



AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

African Association of Agricultural Economists. *Shaping the Future of African Agriculture for Development: The Role of Social Scientists.* Proceedings of the Inaugural Symposium, 6 to 8 December 2004, Grand Regency Hotel, Nairobi, Kenya

Payments for Environmental Services under Emerging International Agreements: A Basis for Inclusion of Agricultural Soil Carbon Sinks

Michael M. Odera¹ and Stephen K. Kimani

Michael M. Odera, Kenya Agricultural Research Institute (KARI), Muguga South Research Center
P.O. Box 30148-00100, Nairobi – Kenya, Tel: 254-66-32881-4,
Cell Phone: 254-722-328563/254-733-685808, E-mail: mikemako67@yahoo.com

Abstract: This review places in context the role agricultural soils play in global carbon dynamics, and their potential interaction with climate change through soil carbon sequestration. The paper first examines the potential of soils as carbon sinks, agricultural practices and dynamics in soil organic carbon, emerging agreements on payments for environmental services (PES) that mitigate global warming through enhanced carbon sinks, exclusion of agricultural activities in PES under Kyoto Protocol, and the basis for inclusion of agricultural soil carbon sinks through sustainability based production systems. Soils are one of the planet's largest sinks for carbon and hold potential for expanded carbon sequestration through changes in management. The global soil organic carbon (SOC) inventory is estimated to be 1200-1600 billion metric tonnes, which is equal to or slightly greater than amounts stored in terrestrial vegetation (500-700 billion metric tonnes) and the atmosphere (750 billion metric tonnes), combined. Agricultural soils, having been depleted of much of their native carbon stocks, and occupying an estimated 1.7 billion hectares, have a more significant potential SOC sink capacity. Global estimates of this sink capacity are in the order of 20-30 billion metric tonnes over the next 50-100 years. The total global agricultural soils' SOC stocks are estimated at 167-170 billion metric tonnes. When soil is put into cultivation, associated biological and physical processes result in a release of SOC over time, often 50% or more, depending on soil conditions and agricultural practices. Consequently, there is potential to increase SOC in most cultivated soils. Many management practices have been demonstrated to increase SOC, including incorporation of crop residues, and increases in cropping intensity and fertilization. Past and on-going biophysical studies have been able to identify and demonstrate organic based soil fertility management practices, with modest applications of mineral fertilizers that would concurrently lead to improvement in SOC levels, nutrient loss amelioration and improved agricultural productivity. Management practices that could add 4 T C ha⁻¹ yr⁻¹ in the system have been demonstrated. Due to the potential impacts of climate change on the environment as a result of increasing concentration of GHGs in the atmosphere, particularly carbon dioxide, the world community established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The responsibility of IPCC is to undertake an assessment of the science, impacts, adaptation, and mitigation options in relation to climate change and advise the Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC). At the sixth Conference of the Parties (COP-6) in Marrakech, Morocco, limits were placed on the nature of activities that could be undertaken and the amount of carbon credits that could be generated through land use change and forestry activities to benefit from PES. These limits excluded all activities associated with management of natural forests and agricultural lands. This review argues that a demonstration of sustainability of carbon sinks in agricultural soils under empirically derived predictable management practices could serve as a basis for arguing the case for inclusion of carbon sinks in such systems in payments for environmental services under the Clean Development (CDM) of Kyoto Protocol.

1. Introduction

Global warming and associated climate change are pressing concerns that affect the future of humanity. Majority of the greenhouse gas emissions responsible for global warming result from burning fossil fuel; inefficient industrial processes, and; land use change, particularly deforestation and soil degradation (Noble and Scholes, 2001). Under the already ratified international agreements on mitigation of global warming,

smallholder farmers in agricultural production systems of the developing economies are best placed to benefit in terms of payments for environment services (PES) under the Clean Development Mechanism (CDM) of the Kyoto Protocol. Although at the sixth Conference of the Parties (COP-6) in Marrakech, Morocco, limits were placed on the nature of activities that could be undertaken and the amount of carbon credits that could be generated through land use change and forestry activities that excluded all activities associated with management of natural forests and agricultural lands and considered only those activities that could be characterized as reforestation or afforestation as eligible for the first commitment period (2008-2012) of the Kyoto Protocol, it is extremely unlikely that agricultural lands will be returned to forests in the foreseeable future. In order for the emerging international agreements on payments for environmental services to be of any benefit to the majority smallholder producers in the developing countries, it is necessary that conditions for certification of carbon reduction be lessened so that the large quantity of carbon that sequestered in such systems as demonstrated below should benefit from such international agreements.

