the order of 20–30 Pg C over the next 50–100 years (Paustian et al., 1997).

There is a rapidly growing scientific literature on various aspects of carbon storage in soils: theoretical (Jarvis et al., 1995; Gifford et al., 1996; Batjes and Sombroek, 1997), taxonomic/survey (Eswaran et al., 1993; Batjes, 1996; Gaston et al., 1998), ecological (Cole et al., 1997; Paustian et al., 1998), and management related (Fisher et al., 1994; Davidson et al., 1995; Cole et al., 1997; Paustian et al., 1997; Woomer et al., 2000). Authors have used several terms when discussing the amounts of carbon that are, or could be, stored in soils. The term “carbon sequestration potential”, in particular, is used with different meanings, sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage. This paper identifies some of the main issues involved regarding carbon sequestration in soils by adopting terminology developed in plant physiology and crop modelling research, and applying this, together with examples from the tropics, to clarify some of the issues as relating to mineral soils.

2. Characterising carbon sequestration

In agroecosystem research, it is possible to differentiate three levels of crop production: *Potential*, *Attainable* and *Actual* (Rabbinge and van Ittersum, 1994; van Ittersum and Rabbinge, 1997). Potential yield of a given crop is theoretically possible when there is no edaphic or climatic constraint to growth, and is based on the generalised physiological processes of photosynthesis. This theoretical maximum target cannot, however, be reached in the field because, in addition to climatic constraints, environmental factors (e.g., sub-optimal nutrient and water availability) limit productivity; and practical agriculture can only to some extent overcome these. Management thus sets the level of attainable yield (which can be very close to potential levels where inputs are high and climate is favourable). However, all crops growing in the field are also exposed to “yield reducing” factors such as weeds, pests, disease and sometimes pollution, which further reduces yield from what could have been attainable to an actual level. Where yield-reducing factors are uncontrolled, and hence become severe, actual yield can be a small fraction of potential yield. The difference between potential and actual yield is termed the “yield gap”.

Applying the concepts of “potential”, “attainable” and “actual” to the management of carbon sequestration in soils will help provide a conceptual framework for discussing management considerations; it will also help by providing a broadly applicable terminology. Fig. 1 (adapted from van Ittersum and Rabbinge (1997)) diagrammatically shows three carbon sequestration “situations” plotted against SOC level. The SOC on the *x*-axis is arbitrarily given a half-life of about 10 years to indicate that freshly input organic material is not being considered, although this may be considerable immediately following, e.g., harvest, but of limited sequestration value due to relatively rapid decomposition. This 10-year period also reflects a timescale in line with many management plans. (The important consideration of timescale is discussed below.)

The three sequestration situations shown on the *y*-axis equate to differing amounts of sequestered carbon. The “potential” is defined by factors which set the physico-chemical maximum limit to storage. The “attainable” is set by factors that limit the input of

