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SOIL CARBON SEQUESTRATION FOR IMPROVED LAND MANAGEMENT

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SOIL CARBON SEQUESTRATION FOR IMPROVED LAND MANAGEMENT

based on the work of
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Preface

The Kyoto Protocol recognizes that net emissions may be reduced either by decreasing the rate at which greenhouse gases are emitted to the atmosphere or by increasing the rate at which greenhouse gases are removed from the atmosphere through sinks. Agricultural soils are among the planet's largest reservoirs of carbon and hold potential for expanded carbon sequestration, and thus provide a prospective way of mitigating the increasing atmospheric concentration of CO_2. Within the context of the Kyoto Protocol and subsequent COP discussions, a number of features make CS on agricultural and forestry lands an attractive strategy for mitigating increases in atmospheric concentrations of green houses gases.

Article 3.4 of the Kyoto Protocol appears to allow for expansion of recognized human-induced sink activities. Recent post Kyoto agreements consider soil sinks in countries, recognizing the substantial potential of agricultural and grassland and forest soils to sequester carbon and the need for provisions of national credits for the buildup of the agricultural soil carbon sink.

A number of agricultural practices are known to stimulate the accumulation of additional soil carbon with soil fertility improvements and positive land productivity and environmental effects. Their role for human management of carbon is likely to increase as we learn more about their characteristics and new approaches, conservation tillage for example, are introduced.

The focus of this paper is on agricultural soils as carbon sinks. The document was prepared with FAO's own resources as a contribution to the FAO/IFAD programme on "*Prevention of Land Degradation, Enhancement of Soil and Plant Biodiversity and Carbon Sequestration through Sustainable Land Management and Land Use change".*

The objective of this programme is to address the urgent need to reverse land degradation due to deforestation and inadequate land use/management in the tropics and sub-tropics. It is proposed to deal with this issue through the promotion of improved land use systems and land management practices which provide economic gains and environmental benefits, greater agro-biodiversity, improved conservation and environmental management and increased carbon sequestration. The programme will contribute to the development of regional and national programmes linking the Convention on Climate Change (UNFCC)-Kyoto Protocol, the Convention to Combat Desertification (CCD) and the Convention on Biodiversity (CBD), focusing on synergies among the three Conventions.

This publication provides a valuable review of a variety of land management practices which could produce win-win effects of increasing production as well as agricultural and forestlands carbon soil stock which could earn credit toward national emission targets. It should contribute significantly to the emerging debates on sustainable land use and climate change mitigation.

It is hoped that this document will prove useful to CDM and funding agencies, planners and administrators by contributing factual information on soil carbon sequestration potential to their decisions to undertake research, development and investment programmes in the agricultural/rural land use sector aiming at improving land management, checking land degradation and deforestation.

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Professor Jules Pretty of the University of Essex, UK; Professor Rattan Lal of the Ohio State University, Professor Anthony Young of the University of East Anglia, Drs Niels Batjes of the International Soil Reference and Information Centre (ISRIC), Dr. Mike Swift, Director TSBF (Tropical Soil Biology and Fertility Programme) and the FAO Interdepartmental Working Group on Climate Change reviewed this work and made suggestions for improvement. Ellen Prior assisted in the preparation of this document.

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Summary

The increasing concern over potentially disastrous effects of global warming in various regions of the world is clashing with the inability of many countries to reduce their net emissions of greenhouse gases at the rate and to the extent required by the Kyoto Protocol. The negotiations under the Kyoto Protocol have shown a trend towards broadening the range of recognised options for compensation of greenhouse gas emissions. The negotiation rounds in 2000 and 2001 have increased the likelihood that carbon sequestration in soils used for agriculture – within the national territory or in certain groups of other countries– can be included as an element in national carbon budgets.

In the past, opinions varied on whether carbon sequestration in soils would be a realistic, practical, potentially large-scale option. In recent years, positive evidence has accumulated on these aspects. Most of the world's soils used for agriculture have been depleted of organic matter over the years under the conventional systems of ploughing or hoeing before every crop, compared with their state under natural vegetation. This degradation process has proved to be reversible. In many farmers' fields, in humid and subhumid climates as well as under irrigation, organic matter contents have been increasing rapidly after a change in land management procedures to conservation agriculture, including zero- or minimum-tillage and retention of residues on the soil surface. Even in semiarid conditions, as in South Texas, the system is working, but at lower rates of carbon sequestration. Measurement of the progress of carbon sequestration in agricultural soils is technically feasible, but to the present, has rarely been achieved other than on an experimental scale. It could be applied regionally or globally only if national or regional soil organizations undertook systematic soil monitoring by a combination of permanent monitoring sites, well distributed soil sampling combined with description of farmers' land management, and remote sensing of land cover.

Once the new land management procedures are well understood and have been applied for a few years, and the needed tools or equipment are in place, the land use system is competitive, as shown by its spread in the countries where the practices were introduced. Besides carbon sequestration, benefits include better yields and increased food security, especially in drought years, lower costs, and better distribution of labour requirements over the year. The system has found acceptance and application over more than 50 million hectares of agricultural land to date, in countries such as Brazil, Paraguay, Argentina, the United States, Australia, and has been validated on a smaller scale in Europe, Africa and countries such as India and Nepal.

Carbon sequestration in agricultural soils from conservation tillage and other methods of improved land management can be permanent as long as the farmers continue to use these practices. Conservation agriculture has spread where farmers have been convinced by experience of its benefits.

However, the transition to conservation agriculture is neither spontaneous nor free of cost. Conventional wisdom on the benefits of ploughing, such as stimulating nitrogen release from soil organic matter, and a lack of knowledge on the resulting damage to the soil system, tend to maintain plough-based agriculture. During the two or three transition years to conservation

agriculture, there may be extra costs for some tools or equipment. The weed incidence, albeit rapidly diminishing with time, may need herbicide applications in the first two years or so, and the yields and the resilience against drought will improve gradually, becoming evident after the first one or two years.

Farmers will need to understand the new system and the reasons for the various procedures, and adapt them to their specific needs and conditions. Funds for carbon sequestration that may become available under one of the mechanisms of the Kyoto Protocol or a post-Kyoto treaty will be essential for spreading the application of conservation agriculture in other areas and countries. This can be done through informing farmers of the system; enabling pilot farmers to experiment with it and to adapt and apply it in their specific conditions; and providing technical and –where needed– credit or small grant support to early adopters. Once the system has been adapted, demonstrated and economically validated on farmers' fields by early adopters in an area, adequate funding through carbon sequestration contracts with farmers may be one possible way to stimulate rapid adoption of the recommended practices by a majority of the farmers.

Grasslands also have potential for carbon sequestration. Particularly, degraded or overgrazed land can be restored to higher productivity by measures such as sowing strips of legumes covering a small proportion of the total area, with phosphate fertilizer or rock phosphate applied in the strips, and alternating grazing with rest periods for the land. The increased primary productivity then initiates a virtuous cycle of better soil cover, greater root mass in the soil, increased bioporosity and infiltration rate, reduction or elimination of runoff and erosion, and improved moisture availability for the vegetation. This process results in strongly increased amounts of stable organic matter in the soil, including in the deeper layers.

As in the case of conservation agriculture, the change from a degrading use of grazing lands to a more productive and sustainable system that sequesters carbon and helps increase food security is not automatic or cost-free. Successful and lasting change needs land users working together in associations, a learning process, and some initial investment – albeit relatively little per hectare.

Once the productivity of arable land and grazing land is increasing and becoming clearly more resilient against drought, this should reduce the pressures on forest areas and improve the chances of their preservation or resource-conserving management. The latter, including harvesting for production of energy or durable wood products, with immediate replanting or regrowth, would essentially maintain the soil organic matter of the forest system. In the case of reforestation or planting permanent crops such as oil palm or rubber on previously deforested land, the soil organic matter content, depleted during and after deforestation, will be gradually replenished to levels similar to those under forest.

Improving land management and checking degradation and deforestation are win-win options: they are desirable for the purpose of poverty alleviation and sustainability and because such measures will also increase C sequestration in soils, thus making investments in the agricultural/rural sector more beneficial to farmers.