In this review, we place in context the role of agricultural soils in mitigation of global warming through carbon sequestration. In part 2 we review the current understanding of soil carbon sequestration. In part 3 we examine greenhouse gas emissions and emerging international agreements. In part 4 we review soil carbon sequestration in agricultural production and argue out the basis for inclusion of such carbon sinks in payments for environmental services. In part 5 we conclude the review.

2. Current Understanding of Soil Carbon Sequestration

The atmosphere in 1994 held about 750 billion tones of C as CO₂ corresponding to an average concentration of 358 parts per million by volume (ppmv) (Metting et al, 1998). During the past decade atmospheric CO₂ concentration has been increasing at about 1.6 ppmv per year. The storage of carbon on land is partitioned between soil and vegetation. On global scale, soils contain more than 75% of all terrestrial carbon stocks, although their contribution to the total varies with latitude and land use (Malhi, et al., 2002). Forests and wooded grasslands/savannahs are by far the biggest carbon storehouses, respectively accounting for 47% and 25% of global total terrestrial carbon. Soils are important both as a source and sink of carbon. Global terrestrial photosynthetic C fixation is estimated to be about 120 billion tones of C yr⁻¹, at least nearly half of which ends up in below ground root and soil components (Oades, 1988). The total amount of stored C in terrestrial ecosystems is about 2,000 billion tones. With global stock of about 1,500 billion tones (~1393 billion tones, Post et al., 1982; ~1576 billion tones, Kimble et al., 1990) of soil organic carbon (SOC), soils hold 2.1 times as much carbon as the atmosphere. Estimates of soil inorganic carbon (SIC) are less accurate although global stocks are estimated to be about 12% larger than SOC (Schlesinger, 1997). SOC is allocated over time to different “pools” as a consequence of root growth and subsequent decomposition, litter fall and decomposition, microbial degradation and synthesis, mixing by soil fauna, and moisture and temperature cycles. The pools are variously defined on the basis of relative recalcitrance, which in turn, governs residence and turnover times. Eswaran et al, (1993) defines four pools based on C dynamics: *active or labile pool* of readily oxidized compounds. Factors controlling the formation and dynamics of this pool include plant residue inputs and climate. Agronomic management practices also affect the size of this pool; *slowly oxidized pool* associated with soil macroaggregates. The factors controlling this pool are soil physical properties, including mineralogy and aggregation. Agronomic practices also affect the size of this pool; *very slowly oxidized pool* associated with soil microaggregates. The controlling factor for this pool is water stability of the aggregates. Agronomic practices have little effect on this pool, and; *passive (recalcitrant) pool* where clay mineralogy is the controlling factor for the carbon pool. Agronomic practices have little effect on this pool. Carbon residence times range from days for labile pool to decades and centuries for very slowly oxidized and passive pools. The soil active fraction comprises the soil microbiota plus labile pool of C. The fraction typically constitutes 2 to 5% of the total C of surface soils and decreases exponentially with depth. Soil texture and structure also influence sequestration and allocation of C. The texture refers to the size distribution of primary mineral constituents – sand, silt and clay. Studies with many soils have shown that SOC preferentially adsorbs to clays (Metting et al, 1998). Clay-associated SOC is generally more recalcitrant. Structure refers to three dimensional aggregate properties of soil. A number of factors influence soil structure including climate, parent materials, and microbial activity (Lynch and Bragg, 1985). It is generally thought that soils have finite C

carrying capacity, dictated ultimately by the interactive temperature and moisture components of the climate. In theory, when the ecosystem is supporting climax plant communities, the annual net primary productivity (NPP) is balanced by decomposition of residues and soil organic matter (SOM), and the system is considered to be in C equilibrium. At the soil will be at its maximum native carrying capacity for C. However, for managed ecosystems, it is possible to increase the soil carrying capacity for C through species selection or by altering microclimate via nutrient and water management. Two principal approaches for increasing soil carbon sequestration are through increasing productivity on crop and forest land and, residue management through judicious incorporation of residue into the soil. Given that most of the required technology is in place today, the full soil carbon sequestration potential of managed systems could be achieved with modest economic incentives.