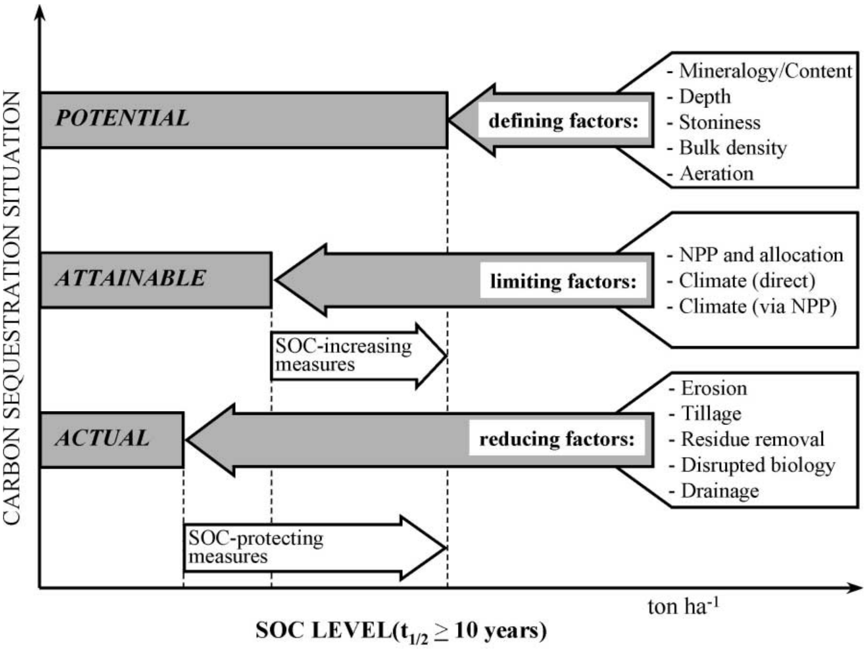

Fig. 1. Carbon sequestration situation against soil organic carbon level (after Rabbinge and van Ittersum (1994)). See text for explanation.

carbon to the soil system. The “actual” is set by factors that reduce carbon storage. These are discussed below.

3. Factors determining carbon storage in soil

3.1. Potential carbon sequestration

Soils have a finite capacity to sequester carbon (Paustian et al., 2000). Finer textured soils generally have higher SOC contents than coarse textured soils when supplied with the same amount of organic inputs. A key factor promoting the stability of SOC is its adsorption to clay and silt particles. The underlying assertion is that, in general, mineral soil has a maximum SOC storage per unit volume determined by the clay and silt ($<20\,\mu m$) content. In a study of temperate and tropical mineral soils to quantify the relationship between soil texture and SOC, and working on the hypothesis that the amounts of carbon that can be associated with clay and silt is limited, Hassink (1997) reported that as the upper limit for the adsorption of organic inputs to clay and silt is reached, adding more organic material to the soil does not lead to increased carbon sequestration. Hassink (1997) observed a close relationship between the proportion of primary particles ($<20\,\mu m$) in the soils and the SOC associated with this fraction in the top 10 cm. The amount of SOC in the $>20\,\mu m$ fraction was not correlated with texture, and cultivation decreased the amount of SOC in the $>20\,\mu m$ fraction more than in the $<20\,\mu m$ fraction indicating SOC associated with the $<20\,\mu m$ is better protected against decomposition.

However, soils with a high clay and silt content may also enable the formation of micro- and macroaggregates which can further protect SOC: once the microaggregates are saturated with organic matter, additional organic matter would be found mainly in the sand-sized macroorganic matter fraction (Carter, 2000), but cultivation would tend to break this down, as evidenced by Hassink (1997). Recent studies in four US soils have also shown that it is important to distinguish between different C fractions and soil aggregates when evaluating C protection in soils. The C fraction associated with fine silt sized particles (2–20 μm) was not significantly affected by tillage and natural abundance ^{13}C analyses showed it to be the oldest C fraction isolated from micro and macroaggregates (Six et al., 2000).

Soil volume (i.e., depth and stoniness) and bulk density are also important when considering SOC levels on an areal basis (Batjes, 1996), as is the soil aeration. The clay mineralogy and depth are essentially fixed and not open to management. While stones can be removed from fields (and have been in some instances, so as to ease tillage operations) and bulk density and texture can be modified by additions of sand (e.g., as was done on a locally significant basis in North Devon, UK last century), widespread modifications of either variable is not practical. This potential sequestration situation equates to the physiological processes that determine potential in crops.

3.2. Attainable carbon sequestration

This is essentially limited by how much carbon is input to the soil system. Net primary productivity (NPP) is the underlying control, and is modified by above-ground vs. below-ground allocation; the more photosynthate entering the soil directly from root systems, the less is available for removal by harvest, grazing, fire, etc. Any management, which increases carbon input (through, e.g., increasing NPP by fertilisation), will tend to increase the attainable level to nearer the potential level. Climate is also significant and has both direct and indirect effects. Decomposition rate increases with temperature, while it decreases with increasingly anaerobic conditions. Indirect climate effects are mediated via vegetation or soil faunal activity.