Acronyms

C	**C**arbon
CBD	The United Nations Convention on Biological Diversity
CCD	The United Nations Convention to Combat Desertification
CDM	Clean Development Mechanism
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Developpement (Centre of International Cooperation in Agricultural Research for Development)
CO_2	Carbon dioxide
COP	Conference of the Parties
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environmental Facility
GHG	Greenhouse gases
GLASOD	Global Assessment of Soil Degradation
GM	Global Mechanism
GPS	Global Positioning System
ICRAF	International Centre for Research in Agro-Forestry
IFAD	International Fund for Agricultural Development
IPCC	Inter Governmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
SOM	Soil organic matter
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1
General trends in carbon sequestration in soils

The increase in greenhouse gases (GHG) in the atmosphere and the resulting climatic change will have major effects in the 21st century. Although current scenarios are still fraught with uncertainty, serious negative effects are expected – though some positive effects are also expected- and it is essential that a number of actions be undertaken in order to reduce GHG emissions and to increase their sequestration in soils and biomass. In this connection, new strategies and appropriate policies for agricultural and forestry management must be developed. One option concerns carbon sequestration in soils or in terrestrial biomass, especially on lands used for agriculture or forestry. Since the Kyoto Protocol, this is referred to as "Land Use, Land-Use Change and Forestry (LULUCF)" and concerns articles 3.3 and 3.4 of the Protocol (IPCC 2000).

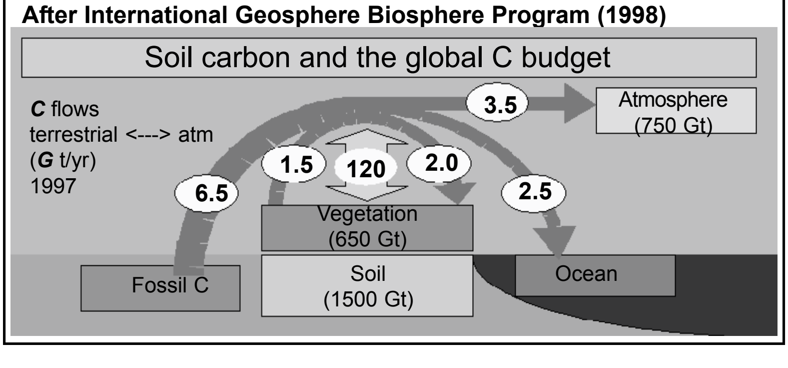
Taking action on C sequestration under the Kyoto Protocol or any post-Kyoto treaty will not only stimulate important changes in land management but will also, through the increase in organic matter content, have significant direct effects on soil properties and a positive impact on environmental or agricultural qualities and biodiversity. The consequences will include increased soil fertility, land productivity for food production and food security. This economic tool will also make agricultural practices more sustainable and help prevent or mitigate land resource degradation.

CARBON AND ORGANIC MATTER IN SOIL

The role of soils in the carbon cycle

The terrestrial carbon cycle is presented in Figure 1. In this cycle, soil organic carbon represents the largest reservoir in interaction with the atmosphere and is estimated at about 1500 Pg C to 1m depth (about 2 456 Pg C to 2m depth)[1]. Inorganic C represents around 1 700 Pg, but it is captured in more stable forms such as caliches. Vegetation (650 Pg) and the atmosphere (750 Pg) store considerably less C than soils do.

FIGURE 1
The terrestrial carbon cycle: Soil carbon and the global C budget. After International Geosphere Biosphere Program (1998)



Fluxes between terrestrial or soil organic carbon and the atmosphere are important and can be positive (sequestration) or negative (emission of CO_2).

Historically, wide variations have been noted. Houghton (1995) estimates that emissions corresponding to change in land use (deforestation and increase in pasture and cultivated lands) were around 140 Pg from 1850 to 1990 (from 0.4 Pg yr^{-1} in 1850 to 1.7 Pg yr^{-1} in 1990), with a net release to the atmosphere of 25 Pg C. According to IPCC (2000), the historical loss from agricultural soils was 50 Pg C over the last half century, which represents 1/3 of the total loss from soil and vegetation.

In the past, the development of agriculture was the main cause of the increasing CO_2 concentration in the atmosphere, but now the combustion of fossil carbon by industry and transport (6.5 Pg yr^{-1}) represents the main contribution. An important point is that, at present, while deforestation in many tropical areas produces C emissions estimated at about 1.5 Pg C per year, elsewhere around 1.8 to 2 Pg C per year is accumulating in terrestrial ecosystems. This represents what is called the “missing carbon” in the cycle: a sink that may be mainly situated in the northern part of the northern hemisphere (Schindler, 1999). The main factors acting on organic matter evolution concern the vegetation (residue input, plant composition), then climatic factors (temperature/moisture conditions) and soil properties (texture, clay content and mineralogy, acidity).

Others factors, relating to soil fertilisation (N, P, or S), or irrigation, have an effect on the plant production and hence on organic matter content. The rate of SOM mineralization depends mainly on temperature and oxygen availability (drainage), land use, cropping system, soil and crop management (Lal et al., 1995). In a given soil type exposed to a constant practice, a near-equilibrium (steady state) SOM content is normally reached after 30 to 50 years (Greenland, 1995). In the context of combating global warming and the Kyoto Protocol, an important question is how to create a major, well-quantified carbon sink in agricultural soils worldwide. Such sequestration will be relevant for protocol articles 3.3 and 3.4. It will also have important additional positive effects for agriculture, environment and biodiversity.

Dynamics of organic carbon in soils

The stock of organic carbon present in natural soils represents a dynamic balance between the input of dead plant material and loss from decomposition (mineralization) (Figure 2). In aerobic soil conditions, most of the carbon entering soil is labile and only a very small fraction (1%) of what enters the soil (55 Pg yr^{-1}) accumulates in the stable, humic fraction (0.4 Pg yr^{-1}).

Soil organic matter (SOM) has a very complex and heterogeneous composition and it is generally mixed or associated with the mineral soil constituents. A wide range of separation methods have been developed to identify among the various SOM constituents, kinetic pools, i.e. pools that can be defined by a given turnover rate of the carbon. The traditional separation of SOM into fulvic and humic fractions does not separate fractions with different turnover rates (Balesdent, 1996), as conceptualized in models. Physical separation methods such as particle size fractionation, density fractionation or aggregate size fractionation allow separation of kinetically meaningful fractions (Feller, 1979; Balesdent, 1996). Among these fractions particulate organic matter is very sensitive to changes in land use (Cambardella, 1998; Gregorich

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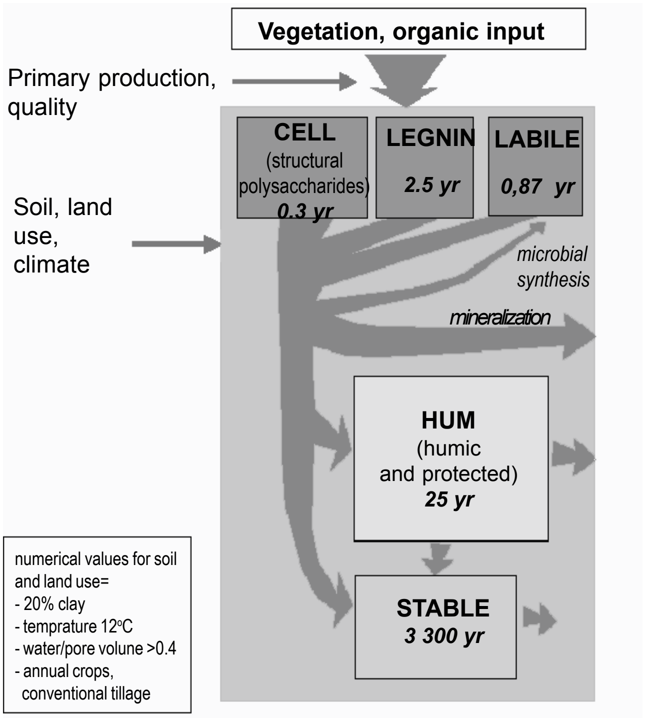
[1] Pg= 10^{15}g = Gt= 10^9 metric tonnes

et al., 1996). Some direct methods exist to determine the microbial biomass, which represents 1 to 5 percent of the total SOM and is a reservoir of nutrients (N, P). This is a very labile fraction the size of which fluctuates with the season and also responds rapidly to soil management changes. Isotopic methods such as 14C dating or 13C natural abundance are very powerful in that they allow estimation of the residence time of soil organic matter and its fractions. 13C natural abundance is suitable for turnover rates of years to centuries and 14C dating for periods of centuries to thousands of years. Both can be applied to bulk soil samples as well as to fractions isolated from soils. The 13C natural abundance method can only be used if the site has undergone a change of vegetation, from a C3 photosynthetic type to C4 type or vice versa.