IPCC estimate that over the next 50 to 100 years, agricultural lands and other managed ecosystems have the potential to remove anywhere between 40 to 80 billion metric tonnes of carbon from the atmosphere. ICRAF (2001) estimates that C sequestration from agroforestry activities in the tropics could sequester on the order of 400 Million t C yr⁻¹ by 2010. In the socio-economic and policy set-up of the Sub-Saharan tropical countries, agriculture offers comparative advantage in carbon offsets compared to other land use systems such as forestry.

Judicious management of soils and adoption of appropriate farming/cropping systems can make soils an important sink for carbon, and soils and cropping systems can be effective tools to mitigate the radiative forcing of other non-agricultural activities (Lal, *et al.*, 1998). Grassland and forest soils tend to lose from 20 to 50% of the original SOC content in the zone of cultivation within the first 40 to 50 years of cultivation (Campbell and Souster, 1982; Tiessen *et al.*, 1982; Mann, 1985; 1986; Schimel, 1986; Johnson and Kern, 1991; Rasmussen and Parton, 1994; Houghton, 1995). In tropical ecosystems, the surface horizon of the soils contains 20-30 g SOC kg⁻¹ under native vegetation (Moorman *et al.*, 1975; Sanchez, *et al.*, 1982). However, continuous cropping with plough-based methods of seedbed preparation causes a rapid decline in SOC content to as low as 5-10 g kg⁻¹ for the plough layer within 5 to 10 years of cultivation (Lal, 1989; Feller *et al.*, 1996). This rate of decline of SOC is, however, significantly lower with use of management practices such as minimum tillage, mulch/residue farming, and/or agroforestry practices than with plough based systems and continuous annual crop monoculture (Paustian *et al.*, 1997a). The use of improved (planted) fallows and cover crops within cropping systems and woody species in agroforestry systems, have proved efficient in increasing SOC content, improving aggregation and soil fertility, and are considered among the most sustainable types of system for humid tropics (Lal, *et al.*, 1979; Wilson, *et al.*, 1982; and Gouyon, *et al.*, 1993). Mixing of organic resources of diverse qualities, harvested *in situ* from cereal-legume intercrops/rotations, combined with cattle manures plus, addition of modest fertilizer N (30kg N ha⁻¹ during the cereal phase) can be integrated with appropriate crop residue management techniques to reverse soil fertility management while at the same time enhancing SOC (Kinyangi, 2002). Kinyangi, (2002), for instance, has demonstrated that organic based soil fertility management practices involving fertilized, manured, cereal-legume rotation land use system (LUS) with appropriate crop residue management practices, is able to achieve an average yield of 3-4 T ha⁻¹ season⁻¹ of maize stover, 3-4 T ha⁻¹ of leaf/litter of *Tephrosia*, and 1.5 T ha⁻¹ season⁻¹ of soybean trash. This when combined with an application of 4 T ha⁻¹ yr⁻¹ of manure would result in C input that approach or exceed 4 T C ha⁻¹ yr⁻¹, which translates into 10 T DM ha⁻¹ yr⁻¹ that is comparable to annual C input in unmanaged forest ecosystems. Woomer *et al.*, (1997) has described a set of land use changes in East African highlands including conversion of annual monoculture crop lands to agroforestry, orchards or woodlots; establishing live fences along farm boundaries; planting drought tolerant relay fallows at the end of the rains; employing better manure collection, storage and application strategies; and retaining low-quality crop residues as litter and soil organic inputs, which when practiced continuously over two decades could result in a gain of 66 t C ha⁻¹, improve yields of food crops and diversify farm enterprises.

Soils are one of the planet's largest sinks for carbon and hold potential for expanded carbon sequestration through changes in management (Marland *et al.*, 1998). The global soil organic carbon (SOC) inventory is estimated to be 1200-1600 billion metric tonnes, which is equal to or slightly greater than amounts stored in terrestrial vegetation (500-700 billion metric tonnes) and the atmosphere (750 billion metric tonnes), combined (Post *et al.*, 1990; Sundquist, 1993). Agricultural soils, having been depleted of much of their native carbon stocks, and occupying an estimated 1.7 billion hectares, have a more significant SOC sink capacity. Global estimates of this sink capacity are in the order of 20-30 billion metric tonnes over the next

50-100 years (Paustian, *et al.*, 1997b). The total global agricultural soils' C stocks are estimated at 167-170 billion metric tonnes (Paustian *et al.*, 2000; Post *et al.*, 1982; Bouwman, 1990; and Sombroek *et al.*, 1993).