3.3. Actual carbon sequestration

This is the amount of carbon a soil contains at a given point in time. A huge effort over several decades has gone into developing methods to determine this, mainly on samples collected and prepared for laboratory analysis. A somewhat lesser effort — but still considerable — has gone into estimating SOC levels on areal bases. Five main management-related factors set the actual level (i.e., reduce the attainable level). First, loss of soil material though erosion reduces soil C, soil volume and/or clay content. Second, increased oxidation by, e.g., tillage or increased soil temperature due to removing vegetative cover can rapidly reduce SOC levels. Third, removal of organic residues reduces carbon inputs. Fourth, disruption of the soil biotic processes responsible for the breakdown of organic inputs will reduce the availability of SOC fractions suitable for forming the stable organo-mineral complexes. Fifth, drainage aerates the soil which promotes oxidation of SOC.

4. Management considerations

There is a very real possibility of improving soil management to sequester more carbon. Davidson and Ackerman (1993) reported that, on average, cultivation resulted in a loss between 25 and 30% of SOC with most of the loss occurring in the first 2–5 years. The main C sequestration strategy should, therefore, be directed towards minimising losses (i.e., promoting SOC protecting measures; Fig. 1) and this is fundamental to much of the science of soil conservation. Juo and Lal (1979) reported nearly doubled SOC contents in the top 10 cm in no-till vs. ploughed treatments in an experiment that evaluated soil changes following 6 years of continuous maize (*Zea mays* L.) cropping. They attributed much of the difference to lower erosion under no-till. Certainly improved soil husbandry will go a long way to increasing carbon sequestration, while — not incidentally — providing a more productive and sustainable resource.

The choice of crop or cropping system has a major effect on carbon inputs to the soil. Most agricultural management practices are aimed at increasing crop or pasture productivity and thus, directly increase organic input levels and raise the attainable level. Management to increase NPP has been mentioned above, and in systems which are nutrient-limited, this is a practical option (Lathwell and Grove, 1986; Binkley et al., 1997). It is important to mention that although soil depth is fixed and not easily changed by management, in many soils of the sub-humid and humid tropics, the effective rooting depth is constrained by lack of nutrients or increasing acidity. For example, where native grasses have low productivity, management can help improve carbon inputs by selecting adapted, deep-rooted grass species (Cerri et al., 1991; Fisher et al., 1994). Removal of forest vegetation to plant deep-rooted pasture grasses, however, resulted in massive losses of C from

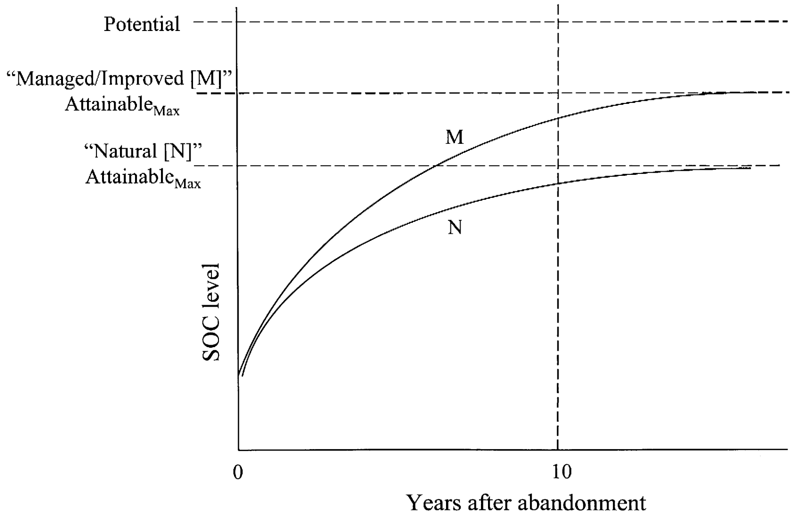

Fig. 2. Influence of management on soil organic carbon level over time. Curves N and M refer to soil carbon accumulation under natural vegetation succession and managed or improved succession. Note both are asymptotic with the maximum attainable levels for respective systems, but neither approaches the potential level.