FIGURE 2
Model of soil carbon dynamics *(from Balesdent et al., 2000)*



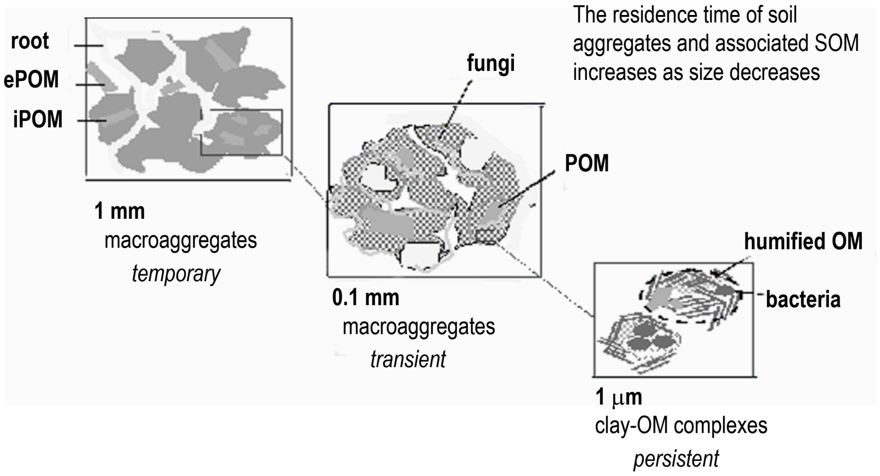
The great advantage of the isotopic methods is that organic turnover can be measured in order to deduce directly the residence time of different compartments. When there is an important change in vegetation (forest/crop or pasture) it is possible to follow the evolution of the different types of plant residues (Cerri et al., 1985).

The different C pools existing in the soil have different mean residence times, ranging from one year to a few years depending on the biochemical composition (lignin, for example, is more stable than cellulose) to decades or more than 1000 years (stable fraction). There is also some connection with the composition, but mainly with the kind of protection or the type of bonds. For the stable carbon fraction, a distinction is made between physical and chemical protection or sequestration; “physical” means an encapsulation of OM fragments by clay particles or soil macro- or microaggregates (Figure 3) (Puget *et al.*, 1995; Balesdent *et al.*, 2000); “chemical” refers to specific bonds of OM with other soil constituents (colloids or clays), but most often this concerns very stable organic compounds. However, the general term “sequestration”, as used in the Kyoto Protocol does not take such distinctions into consideration and is equivalent to the term “storage”, whatever the form of carbon.

The different organic matter pools in soils are influenced by different factors. Free organic matter particles and microbial biomass in soils are controlled by residue inputs (management of crop residues or mulching...) and climate. Soil aggregation, texture and mineralogy control organic matter in macro-aggregates. Hence, tillage has a great effect on the size of this pool.

FIGURE 3

Soil organic matter locations in the soil matrix (Chenu, unpublished); ePOM : external particulate organic matter; iPOM: internal particulate organic matter



The other pools are less influenced by agronomic factors but mainly by pedological factors (micro-aggregation, clay composition).

The key role of organic matter in soils

Soil organic matter represents a key indicator for soil quality, both for agricultural functions (i.e. production and economy) and for environmental functions (e.g., C sequestration and air quality). Soil organic matter is the main determinant of biological activity. The amount, diversity and activity of soil fauna and microorganisms are directly related to the organic matter. Organic matter, and the biological activity that it generates, have a major influence on the physical and chemical properties of soils (Robert, 1996b). Aggregation and stability of soil structure increase with organic matter content. These in turn increase infiltration rate and available water capacity of the soil, as well as resistance against erosion by water and wind. Soil organic matter also improves the dynamics and bioavailability of main plant nutrient elements.

CARBON MANAGEMENT IN DRY LANDS AND TROPICAL AREAS

This report is mainly focused on drylands and tropical areas, which are of main concern for developing countries.

Drylands are defined by an aridity index which represents the ratio of precipitation to potential evapotranspiration (P/PET) with values < 0.05 for hyper-arid, < 0.20 for arid and 0.20 - 0.50 for semi-arid. These are the most characteristic drylands, but often the dry sub-humid area (0.50 - 0.65) is also included (Middleton and Thomas, 1997). Drylands represent about 40 percent of the world's land. The natural hyper-arid zone covers an estimated 1 billion ha while the arid, semi-arid and dry sub-humid areas represent 5.1 billion ha.

Even if the carbon content and CO_2 fixing capacity per ha of dry lands are low, they can make an important contribution to global carbon sequestration, at the same time preventing or decreasing the rate of desertification. With such a broad definition, a large part of drylands is included in the tropical area defined as the part of the world between the two Tropics which represents 37.2 percent of the land surface (4.9 billion ha). Lands can be categorized according to their type of occupation.

Cultivated lands represent 0.75 billion ha in the temperate zone and 0.65 billion ha in the tropical zone. The total extent potentially available for crops (with rainfed crop production) would be 2.6 billion ha, but forests cover a part of this (1.7 billion ha) and another part cannot be used effectively because of severe constraints (Alexandratos, 1995). Irrigated soils (0.12 billion ha) are included.

Tropical forests cover large areas representing more than two billion ha, and are very important for the health of the planet. Most of this area is in developing countries. The best solution would be to protect them or at least ensure the best possible management, especially for the part of them that is already degraded (13 percent for S. America, 19 percent for Africa and 27 percent for Asia); others possible solutions will be provided later.

Permanent pastures or rangelands cover more than 3 billion ha, the majority in dryland areas; the state of degradation of these lands is estimated at 14 to 31 percent.

Table 1

Soil degradation worldwide relative to the four main degradation processes* (moderately to extremely degraded terrain, million ha) (from Oldeman *et al.*, 1991)

Area **	Erosion by water	Erosion by wind	Chemical degradation	Physical degradation	Total (x 10^6 ha)
Africa	170	98	36	17	321
Asia	315	90	41	6	452
South America	77	16	44	1	138
North and central America	90	37	7	5	139
Europe	93	39	18	8	158
Australia	3	15	1	2	6
Total	748	295	147	39	1 229**

* The three main causative factors, of similar importance, are deforestation, overgrazing and agricultural mismanagement.

** Total of 1 965 million/ha if the slightly degraded soils are included.

According to the Global Assessment of Soil Degradation (GLASOD, Oldeman et al., 1991), degraded lands represent a large proportion of the different types of lands, whatever the kind of occupation. The total amounts to 1 965 million ha across the world, most of this in tropical areas and drylands.

Physical and chemical degradation, which are the main and primary processes, very often result in biological degradation (Robert and Stengel, 1999). Erosion by water and by wind is quantitatively by far the most important degradation process. The main causes are deforestation, overgrazing and inappropriate land management. The loss of organic matter was not identified as a specific degradation process, but roughly half of the chemically degraded soils are depleted.

The soil organic matter content is generally lower where degradation is more severe. The amount of carbon that can be sequestered through the rehabilitation of degraded land therefore can be considerable, in areas where this is a technically and socio-economically viable option. In tropical regions, human induced soil degradation affects 45 to 65 percent of agricultural lands, depending on the continent (GLASOD, Oldeman et al., 1991). This situation makes the scope for progress in carbon sequestration very high for degraded tropical soils. Related benefits will include improvements in chemical properties, bioavailability of elements (higher fertility), and resilience against physical degradation, especially erosion. Hence, C sequestration will help restore the quality of degraded soils.

Forest ecosystems: CO_2 emission and C sequestration in soils

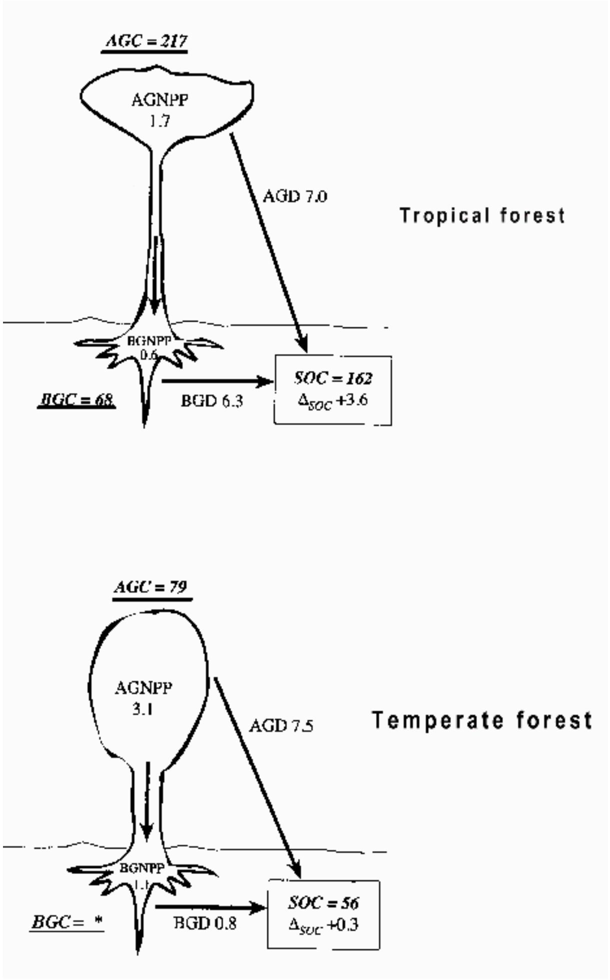
C storage and release by forest ecosystems (through afforestation, reforestation or deforestation) are dealt with in Article 3.3 of the Kyoto Protocol. However, Article 3.4 comes into play when forest management in tropical areas is considered, because of the significant interactions with carbon sequestration in soils.