Soil science has established that there is a steady state level or saturation point for soil C that can be stored in soil for a given soil type, climate, and set of management practices (Watson *et al.*, 2000; West *et al.*, 2000). In addition, soil research has shown that sequestered carbon is "volatile" and it has been found that if practices sequestering soil C are discontinued the C stored in the soil can be released back into the atmosphere in a short period of time. For instance, if a farmer practicing reduced tillage reverts to conventional ploughing, the accumulated soil C may be released over a few years, and the soil C level can return to the level before the reduced tillage was adopted. One way to address the permanence issue is to view farmers who enter into soil C contracts as providing a "service" in the form of accumulating and storing soil C. During the time period in which C is being accumulated, the farmer is providing both accumulation and storage services. Once the soil C reaches the saturation point, the farmer is providing only storage services. The issues of saturation and permanence, with regard to soil C, show that contract between buyers and sellers of environmental services are different from contracts for conventional agricultural commodities. The buyer never actually takes delivery of the commodity; rather the commodity is stored in the soil that belongs to the land owner. In essence it is more accurate to describe the farmer as providing a service for a specified period of time.

3. Greenhouse Gases (GHGs) Emissions Mitigation and Emerging International Agreements

Carbon in the form of carbon dioxide (CO₂) is currently accumulating in the atmosphere at rate of 3.4 billion metric tones per annum (Rosenberg *et al.*, 1998), as a result of fossil fuel combustion, tropical deforestation and other land-use changes. In Africa alone, International Energy Agency (IEA) (2001) estimates that the three main energy sources, namely coal, oil and gas emits 800 million tons of CO₂ equivalent per year. Carbon dioxide is the one causing the greatest concern on account of its abundance and long life-span (up to 100 years in the atmosphere before disintegration), and alarming rate at which its concentration is increasing among the greenhouse gases (GHGs), so called because they let through short wavelength solar radiation to heat the earth's surface while they trap the out-going long wavelength terrestrial radiation, thus raising the temperature of the atmosphere with potential for significant changes in the climate. Other commonly found GHGs in the atmosphere are methane (NH₄), and nitrous oxide (N₂O).

Due to the potential impacts of climate change on the environment as a result of increasing concentration of GHGs in the atmosphere, the world community established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The responsibility of IPCC is to undertake an assessment of the science, impacts, adaptation, and mitigation options in relation to climate change and advise the Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of UNFCCC as cited in article 2 is "*to achieve stabilization of green house gas concentrations in the atmosphere to a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*". Kenya ratified the UNFCCC in 1994. The convention came into force at the first Session of the Conference of Parties (COP 1) held in Berlin in 1995 after it was ratified by 150 countries. On ratification of the convention, it was recognized that the general commitments were not adequate in terms of targets and time-frame for achieving them. In recognition of this, the Kyoto protocol was signed at the Third Conference of Parties (COP 3) to the UNFCCC in 1997 in Kyoto, Japan. The protocols main features include: (i) the Clean Development Mechanism (CDM), which allows for creation of Certified Emission Reductions (CERs) through investment in non-Annex I Parties (mainly developing countries); (ii) Joint Implementation (JI), which involves the creation of emission reduction units derived from investment between Annex I Parties; (iii) International Emission Trading (IET) system, which allows a country that exceeds its emission reduction target to sell the excess to one that has not achieves its target, through international transfer of national allotments of emission permits; (iv) placement of a provision binding agreement by industrialized countries to reduce greenhouse gas emissions to 1990 CO₂ or equivalent levels; (v) establishment of strict measures for carbon inventory, reporting, and registry of

offsets; (vi) enacting a compliance regime with distinct branches for facilitation and enforcement, as well as putting together punitive measures for non-compliance; (vii) controlled use of forests and agricultural sinks to meet commitments; and (viii) enhancing flows of finance and technology transfer to developing countries for capacity building on climate change mitigation and adaptation