the forest biomass in one study (Davidson et al., 1995). Agroforestry-based management options involving fast-growing, N-fixing tree species for rehabilitating degraded land (i.e., where SOC levels have seriously declined) are aimed at this, and are diagramatically shown in Fig. 2 (curve M), whereas curve N indicates the "natural" build-up of SOC. Lal et al. (1979) reported that fallows planted with several different species of grasses or legumes increase SOC by between 18 and 30% after 2 years on an eroded Alfisol in Nigeria. Koto-Same et al. (1997) have shown how this can be realised in a West African system, and Woomer et al. (2000) give further very convincing results from a multi-location experiment throughout the tropics. It is helpful, when considering management options, to appreciate whether they are aimed at SOM-increasing or SOM-protecting measures, or both.

5. Timescale

In addition to problems with terminology, there is considerable ambiguity about the timescale over which sequestration is being considered. Literature often indicates an increase in SOC levels for a given management or experimental treatment, and, within the period of measurement, determines which management leads to greater sequestration. Fig. 3 shows how the time interval is critical in determining which management option is "better", and has great bearing on the rapidly developing "industry" of carbon sequestration certification. Management A, e.g., results in more carbon sequestered in the short-term, whereas Management B is "better" in the longer-term. Note both curves are shown to approach (but not to reach) Attainable$_{max}$, which is suggested as the preferred term for carbon sequestration; it is more relevant to management than "potential" and thereby of greater practical value.

For simplicity, discussion has been avoided of carbon fractions and their different susceptibility to stabilisation and decomposition, but the consequence of this on carbon loss and sequestration is clearly important. Inference has, however, been placed on those pools with the longer turnover times, i.e., "slow" and "passive" as defined for the simulation model CENTURY (Parton et al., 1987). The differing turnover times of these pools are accounted for in many SOC turnover models, which provide the only tools with which to estimate the long-term efficacy of different soil carbon sequestration strategies. Research on evaluating and developing methods to objectively quantify the various "conceptual" pools in SOC turnover models should be accelerated (Fernandes et al., 1997).

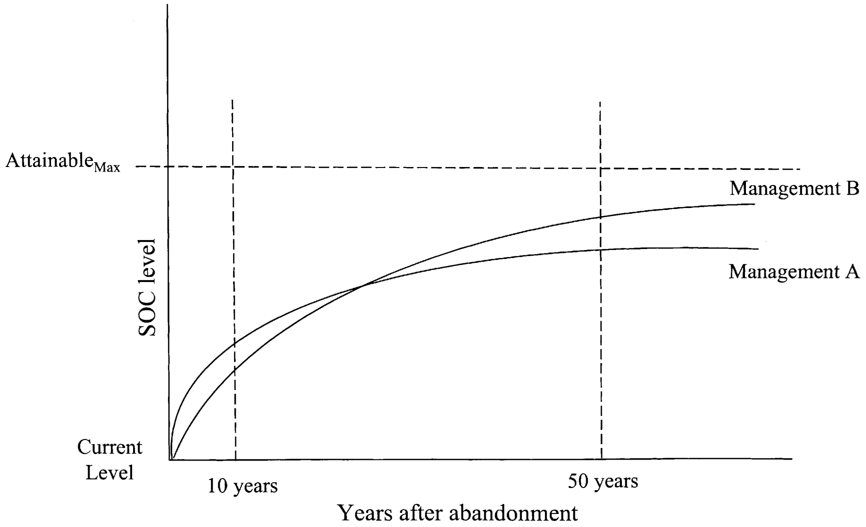

Fig. 3. Influence of timeframe on management considerations for sequestering carbon in soil. Management A results in higher gains relative to Management B in the short-term, but lower in the long-term.