Forests cover 29 percent of terrestrial lands and account for 60 percent of carbon in terrestrial vegetation. Carbon stored in forest soils represents 36 percent of the total C soil pool to 1 m depth (1 500 Pg). Recently, a complete C balance of French forests was undertaken by Dupouey *et al.*, 1999. This covered 540 plots from the European forest-monitoring network. The total mean carbon of the ecosystem was 137 t C ha^{-1}; of this total, soil represents 51 percent (71 t), litter 6 percent, roots 6 percent. These statistics are very close to those given in the last IPCC report (IPCC 2000) for forest in Tennessee. Data are also given for tropical rain forest near Manaos. The total C in the system is higher (447 t ha^{-1}) and so is the soil organic stock (162 t, 36 percent of the total) (Figure 4).

Forest ecosystems contain more carbon per unit area than any other land use type, and their soils - which contain around 40 percent of the total carbon - are of major importance when considering forest management.

FIGURE 4

Estimated annual total carbon stocks (t C ha^{-1}) in tropical and temperate forests *(from IPCC, 2000)*



AGC and BGC = above and below ground carbon;
AGD and BGD = above and below ground debris;
AGNPP and BGNPP = above and below ground net primary production;
SOC = soil organic carbon
*not given in original

Normally, soil carbon is in steady-state equilibrium in natural forest, but as soon as deforestation (or afforestation) occurs, the equilibrium will be affected. It is presently estimated that 15 to 17 million ha/year are being deforested, mainly in the tropics (FAO, 1993) and very often part of the soil organic C is lost, giving rise to considerable CO_2 emission. Therefore, where deforestation cannot be stopped, proper management is necessary to minimise carbon losses. Afforestation, particularly on degraded soils with low organic matter contents, will be an important way of long-term carbon sequestration both in biomass and in the soil.

Grasslands: a great potential reservoir for carbon

Grasslands are included in Article 3.4 of the Kyoto Protocol and, like forest, they play an important role in carbon sequestration. Firstly, grasslands occupy billions of hectares (3.2, according to FAO) and they store from 200 to 420 Pg in the total ecosystem, a large part of this being below the surface and therefore in a relatively stable state. Soil carbon amounts under grassland are estimated at 70 t ha^{-1}, similar to the quantities stored in forest soils (Trumbmore *et al.*, 1995; Balesdent and Arrouays, 1999). Owing to the unreliability of the data, FAO land use statistics no longer give the area of grasslands.

Many grassland areas in tropical zones and drylands are badly managed and degraded; these offer a range of carbon sequestration possibilities.

Cultivated lands: the role of agronomic practices

The development of agriculture has involved a large loss of soil organic matter. There are various ways in which different land management practices can be used to increase soil organic matter content (Figure 9), such as increasing the productivity and biomass (varieties, fertilisation and irrigation). Global climatic change may have a similar effect. Sources of OM also include organic residues, composts and cover crops.

The main ways to achieve an increase in organic matter in the soil are through conservation agriculture, involving minimum or zero tillage and a largely continuous protective cover of living or dead vegetal material on the soil surface.

Chapter 2
The evaluation of soil carbon storage and main changes

In order to estimate the potential of carbon sequestration in soils under various scenarios over the next 25 years (Batjes, 1999), two aspects need to be distinguished: what are the original C stocks in soils; and what are the changes in C stocks.

MEASUREMENT OF SOIL CARBON STOCKS

Organic matter that is above the soil surface in the litter layer is not taken into account in the assessment of soil carbon stocks. For cultivated soils, this means that plant or crop residues are considered as a transitory phase. However, crop residues, cover crops or mulch are important parts of the agro-ecosystem. Similarly, forest litter can amount to some 8 or 9 kg C m-^{2} for temperate forests (Dupouey *et al.*, 1999), 5 or 6 kg C m-^{2} a tropical forest on a Ferralsol (Andreux and Choné, 1993). Live roots are considered as C biomass and in grasslands, for example, this compartment can contribute the greater part of soil C.

The method most commonly applied is to determine total organic carbon at different depths or globally for one or more horizons and to transform the data, taking into account the bulk density and stoniness of the soil. Statistics are calculated on different samples to determine C stocks. The results may be expressed in kg/m^{2}, t/ha or Gt (Pg) totals over specified areas and depth ranges.

The scale can be the site or plot, the watershed, the region, a specific country or continent or the agroecological zone (FAO/IIASA, 1999). The spatial extension is made using digitised maps for the different soil units considered. The number of soil profile analyses used is very important and until now there has been a lack of good, site-referenced data.

With respect to soil carbon stocks at world scale, there are three important references. Sombroek *et al.*, (1993), used the FAO/Unesco Soil Map of the World (at 1:5 000 000 scale) and about 400 soil profiles, grouped per FAO soil unit, with range and median values for organic carbon content and bulk density for each soil unit. They were able to estimate organic carbon stocks by FAO soil groups and the soil carbon stock of the world.

Post *et al.*, 1982, Eswaran *et al.*, 1993, used the US Soil Taxonomy and more profile analyses (close to 16 000), with the majority coming from pedons in the USA (WSR-SCS). The total estimate of organic C stock is 1 550 Pg. More details are given concerning stocks for the different soil suborders or orders, or for the different profile depths. In conclusion, the authors stress in the estimation the importance of taking into account land use and land management changes.

More recently, Batjes (1996) carried out a revision of the estimate using the Wise database with 4 353 profiles (19 222 C analyses) with a more representative geographical distribution.

TABLE 2
Mean organic carbon content for some FAO-Unesco and WRB soil units

Soil unit		Mean C content kg/m^2		
FAO-UNESCO	**WRB**	**0 - 30 cm**	**0 - 100 cm**	**0 - 200 cm**
Podzols	Podzols	13.6	24.2	59.1
Rendzinas	Leptosols	13.3	-	-
Lithosols	Leptosols	3.6	-	-
Chernozems	Chernozems	6	12.5	19.6
Nitosols	Nitosols	4.1	8.4	11.3
Xerosols	Calcisols/Cambisols	2	4.8	8.7
Yermosols	Calcisols/Gypsisols	1.3	3	6.6
Ferralsols	Ferralsols	5.7	10.7	16.9
Vertisols	Vertisols	4.5	11.1	19.1
Andosols	Andosols	11.4	25.4	31

Notes: 1:1 correlation with WRB units secures “risky”for some of these units.
Source: FAO - Unesco (1974) and WRB soil units (from Batjes, 1996)

This study confirmed a total soil C of about 1 500 Pg in the upper horizons (0-100 cm), but also revealed the presence of important and stable C stocks at depths between 100 and 200 cm, especially in tropical soils (Table 2). The author considered that the general soil information system (FAO/Unesco 1974) was not completely adapted to enable estimation of changes in soil properties induced by land use changes or other factors (for example, climatic change).

The data presented in Table 2 illustrate the great variation of organic carbon in relation with soil types. Values are from 2 kg C m-^{2} for Xerosols or Arenosols to more than 10 kg for Podzols, Andosols or Rendzinas. Total amounts of C in soils of arid areas (Xerosols, Yermosols) are low around 7 kg Cm^{-2}, compared with soils in the tropics, in the order of 15 to 30 kg/m^2, but these are diverse depending on texture and mineralogy.

Soil carbon contents depend on the main long-term factors of soil formation, but can be strongly modified (degraded or improved) by land use changes and land management.

Most of the cited statistical studies on soil C stocks and distribution are based essentially on soil maps. Recently, similar evaluations have been made in France (Arrouays *et al.*, 1999) which take into account both soil types and vegetation cover. Soil C analyses which were available were georeferenced pedological data from the national database and data from a systematic soil monitoring network (16 x 16 km) available at European scale, but only for forest soils. Information from a soil map and a land use map was used to produce simple statistics on carbon stocks in different land uses (with 13 types of uses, according to the Corine Land Cover-definitions) and soil types (with 17 FAO-defined groups of soils). The total number of existing combinations was 138. The resulting soil carbon map of France allowed an estimate to be made of the carbon stock (3.1 Pg to a depth of 30 cm), and also to identify the main controlling factors of the carbon distribution: land use, soil type or other characteristics (climatic, pedologic, etc.).