Of the key provisions in the Kyoto Protocol, the Clean Development Mechanism is the most relevant to the interests of the developing world, particularly African countries. This is mainly because CDM was designed to favour the transfer of clean energy technologies to developing countries and thus, restrict their emissions within environmentally sustainable ranges. The CDM enables voluntary participation of African countries (which have no commitment or specified targets for reducing greenhouse gases under the protocol), and therefore offers new sources for financing sustainable development and poverty reduction in the developing countries. ICRAF (2001) estimates that C sequestration from agroforestry activities in the tropics could sequester on the order of 400 Million t C yr⁻¹ by 2010. Using the low-end estimates of US\$20 to US\$30 to be paid per ton of sequestered carbon under the carbon emission offset credit schemes as provided for under the Clean CDM, farmers in the tropics have the potential of adding US\$12 to US\$16 billion of gross income to farm economies per year through uptake and participation in carbon sequestering management practices.

At the sixth Conference of the Parties (COP-6) in Marrakech, Morocco, limits were placed on the nature of activities that could be undertaken and the amount of carbon credits that could be generated through land use change and forestry activities. These limits excluded all activities associated with management of natural forests and agricultural lands. Only activities that could be characterized as reforestation or afforestation were deemed eligible for the first commitment period (2008-2012) of the Kyoto Protocol. At the recent ninth Conference of Parties (COP-9) meeting in Milan, Italy, the rules for reforestation and afforestation projects under the CDM were finalized. For instance, under UNFCCC decision 19 of COP-9, the small scale afforestation and reforestation project activities under the CDM are those that are expected to result in net anthropogenic GHG removals by sinks of less than 8000 tones of CO₂ equivalent (CO₂e) per year and are developed or implemented by low-income communities and individuals as determined by host party. In instances where small-scale reforestation and afforestation project activity under CDM results in net anthropogenic greenhouse gas removals by sinks greater than 8000 tones of CO₂ equivalent per year, the excess removal will not be eligible for issuance of Certified Emissions Reductions (CERs). The rules also specify how projects are to set baselines, treat off-site impacts, and show that they are truly having additional impacts on atmosphere over and above what would have happened without CDM.

4. Soil Carbon Sequestration in Agricultural Production Systems as basis for Inclusion of Agricultural Soil Carbon Sinks in PES

Empirical research has adequately demonstrated the inherent potential of agricultural soils as carbon sinks and thus, their role in GHGs emissions mitigation: theoretical (Jarvis et al., 1995; Gifford et al., 1996; Batjes and Sombroek, 1997), 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 1997a; Woomer et al., 2000). Paustian *et al.*, (2000) estimate that crop-based agriculture occupies 1.7 billion hectares, globally, with a soil C stock of approximately 170 billion metric tons. The oxidation of soil organic matter in cultivated soils is estimated to have contributed approximately 50 billion metric tons of C to the atmosphere (Ingram and Fernandes, 2001). Returning the lost soil carbon via increasing C storage in the 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 Green House Gas Inventories under the terms of UNFCCC (IGBP, 1998). Estimates of the capacity for C sequestration globally are in order of 20-30 billion metric tons C over the next 50-100 years (Paustian et al., 1997c). Despite the demonstrated evidence for carbon sequestration of agricultural systems, soil carbon sinks have not been included in the retinue of those activities that qualify for carbon credit generated through land use change and forestry activities. This is mainly due to two main constraining factors. First one is the perceived difficulties in carbon measurements. It is assumed that carbon fixation in agriculture and forestry projects are accomplished in soil in many areas of the world. Measurements of carbon stocks at large scales required for CDM project is assumed to be difficult, however this paper argues that is possible with remote sensing using aerial photos, satellite imagery and employment of geographical information system (GIS).

The second factor concerns permanence of carbon in agricultural systems. This paper argues strongly that it is lack of empirically based understanding of sustainability of carbon sequestering best management practices that has created the constraint associated with permanence of carbon sinks in agricultural systems. In the developed countries of western Europe and north America, where profitability is the main determinant of land use systems and land use changes, a number of studies have been conducted and estimates of soil carbon sinks, documented over space and time (Antle, and Capalbo, 2001; Antle and McCarl, 2001; Antle et.al., 2001a; Antle et al., 2001b; Antle et al., 2001c; West et al., 2000; and CAST, 2000). However, in smallholder production systems of Africa, and particularly in the Sub-Saharan Africa (SSA), where subsistence production dominates most of the agricultural production systems, use of emerging sustainability based modeling approaches such as Tradeoffs Model Analysis (TOA), that integrates bio-physical and socio-economic components of the production systems, could make it possible to determine the permanence of carbon sinks in the subsistence based production systems. This paper argues that there is a strong case for inclusion of carbon sinks in agricultural systems in activities that qualify for the payments for environmental services under the Kyoto protocol. The existing knowledge on modeling and simulation is adequate to provide the required carbon estimates in varying production environments over spatial and temporal scales.