6. Conclusions

An attempt has been made to clarify some of the issues involved in the debate about carbon sequestration in soils, and to offer (and justify) a terminology to avoid misunderstandings. The conceptual framework outlined is robust for many mineral soils but should not be taken too literally. It would not apply, for instance, should the soil system be subject to massive and sustained inputs of organic inputs (e.g., farmyard manure, sewage sludge), where a new “steady-state” SOC level resulting from the balance of inputs to outputs (Andrén and Kätterer, 2000) may be achieved as the soil is changed from “mineral” to “organic”. This situation is, however, unlikely for most arable systems. It is also worth noting that protection of current soil carbon stocks will likely have a far greater impact on carbon fluxes than will targeted sequestration in soil per se: the impact of narrowing the gap between “actual” and “attainable” through improved soil conservation (i.e., minimising losses) will significantly outweigh that of narrowing the gap between “attainable” and “potential”. The fossil fuel requirements for the increased productivity and contribution of C to the soil in managed systems must also be accounted for in the C flux and sequestration calculations.

Finally, although the discussion above is directed toward the soil system, from a sequestration point of view the critical aspect is “total system carbon” (cf. Davidson et al., 1995; Koto-Same et al., 1997). Effective management must consider both above and below ground compartments.

Acknowledgements

The authors acknowledge valuable comments on an earlier version of the manuscript by Olof Andrén and Martin Carter.

References

Andrén, O., Kätterer, T., 2000. Basic principles for carbon sequestration and calculating dynamic country-level balances including future scenarios. In: Lal, et al. (Eds.), Methods for Soil Carbon Sequestration. CRC Press, Boca Raton, FL.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47 (2), 151–163.

Batjes, N.H., Sombroek, W.G., 1997. Possibilities for carbon sequestration in tropical and subtropical soils. Global Change Biol. 3 (2), 161–173.

Binkley, D., O'Connell, A.M., Sankaran, K.V., 1997. Management of soil, nutrients and water in tropical plantation forests. In: Nambiar, E.K.S., Brown, A.G. (Eds.), Stand Development and Productivity. Australian Centre for International Agricultural Research (ACIAR), pp. 419–442.

Carter, M.R., 2000. Organic matter and sustainability. In: Sustainable Management of Soil Organic Matter. CAB International, Oxford, UK.

Cerri, C.C., Volkov, B., Andreaux, F., 1991. Nature and behaviour of organic matter in soils under natural forest, and after deforestation, burning and cultivation, near Manaus. For. Ecol. Mgmt. 38, 247–257.

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., Zhao, Q., 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr. Cycl. Agroecosyst. 49, 221–228.

Davidson, E.A., Ackerman, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20, 161–193.

Davidson, E.A., Nepstad, D.C., Klink, C., Trumbore, S.E., 1995. Pasture soils as carbon sink. Nature 376, 472–473.

Detwiler, R.P., 1986. Land use change and the global carbon cycle: the role of tropical soils. Biogeochemistry 2, 67–93.

Eswaran, H., Berg, E., van den Reich, P., 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57, 192–194.

Fernandes, E.C.M., Motavalli, P., Castilla, C., Mukurumbira, L., 1997. Management control of soil organic matter dynamics in tropical land-use systems. Geoderma 79, 49–67.

Fisher, M.J., Rao, M.I., Ayarza, M.A., Lascano, C.E., Sanz, J.I., Thomas, R.J., Vera, R.R., 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371, 236–238.

Gaston, G., Brown, S., Lorenzini, M., Singh, K.D., 1998. State and change in carbon pools in the forests of tropical Africa. Global Change Biol. 4, 97–114.