Other papers have attempted similar combinations between soil type and vegetation (Howard *et al.*, 1995 for Great Britain; Moraes *et al.*, 1998 for Rondônia, Brazil; Van Noordwijk *et al.*, 1997 for the humid forest zones).

Both soil and land use data should be used in determining soil carbon stocks. While soil factors are important, as are climatic factors, in explaining carbon storage or pools over long periods of time, changes in vegetation or land use determine the changes in carbon sequestration

TABLE 3
Total stocks of soil organic carbon (SOC) (Pg C) and mean C contents(kg Cm^{-2}) by major Agro-Ecological Zone (for upper 0.3 m and 1m)

Agro-ecological zone	Spatially weighted SOC pools (Pg C)		Mean SOC density (kg/m^{-2})	
	to 0.3 m depth	to 1 m depth	to 0.3 m depth	to 1 m. depth
Tropics, warm humid	92 - 95	176 - 182	5.2 - 5.4	10.0 - 10.4
Tropics, warm seasonally dry	63 - 67	122 - 128	3.6 - 3.8	7.0 - 7.3
Tropics, cool	29 - 31	56 - 59	4.4 - 4.7	8.4 - 8.9
Arid	49 - 55	91 - 100	2.0 - 2.2	3.7 - 4.1
Subtropics with summer rains	33 - 36	64 - 68	4.5 - 4.7	8.6 - 9.1
Subtropics with winter rains	18 - 20	37 - 41	3.6 - 3.9	7.2 - 8.0
Temperate oceanic	20 - 22	40 - 44	5.8 - 6.4	11.7 - 12.9
Temperate continental	21 - 126	1233 - 243	5.6 - 5.9	10.8 - 11.3
Boreal	203 - 210	478 - 435	9.8 - 10.2	23.1 - 24
Polar and Alpine (excl. land ice)	57 - 63	167 - 188	7.0 - 7.8	20.6 - 23.8

Source: Batjes, 1999

over shorter periods. Often, however, the land use history has not been documented for most of the available soil profiles.

Batjes (1999) also discussed the total soil C stock distribution by major ecological zones. Such zones show large differences in organic carbon storage (Table 3), mainly in relation to temperature and rainfall. Soil C stocks down to 1 m depth range from about 4 kg m-^{2} (in the arid zone) to 21-24 kg m-^{2} (in polar or boreal regions); with intermediate values of 8 to 10 kg m-^{2} in tropical zones. The contribution of the tropical regions to the global pool of soil carbon is 384-403 Pg C to 1 m and 616-640 Pg C to 2m depth (Batjes, 1996), compared to about 1 500 Pg C to 1 m for the world (2 736-2 456 Pg to 2 m depth).

The arid zone, which covers 40 percent of the global land surface, stocks only 5 percent (100 Pg) of the total. These agro-ecological zones, developed by FAO, can constitute a reference framework to evaluate and monitor soil C storage in soils.

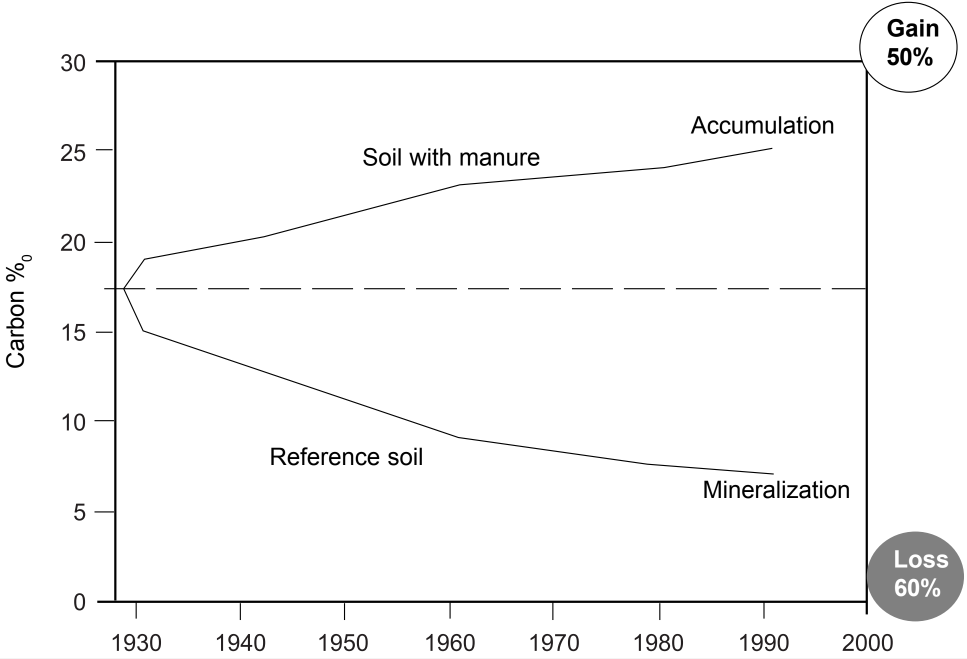
STORAGE CHANGE EVALUATION

There are numerous well-documented, historical examples of changes in soil carbon stocks from the temperate zones, most of them from long-term agronomic experiments.

The Versailles experiment (France), known as “The 42 plots”, was set up in 1929, without a crop and removing the natural vegetation, and with or without fertilisation or amendments. The soil is a characteristic loamy soil with an initial C content of 1.7 percent. In 50 years organic C content in the unamended soil, decreased by 60 percent to 0.7 percent; in the soil receiving manure (100 t /ha^{-1}yr^{-1}), it increased by 50 percent to 2.5 percent (Figure 5). In both cases, the rate of change is decreasing, and the plateau (new steady state) is close.

The Rothamsted experiment (Broadbalk wheat) is the oldest long-term agronomic experiment. Set up in 1843, with continuous wheat cultivation and with rotations, the plots have been subjected to different treatments. Application of farmyard manure has resulted in doubling the organic C content, but with only crop residues, the soil C content has remained stable. In the same set of experiments (Rothamsted Highfield), grass to arable conversion resulted in 55

Figure 5
Evolution of soil carbon concentration in a loamy soils between 1928 and 1991 with or without addition of manures (experimental site of INRA Versailles "42 plots")

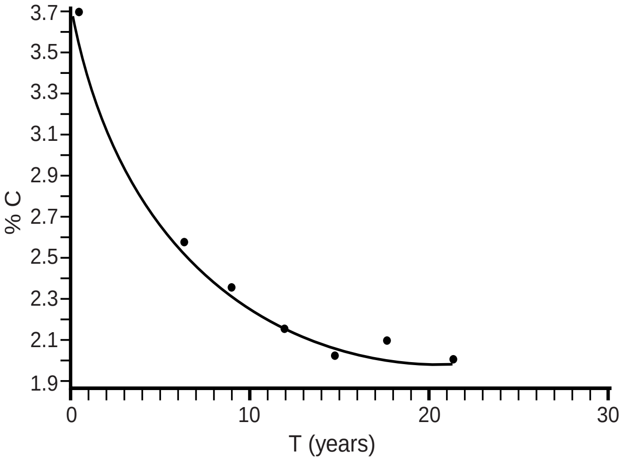


percent C loss over 20 years, from 3.5 to 2 percent C (Figure 6). Similar C losses are found where natural prairie was converted to cultivated land in Canada or the USA.

Another long-term experiment (90 years) is the Bad Lauchstadt static fertiliser experiment where the results demonstrate the positive effect of fertilisation (especially N) on the soil C content.

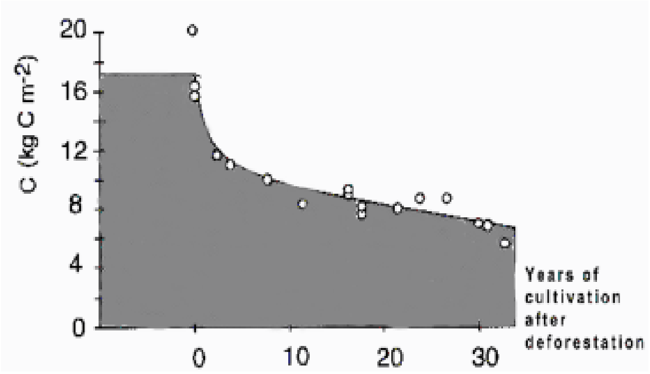
Such long-term experiments provide data with which it is possible to evaluate the effect of changes in land cover and land use, but also to set up or to evaluate models. They are now included in SOMNET, a soil organic matter network (Powlson *et al.*, 1998).