5. Conclusion

An attempt has been made to document evidence of soil carbon sequestration in agricultural production systems. The conceptual framework outlined is robust for C sequestration in both commercial-oriented and subsistence based agricultural systems. The carbon sequestered in agricultural systems should not be locked out of payments for environmental services under the guise of difficult in measurement and issues relating to permanence of carbon sinks. Emerging advances in modeling and technological options for remote based measurement of carbon sinks makes it possible to measure the carbon sequestered and estimate the future dynamics in systems' carbon sink. This can form a basis for inclusion of such sinks in payments for environmental services for the benefit of majority smallholder producers in developing countries.

References

- Antle, J.M., and S.M. Capalbo (2001). "Econometric Process Models for Integrated Assessment of Agricultural Production Systems". *American Journal of Agricultural Economics* **83**(2): 389-401
- Antle, J.M., and B.A. McCarl (2001). "The Economics of Carbon Sequestration in Agricultural Soils". T. Tietenberg and H. Folmer, eds., *International Year Book of Environmental and Resource Economics*, Volume VI, Edward Elgar Publishers
- Antle, J., and Mooney, S., (2001). Designing efficient policies for agricultural soil carbon sequestration. Preliminary version of a chapter published in *Agriculture Practices and Policies for Carbon Sequestration in Soils*, J. Kimble, editor, CRC Press LLC, Boca Raton, FL, pp. 323-336
- Antle, J.M., S.M. Calbo, S.Mooney, E.T. Elliot, and K.H. Pautian (2001a). "Economic Analysis of Agricultural Soils Carbon Sequestration: An Integrated Assessment Approach". *Journal of Agriculture and Resource Economics*, in press
- Antle, J.M., S.M. Calbo, S.Mooney, E.T. Elliot, and K.H. Pautian (2001b). "Spatial Heterogeneity, Contract Design and Efficiency of Carbon Sequestration Policies for Agriculture". Unpublished Manuscript.
- Antle, J.M., S.M. Capalbo, S.Mooney, E.T. Elliot, and K.H. Pautian (2001c). "A comparative analysis of efficiency of sequestering carbon in US agricultural soils". *American Journal of Alternative Agriculture*, in press
- Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* **47**(2): 151-163
- Batjes, N.H., and Sombroek, W.G., 1997. Possibilities for carbon sequestration in tropical and subtropical soils. *Global Change Biology* **3**(2): 161-173