Gifford, R.M., Lutze, J.L., Barrett, D., 1996. Global atmospheric change effects on terrestrial carbon sequestration: exploration with a global C- and N-cycle model (CQUESTN). Plant and Soil 187, 369–387.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil 191, 77–87.

Houghton, R.A., Hackler, J.L., 1994. The net fux of carbon from deforestation and degradation in South and Southeast Asia. In: Dale, V. (Ed.), Effects of Land-use Change on Atmospheric CO_2 Concentrations: South and Southeast Asia as a Case Study. Springer, New York, pp. 301–327.

Houghton, R.A., Skole, D.L., Lefkowitz, D.S., 1991. Changes in the landscape of Latin America between 1850 and 1985. II. Net release of CO_2 to the atmosphere. For. Ecol. Mgmt. 38, 173–199.

IGBP Terrestrial Carbon Working Group, 1998. The terrestrial carbon cycle: implications for the Kyoto protocol. Science 280, 1393–1394.

Jarvis, P.G., Grace, J., Moncrieff, J.B., Massheder, J.M., Malhi, Y., Rayment, M., Meir, P., 1995. Looking for the missing carbon sink in tropical and boreal forests. In: Mathis, P. (Ed.), Photosynthesis: From Light to Biosphere, Vol. V. Proceedings of the 10th International Photosynthesis Congress, Montpellier, France, August 20–25, 1995. Kluwer Academic Publishers, Dordrecht, pp. 773–778.

Juo, A.S.R., Lal, R., 1979. Nutrient profile in a tropical Alfisol under conventional and no-till systems. Soil Sci. 127, 168–713.

Koto-Same, J., Woomer, P.L., Appolinaire, M., Louis, Z., 1997. Carbon dynamics in slash-and-burn agriculture and land use alternatives of the humid forest zone in Cameroon. Agric. Ecosyst. Environ. 65, 245–256.

Lal, R., Wilson, G.F., Okigbo, B.N., 1979. Changes in properties of an Alfisol produced by various crop covers. Soil Sci. 127 (6), 377–382.

Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), 1998. Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, 609 pp.

Lathwell, D.J., Grove, T.L., 1986. Soil–plant relationships in the tropics. Ann. Rev. Ecol. Syst. 17, 1–16.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D., 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. Soil Sci. Soc. Am. J. 51, 1173–1179.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Mgmt. 13 (Suppl. 4), 230–244.

Paustian, K., Elliott, E.T., Killian, K., 1998. Modeling soil carbon in relation to management and climate change in some agroecosystems in central North America. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 459–471.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48 (1), 147–163.

Rabbinge, R., van Ittersum, M.K., 1994. Tension between aggregation levels. In: Fresco, L.O., Stroosnijder, L., Bouma, J., van Keulen, H. (Eds.), The Future of the Land: Mobilising and Integrating Knowledge from Land Use Options. Wiley, Chichester, UK.

Sanchez, P.A., Palm, C.A., Szott, L.T., Cuevas, E., Lal, R., 1989. Organic input management in tropical agroecosystems. In: Coleman, D.C., Oades, J.M., Uehara, G. (Eds.), Dynamics of Soil Organic Matter in Tropical Ecosystems. University of Hawaii Press, Honolulu, Hawaii, pp. 125–152.

Six, J., Merckx, R., Kimpe, K., Paustian, K., Elliott, E.T., 2000. A re-evaluation of the enriched labile soil organic matter fraction. Eur. J. Soil Sci. 51 (2), 283–293.

van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input–output combinations. Field Crops Res. 52, 197–208.

Woomer, P.L., Palm, C.A., Alegre, J., Castilla, C., Cordeiro, D.G., Hairaah, K., Kotto-Same, J., Moukam, A., Riese, A., Rodrigues, V., van Noordwijk, M., 2000. Slash and burn effects on carbon stocks in the humid tropics. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.), Global Climate Change and Tropical Ecosystems. CRC Press, Boca Raton, FL, pp. 99–115.