Figure 6
Carbon evolution in the Rothamstead Highfield grass-to-arable conversion experiment (from Johnston, 1973)



In all these experiments, regular ploughing was included in the standard practices. However, a number of relatively long-term experiments (around 20 years) in USA (Dick *et al.*, 1998), Germany (Tebrugge and During, 1999) and Russia (Kolchugina *et al.*, 1995) make it possible to evaluate effects of different kinds of tillage and zero-tillage on C storage. Ploughing can decrease the organic C content by 10 to 30 percent. In the USA, a specific regional network (Central Great Plains) has been set up on this subject (Lyon, 1998).

Figure 7
Soil organic carbon decrease following forest clearing and maize cultivation. (Arrouays and Pélissier, 1994).



Similar experiments exist for temperate (Arrouays and Pélissier, 1994) and tropical forests (Neill *et al.*, 1998), which allow evaluation of the effects of deforestation and afforestation on soil C storage. Deforestation generally entails an almost total loss of biomass and a loss of below-ground C of between 40 and 50 percent in the space of a few decades – about half of which occurs in less than 5 years (Figure 7). The new steady state will then depend on the new land use (Davidson and Ackerman, 1993; Sombroek *et al.*, 1993). In the case of deforestation followed by pasture (Neill *et al.*, 1998; Choné *et al.*, 1991) C isotopic studies show the relatively rapid replacement of the original forest soil carbon pool by carbon compounds derived from pasture. With afforestation, both the above- and belowground C will increase only slowly, depending on the rate of tree growth.

Various other long-term experiments on soil carbon emissions and sequestration have been conducted in temperate regions. A wide range of long-term comparative studies show that organic and sustainable systems improve soils through accumulation of organic matter and soil carbon, with accompanying increases in microbial activity, in the USA (Lockeretz *et al.*, 1989; Wander *et al.*, 1994, 1995; Petersen *et al.*, 2000), Germany (El Titi, 1999; Tebruegge, 2000), UK (Smith *et al.*, 1998; Tilman, 1998), Scandinavia (Kätterer and Andrén, 1999), Switzerland (FiBL, 2000), and New Zealand (Reganold *et al.*, 1987, 1993).

Long-term experiments also exist in other parts of the world; a partial annotated list is available on the FAO website[1]. They often are in relation with international agricultural research centers (Greenland, 1994). Concerning sustainable land use, a database needs to be established (Swift *et al.*, 1994).

The recent evaluation of the US carbon budget and especially of the contributions of land use changes (Lal *et al.*, 1998a; Young (p.62-67, FAO/IFAD 1999), Houghton *et al.*, 1999) has given rise to some polemics about the not-so-large US carbon sink (Field and Fung, 1999). In this case, the United States were divided into seven geographic regions, each of them comprising two to five natural ecosystems, not including croplands and pastures. In these evaluations, the soil type was not taken into account. The study estimated changes in soil carbon stocks in relation to historical land use changes from 1700 to 1990. The total amount of carbon released by US soils today is estimated by Lal at 3 to 5 Pg.

Using modelling, an accumulation of 2 Pg was projected, in relation to reduced tillage.

The simulated total soil carbon changes for a depth of 0-20 cm are presented in Figure 8 (Smith, 1999). Depending on the development of reduced tillage the rate of soil carbon increase can be higher.

In northern countries (Canada, former Soviet Union) there are similar evolutions and the same kind of simulation results in the case of no-till management (Gaston *et al.*, 1993).

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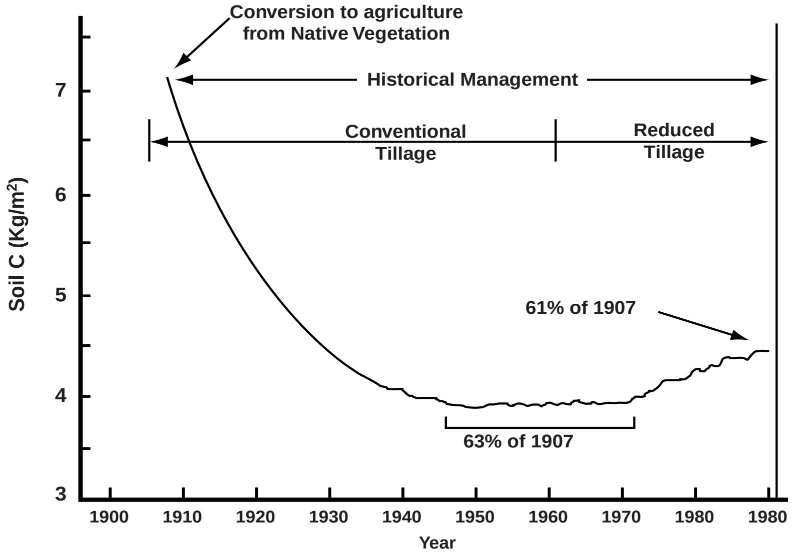
[1] http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGL/agll/globdir/index.htm

FIGURE 8

Simulated total soil carbon changes (0 to 20 cm depth) from 1907 to 1990 for the central U.S. corn belt (from Smith, 1999)



Similar estimates of the annual fluxes of carbon storage in soils were carried out for France by Balesdent and Arrouays (1999). The calculation was based on historical records of land use areas, with some attributions of mean C pool in equilibrium for each type of soil use. The values for the pools range from 20 t/ha for fallow or vineyard areas, to 50 for grassland and 60 for forest. In order to evaluate the effect of land use on the pools, a simple model of soil C dynamics was coupled with various constant rates of organic matter decomposition. Using this method, it was possible to demonstrate that soils in France have accumulated more than 4 t Cha^{-1} over the last century, with high historical variations. A recent map of carbon is presented in annex 1 (Arrouays *et al.*, 2000). These approaches, based on land use and fluxes, are complementary to those based on C pools in soils.

There are several models of land use changes and C dynamics that permit spatial generalisation or simulation of the evolution of soil C under land use changes (See Geoderma special volume, 1997, 81(1-2)). In the USA, two models are most commonly used: Century and DNDC (which can couple denitrification and decomposition processes). They are normally linked to a Geographical Information System (GIS). Both models require climatic data (temperature and precipitation) at the sites, which are grouped according to broad, climate, soil characteristics (mainly texture), and information on land management (crop rotation and yield, tillage, irrigation, fertilisation...). Concerning organic matter, two forms of litter are distinguished (metabolic and structural) as well as three SOM compartments (active, slow, passive), with different residence times. These models are run for only one soil type and one crop rotation and tillage scenario at a time, within a given climate. Outputs of the models are soil C storage, crop yield and emissions of different gases.

A French model was set up by Arrouays and Pélissier, 1994, for the main purpose of predicting the effect of land use on C dynamics. This model, called Morgane, takes into account different organic matter compartments. It will be tested in several tropical countries (West Indies or Brazil). A special issue of Geoderma (1993,81) was devoted to a comparison of nine different simulation models using data from long-term experiments in temperate regions, and an application was made by Smith *et al.* (1997) to tropical ecosystems. These models can also be used to simulate the effects of climate change (Paustian *et al.*, 1998 b).

The FAO-IFAD project on C sequestration runs a model called “RothC-26-3” (Jenkinson and Rayner (1977), set up during the Rothamsted experiments for organic matter turnover in temperate regions, but now extended to tropical regions (Ponce-Hernandez, 1999).

The RothC model, linked to GIS, has already been used at the national level in Hungary (Falloon *et al.*, 1998, Biol Fert. Soils 27:236-241). It is also considered as one of the candidate models for assessing the soil carbon sequestration potential for Western Africa, using a Land Resources Information System (Batjes, 2001).

Chapter 3

Management of forest, pasture and cultivated land to increase carbon sequestration in soils

FOREST

Even if their rates of C sequestration can vary considerably, natural forests can be considered in dynamic-equilibrium with regard to carbon under certain climatic conditions and for a given atmospheric CO_2 concentration. According to Woomer *et al.* (1998), the original primary forest, for example in Amazonia, is the ecosystem which contains the highest quantity of carbon (305 t/ha, of which 28 percent is below ground). All changes in management of such ecosystems induce major changes in carbon dynamics, resulting in smaller C stocks than in the original forest. These forms of management include slash-and-burn agriculture, deforestation, afforestation and agroforestry.

Deforestation is dealt with in Article 3.4 and afforestation in Article 3.3 of the Kyoto Protocol. Legal aspects of forest definition are not discussed here; only aspects related to change in land use (mainly Article 3.4) are considered.

According to FAO Global Forest Resources Assessment the current global rate of deforestation is around 17 million ha per year (FAO, 1993), about 0.45 percent of the remaining forest ecosystem. The immediate and important C loss which results is partly accounted for in the 1.6 Gt C emission of the carbon cycle (Figure 1).