- Bouwman, A.F., 1990. Global Distribution of the major soils and land cover types. In: *Soils and the greenhouse effects* (ed: A.F. Bouwman), John Wiley and Sons, Ltd, pp. 33-59.
- Campbell, C.A., and Souster, W., 1982. Loss of organic matter and potentially mineralizable N from Saskatchewan soils due to cropping. *Can. Journ. Soil Sci.* **62**:651-656
- CAST (Council for Agricultural Science and Technology) (2000). Storing Carbon in Agricultural Soils to Help Mitigate Global Warming, Issue Paper No. 14, Ames, IA.
- Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., and Zhao, Q., 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient Cycling and Agroecosystems* **49**: 221-228
- Davidson, E.A., and Ackermann, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* **20**:, 161-164
- Eswaran, H., Berge, E., and van den Reich, P., 1993. Organic carbon in soils of the world. *Soil Science Society of America Journal* **57**: 192-194
- Feller, C., Albrecht, A., and Tessier, D., 1996. Aggregation and organic matter storage in Kaolinitic and Smectitic tropical soils. In: *Structures and Organic Matter Storage in Agricultural Soils. Advances in Soil Science* (eds: MR Carter and B.A. Stewart), CRS Lewis Publishers, Boca Raton, Florida, pp. 309-360.
- Fisher, M.J., Rao, M.I., Ayarza, M.A., Lascano, C.E., Thomas, R.J., and Vera, R.R., 1994. Carbon storage by introduced deep-rooted grasses in South America savannas. *Nature* **371**: 236-238
- Gaston, G., Brown, S., Lorenzini, M., and Singh, K.D., 1998. State and change in carbon pools in forests of tropical Africa. *Global Change Biology* **4**: 97-114
- Gifford, R.M., Lutze, J.L., and Barrett, D., 1996. Global atmospheric change effects on terrestrial carbon sequestration: exploration with global C- and N-cycle model (CQUESTN). *Plant and Soil* **187**: 369-387
- Gouyon, A., De Foresta, H., and Levang, P., 1993. Does Jungle Rubber deserve its name? An analysis of rubber agroforestry systems in southeast Sumatra. *Agroforestry Systems* **22**:181-206
- Houghton, R.A., 1995. Changes in storage of terrestrial carbon since 1850. In R. Lal, J. Kimble, E. Levine and B.A. Stewart (eds) "Soils and Global Change". CRC/Lewis Publishers, Boca Raton, FL.
- CRAF, (2001). Tackling the Carbon Question. Future Harvest. International Centre for Research in Agroforestry, Nairobi, Kenya.
- International Energy Agency (IEA), 2001. *World Energy Outlook*, Paris, France
- IGBP Terrestrial carbon Working Group, (1998). The Terrestrial Carbon Cycle: Implications for the Kyoto Protocol. *Science* **280**: 1393-1394
- Ingram, J.S.I., and Fernandes, E.C.M., (2001). Managing Carbon Sequestration in Soils: Concepts and Terminology. *Agricultural Ecosystems and Environment* **87**:111-117
- Jarvis, P.G., Grace, J., Moncrieff, J.B., Massheder, J.M., Malhi, Y., Raymet, M., and Meir, P., 1995. Looking for the missing carbon sink in tropical and boreal forests. In: P.Mathis, (ed.), *Photosynthesis: From Light to Biosphere, Volume V. Proceedings of 10th International Photosynthesis Congress*, Montpellier, France. Kluwer Academic Publishers, Dordrecht, pp. 773-778
- Johnson, M.G., and Kern, J.S., 1991. Sequestering C in Soils: A workshop to explore the potential for mitigating global climate change. USEPA Rep. 600/3-91-031. USEPA Environmental Res. Lab., Corvallis, OR.
- Kimble, J.M., Eswaran, H., and Cook, T., 1990. Organic carbon on a volume basis in tropical and temperate soils. *14th International Soil Science Congress* **5**: 248-258. Kyoto Japan
- Kinyangi, J.M., 2002. Targeting Organic Resource Quality and Diversity to Sequester Carbon, Build Nitrogen Capital, and Decelerate Soil Nutrient Depletion. Ph.D. Research Proposal Submitted to Cornell University, Ithaca, USA
- Lal, R., Wilson, G.F., and Okigbo, B.N., 1979. Changes in properties of of an Alfisol produced by various crop covers. *Soil Sci.* **127**: 377-38
- Lal, R., 1989. Conservation tillage for sustainable agriculture. Tropics vs. temperate environments. *Advances in Agronomy* **42**: 84-91
- Lal, R., Kimble, J.M., Follet, R.F., Stewart B.A., (eds). (1998). *Soil Processes and the Carbon Cycle*. CRC Press. Boca Raton, FL, 609 pp.
- Lynch, J.M., and Bragg, E., 1985. Microorganisms and soil aggregate stability. *Advances in Soil Science* **2**:133-171.

- Malhi, A., Meir, P., and Brown, S., (2002). Forests, Carbon and Global Climate. *Phil. Trans. Royal Soc. Lond.* **360**: 1567-1591
- Mann, L.K., 1985. A regional comparison of C in cultivated and uncultivated Alfisols and Mollisols in Central United States. *Geoderma* **36**:241-253
- Mann, L.K., 1986. Changes in soil C. storage after cultivation. *Soil Sci.* **142**: 279-288
- Marland, G., McCarl, B.A., and Schneider, U., (1998). Soil Carbon: Policy and Economics. In: Rosenberg, J.N., R.C. Izaurralde, and E.L. Malone (eds). Carbon Sequestration in Soils: Science, Monitoring and Beyond. Proceedings of St. Michaels Workshop. Rattelle Press, Columbus, Richland, USA.
- Metting, B.F., Smith, J.L., and Amthor, J.S., 1998. Science needs and new technology for soil carbon sequestration. In Rosenberg, J.N., R.C. Izaurralde, and E.L. Malone (eds). Carbon Sequestration in Soils: Science, Monitoring and Beyond. Proceedings of St. Michaels Workshop. Rattelle Press, Columbus, Richland, USA.
- Moorman, F.R., Lal, R., and Juo, A.S.R., 1975. Soils of IITA. IITA Technical Bulletin 3, IITA, Ibadan, Nigeria.
- Noble, I., and Scholes, R.J., 2001. Sinks and Kyoto Protocol. *Climate Policy* 1:5-25
- Oades, J.M., 1988. The retention of organic matter in soils. *Biogeochemistry* **5**: 35-70
- Paustian, K., Andr en, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., and Wooper, P.L., (1997a). Agricultural Soils as a Sink to Mitigate CO₂ Emissions. *Soil Use and Management*, **13**:1-15
- Paustian, K., Collins, H.P., and Paul E.A., 1997b. Management controls on soil carbon. In: E.A. Paul, K. Paustian, E.T Elliot, and C.V. Cole (eds.). *Soil Organic Matter in Temperate Agroecosystems: Long Term Experiments in North-America*. CRC Press, Boca Raton, Florida, pp. 15-49.
- Paustian, K., Andr en, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., and Wooper, P.L., (1997c). Agricultural Soils as a Sink to Mitigate CO₂ Emissions. *Soil Use and Management*, **13 (Suppl. 4)**:230-244
- Paustian, K., Elliot E.T., and Killian, K., 1998. Modeling soil carbon in relation to management and climate change in some agroecosystems in central North America. In: R. Lal, J.M. Kimble., R.F. Follet, and B.A., Stewart (eds.). *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL, pp. 459-471
- Paustian, K., Six, J., Elliot, E.T., and Hunt, H.W., 2000. Mangement Opyions for Reducing CO₂ Emissions from Agricultural Soils. *Biogeochemistry* **48(1)**: 147-163
- Post, .M., Emanuel, W.R., Zinke, P.J., and Strangenberger, A.J., 1982. Soil Carbon Pools and Wold Life Zones. *Nature* **298**: 156-159
- Rasmussen, P.E., and Parton, W.J., 1994. Long-term effects of residue management in wheat-fallow: Inputs, yield and soil organic matter: *Soil Sci. Soc. Am. Journ.* **58**:523-530
- Rosenberg, J.N., R.C. Izaurralde, and E.L. Malone (1998). Carbon Sequestration in Soils: Science, Monitoring and Beyond. Proceedings of St. Michaels Workshop. Rattelle Press, Columbus, Richland, USA
- Sanchez, P., Gichuru, M.P., and Kartz, L.B., 1982. Organic matter in major soils of temperate and tropical regions. Transactions XIIth International Congress of Soil Science, New Delhi, India **1**: 99-114
- Scimmel, D.S., 1986. Carbon and N turnover in adjacent grassland and cropland ecosystems. *Biogeochemistry* **2**:345-357
- Schlesinger, W.H., 1997. Biogeochemistry. An analysis of Global Change. 2nd Edition. Academic Press, San Diego.
- Sombroek, W.G., Nightergaele, F.O., and Hebel, A., 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio* **22**: 417-426.
- Sundquist, E., 1993. The global carbon dioxide budget. *Science* **259**: 934-941
- Tiessen, H., Stewart, J.W.B., and Betany, J.R., 1982. Cultivation effects on the amounts and concentration of C,N and P in grassland Soils. *Agron. Journ.* **74**:831-835
- Watson, R.T., Noble, I.R., Bolin, B., Ravindrananth, N.H., Verardo, D.J., and Dokken, D.J. (Eds.) 2000. *Land Use, Land-Use Change, and Forestry*. A special report of IPCC, Cambridge, England: Cambridge University Press
- West, T., Post, M., Amthor, J., and Marland, G., 2000. "Review of Task 2.1, National Carbon Sequestration Assessment." Presentation at Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSITE) Program Review, Oakridge National Laboratories, TN.
- Wilson, G.F., Lal, R., and Okigbo, B.N., 1982. Effects of cover crops on soil structure and on yield of subsequent arable crops grown under strip tillage on eroded Alfisol. *Soil Tillage Research* **2**:233-250

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