Even if the upper biomass is removed and burned, between 50 and 60 percent of the total C in the system is on the soil surface or in the soil (litter, soil OM, and roots...) and can be managed properly.

ECEREX experiments in French Guyana (Sarrailh, 1990) showed that, depending on the kind of deforestation and the intensity of physical disturbance, (mechanised or manual), the erosion rate may be increased from 0 to 20 t ha^{-1} yr^{-1} and runoff from 0 to 250 mm per year. Specific conservation measure (Chauvel *et al.*, 1991; Lal, 1990) can prevent a large part of such degradation and the resulting C loss (Table 4).

TABLE 4
Effects of deforestation on runoff and soil erosion (Sarrailh, 1990, and Lal, 1990)

Method to deforestation	Runoff (mm/yr)	Soil erosion t/ha/yr
Original Forest	0	0
Traditional	6.6	0.02
Manual	48	5
Total clearing	104	4.80
Mechanized	250	20

Slash-and-burn, or shifting cultivation, accounts for around 60 percent of the tropical deforestation. It is carried out by between 300 to 500 million small farmers in the tropics, to undertake subsistence agriculture.

The forest is cleared by burning, involving mainly the above-ground biomass, and a small part of the soil C down to about 3 cm depth (Choné *et al.*, 1991). Burning and the resulting OM mineralisation provide the nutrients for the plant growth.

The extent of further losses from the remaining C pool will depend on the kind of land use replacing the forest cover. Under arable cultivation, loss of C carbon will be considerable, as shown earlier (40 to 50 percent in a few dozen years) with a high level of release during the first five years. These losses are largely due to tillage.

In slash-and-burn agriculture, a bush fallow period is included in the cycle and depending on its length this can restore part of the soil carbon and make the system more or less sustainable (Ponce-Hernandez, 1999). If pasture is established, the loss is much smaller and a certain amount of C recovery is possible over a few years, thanks to the OM of the grass (De Moraes *et al.*, 1996).

Agroforestry association of trees with crops or pastures, can represent a sustainable alternative to deforestation and shifting cultivation (Winterbottom and Hazlwood, 1987; Sanchez *et al.*, 1999; Schroeder, 1994; Sanchez, 1995). It has a huge potential for carbon sequestration in croplands (Sanchez *et al.*, 1999).

Schroeder (1994) presented an evaluation of carbon storage in the different ecoregions. In tropical areas, carbon storage of 21 (sub-humid) to 50 t C ha^{-1}. (humid) can be obtained with cutting cycles of 8 or 5 years, far shorter than for forests. In these calculations ground C is not included and the roots alone would increase these values by 10 percent. In the main agroforestry systems, initial forest soil C could be maintained. In some cases, for example under cocoa or cocoa/Erythrina, increases of 10 and 22 t/ha respectively were obtained over a 10-year period (Fassbender *et al.*, 1991).

Schroeder (1994) also carried out a global evaluation of the land potentially available for conversion to agroforestry. Even if the potential extent is as much as 600 to 1000 million ha, Schroeder estimates that 160 million ha are suitable in the tropics. The global C storage would be somewhere between 1.5 and 8 Gt.

Other estimates of the extent available for agroforestry are higher: 400 million ha for the next 25 years, including 100 million ha of forest (devoted to deforestation) and 300 ha of degraded agricultural lands (IPCC 2000). Complementary estimates indicate 630 million ha additional croplands and grasslands for the tropics.

Additional estimates of the potential C gains from agroforestry are summarized in Young (1997).

IPCC (2000) makes two types of evaluation to arrive at realistic rates for annual land conversion. The first concerns the transformation of forests after slash-and- burn or other kinds of deforestation. IPCC estimates this at 10.5 M ha^{-1} yr^{-1}, corresponding to 20 percent of the 15 million ha which are currently deforested (3 M ha) plus 3 percent of the 250 M ha of degraded lands at the forest margins (7.5 M ha.). Taking the modal differential value of 57 M ha between the land uses, the global contribution of agroforestry would be around 0.3 Gt C yr^{-1}.

Secondly, agroforestry systems can be established on unproductive croplands with low levels of OM and nutrients. Such areas are widespread in sub-humid areas of tropical Africa. In this case, belowground C is the main concern. The conversion to agroforestry would permit tripling the C stocks, from 23 t to 70 t/ha over a 25-year period. In sub-humid tropical Africa alone, the benefit would be around 0.04 to 0.19 Gt C yr^{-1}. As a first step, a leguminous cover crop can be used, such as Sesbania sesban, Tephrosia vogelii, Gliricidia sepium, Crotalaria grahamiana, Cajanus cajan, which can supply 0.1 to 0.2 t N ha^{-1} yr^{-1}. Pueraria is also a well-known leguminous plant (both in Amazonia and Africa) that can regenerate the soil structure, thanks to its abundant root development.

In principle, therefore, agroforestry would be one of the interesting changes in land use related to C sequestration, for various reasons. First, the surface involved is considerable and the rate of C gain is relatively high (0.2 to 3.1 t ha^{-1} yr^{-1} according to IPCC (2000), or even more, depending on the residence time of the trees). Secondly, it can mitigate the important CO_2 emission coming from deforestation (Dixon, 1995). Thirdly, it could provide a sustainable system from technical, ecological and economic points of view. However, for social and cultural reasons, such land management may be difficult to promote. Therefore agroforestry will probably be a less major contribution to carbon sequestration.

Global values exist to estimate the annual sequestration rates of afforestation in different climatic zones. The total rate (above and below ground) in t C ha per year, increases from boreal (0.4-1.2) and temperate (1.5-4.5), to tropical regions (4-8) (Dixon, 1995). Data from IPCC (2000), on the distribution of carbon among above-ground biomass, roots, litter and soil carbon indicate that soil carbon alone represents more than forest biomass C. Such proportions differ depending on the climatic zone, the soil C being maximum in cold countries (boreal and temperate) and minimum in tropical areas. Recently Post and Kwon (2000) found lower potential C accumulation rates in soil for forest (0.3 to 0.6 t C ha-^{1} year-^{1}) than for grassland.

Amendment (by calcium carbonate) or fertilisation increases biomass, both above and below ground, provided other conditions are not limiting. As a result the soil C will generally be increased, but this is mainly an issue in developed countries. CO_2 fertilisation, in relation to increased atmospheric CO_2 levels, will have a similar effect.

GRASSLANDS

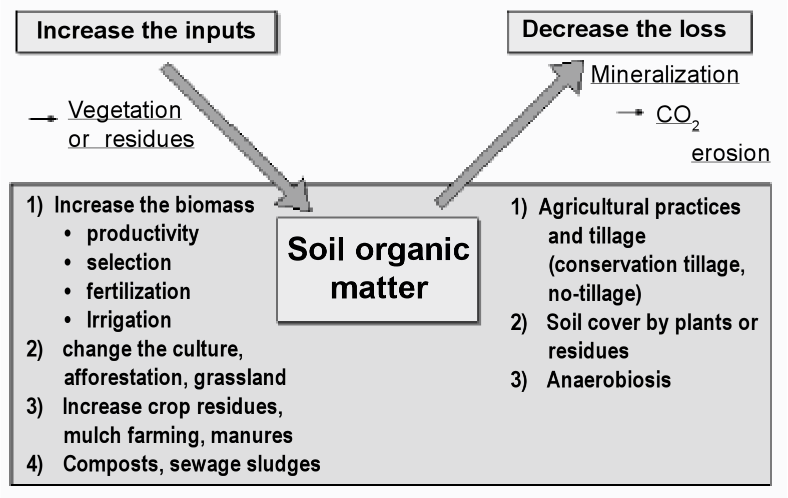
Both the large extent of grasslands and the importance of the C pool have been mentioned. While the total C present in the grassland ecosystem is less than in some forest ecosystems, the belowground part of C may be higher. In general, C content of a soil under grassland is higher than under crops.

But the majority (close to 70 percent) of grasslands is degraded. Overgrazing is one of the main causes of degradation, especially in sub-humid, semi-arid or arid zones where grasslands are predominant (Pieri, 1989). Fire management is another method used to control woody species, involving some C loss to the atmosphere but with the main transfer being to stable charcoal, which can amount to up to 30 percent of the total soil C (Skjemstad et al, 1996).

The main solution used in managing pastures is grazing control (intensity, frequency, seasonality); and better fire management for the control of woody growth. Other solutions include the improvement of soil and grass quality.

As regards soil, one of the main limiting factors for plant growth is nutrient deficiency. Fertilisation at low dosage can be a solution (P rather than N). However, a better one (for N), more ecological and sustainable, is to introduce nitrogen-fixing legumes. Another solution is to modify the grass quality and to introduce more productive species with deeper root systems, more resistant to pasture degradation. All these solutions will increase carbon sequestration to a considerable extent (Fisher *et al.*, 1994) since pastures can store very high quantities of C in a very stable form. The accompanying increase in yield can also be very important (x 2 or 3).

Figure 9
Management of soil organic matter in agriculture



Cultivated land

As stated earlier, soil and crop management can greatly improve the residence time and new C storage in soil, which is worthy of consideration under the Kyoto Protocol (Buyanovski and Wagner, 1998) or any post-Kyoto treaty.

Different land uses and agronomic practices were evaluated with respect to their effect on carbon sequestration or release (Lal, 1999; Batjes, 1999). A distinction is made between practices causing a decrease of carbon loss, an increase in carbon input into the soil, or a combination of both (Figure 9).

Decrease of the C loss

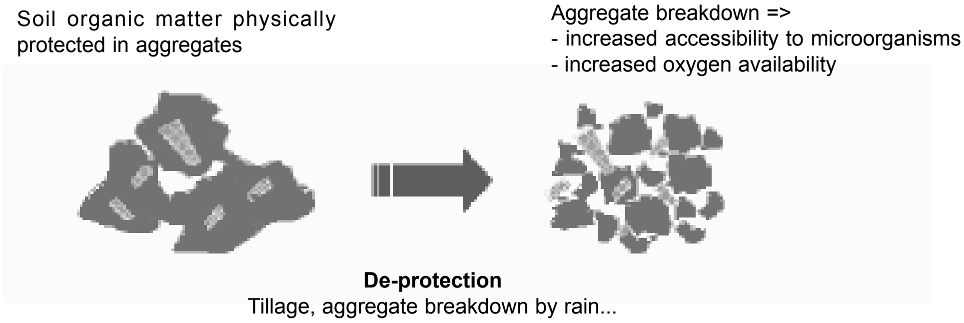
Apart from climatic factors (mainly temperature), the main processes causing losses in soil C are soil erosion and mineralisation of organic matter. Leaching of dissolved organic and inorganic carbon is another important mechanism of loss of carbon from the soil.

Soil erosion by water or wind, represents the most important soil degradation process and affects more than 1 billion hectares globally. The soil loss generally ranges from 1 to 10 t ha^{-1} yr^{-1} and in some cases, up to 50 t.

Organic matter in the upper soil horizon is an important part of this soil loss. Exact evaluation of this C pool is difficult because of the heterogeneity in time and space. The global loss by erosion would be in the range of 150 to 1500 million t per year, which is rather less than was estimated at the continental level (Lal, 1995; Gregorich *et al.*, 1998).

With the exception of some specific erosion control methods developed in the past, such as terraces or contour ridges, most of the methods used to prevent soil erosion aim to increase the soil stability (of which organic matter is one of the main factors) or to protect the soil surface with a cover of vegetation, plant residues, etc. Such methods for preventing erosion will also be good for C sequestration (and vice-versa). Hence a decrease of erosion will increase the

FIGURE 10
Physical protection of Soil Organic Matter and deprotection by tillage (Balesdent *et al.*, 2000)

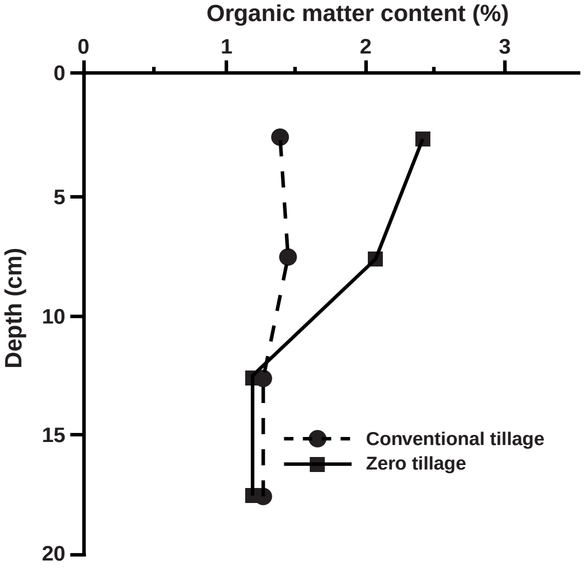


beneficial effects of soil conservation and management methods (soil cover, minimum tillage, increase in soil organic matter). On the other hand, good management of carbon will help prevent erosion.

Tillage has a long history dating back millennia, and aimed to give soil aeration and to control weeds. Tillage operations also stimulates N release from SOM.The increase in aeration of the soil and the intense disturbance are the main factors stimulating the mineralisation of organic matter by the soil micro-organisms. Recent work (Balesdent *et al.*, 2000) demonstrates that tillage plays a main role in the "deprotection" of OM present in macro- (and to some extent in micro-) aggregates (Figure 10). Tillage practices have been causing the general decrease in OM of intensively cultivated soils, especially in Europe, and the important CO_2 emissions linked to agriculture in the past.

Much literature has been devoted to the effects of different types of tillage (Monnier *et al.*, 1994; Paustian *et al.*, 1998a; Lal, 1997; Reicosky and Lindstrom, 1995). The Special Issue of Soil and Tillage Research 47 (1998) gives an overview of the results obtained in 50 long-term field experiments. The main results concern Canada and USA and different cultures. Increases in soil carbon, from conventional tillage to no-till, range from 10 to 30 percent (Figure 11). C sequestration between conventional and no-tillage varies with AEZ and soil type. There is a need to distinguish between the different types of conservation tillage. Where C content is very similar in the two conditions, this may be due to the quite cold climatic conditions of the experiments.

FIGURE 11
Effect of conventional tillage and no-till on organic matter content in the soil profile



Conservation tillage and all types of zero-tillage do not have the same effect on carbon sinks in the soil. There is clear empirical evidence that conservation agriculture, e.g. better land husbandry, land stewardship in industrialised countries (eg USA, Australia) should not be dealt with in the same way as zero-tillage in Latin America. Conservation tillage with intensive rotations of monocultures does not lead to much accumulation of carbon. Much of conservation agriculture in the USA still tends to be simplified modern agriculture systems – so saving on soil erosion, but with little use of agro-ecological principles for nutrient, weed and pest management (Pretty and Ball A., 2001).

In conservation agriculture, crop residues should cover more than 30 percent of the soil surface (Lal, 1997). Under conservation agriculture, 0.5 -1.0 t C ha^{-1} yr^{-1} can be sequestered in humid temperate conditions, 0.2 - 0.5 in humid tropics and 0.1 - 0.2 in semi-arid zones (Lal, 1999). But zero-tillage with cover crops and/or green manures in a complex rotation patterns leads to large amounts of carbon sequestered. Such practices now occupy more than 50 million ha., the majority being in North America (19 in the USA, 4 in Canada), South America (Brazil, 13 million, Argentina 9 million, Paraguay + Mexico + Bolivia, 1.7 million) and Australia (8 million). Data vary from year to year (some give 60 million ha) because of the fast rate of development of these practices, especially in Brazil and Argentina. The widespread development of conservation tillage in USA accounts for the fact that agriculture is now sequestering C in soils. Table 5 shows the small extent in Europe. This could expand through facilitating policies with agro- environmental funding.

In some cases, no-tillage can have an unfavourable effect due to an increase in water content and hydromorphy with consequent emission of greenhouse gas (Dao, 1998). The different effects in relation to soil characteristics have not yet been completely ascertained (Tavarez-Filho and Tessier, 1998).

Table 5
World surface area of cultivated soils under zero-tillage

Country	Surface area (million ha)
USA[1]	19
Brazil[2]	13
Argentina[3]	9
Australia[4]	8
Canada[5]	4
Paraguay[6]	0.8
Mexico[7]	0 .7
Bolivia[8]	0 .2
Chile[9]	0 .1
Colombia[10]	0.07
Uruguay[11]	0.05
Venezuela[12]	0.05
Europe[12]	0.5 or 1

Source: 1) No till Farmer, March 1999;
2) FEBRAPDP, 2000;
3) AAPRESID, 2000;
4) Bill Crabtree, WANTFA;
5) Hebblethwalte, CTIC, 1997;
6) MAG-GTZ, CIMMYT, 1999;
7) CIMMYT, 1999;
8) Dr. Patrick Wall, CIMMYT, 1999;
9) Carlos Crovetto, 1999;
10) Roberto Tisnes, Armenia, 1999;
11) AUSID, 1999; 12) Estimates

Weed control, in which ploughing played a part, has to be undertaken in other ways, generally with herbicides during the transition to conservation agriculture, and an ecological evaluation is needed (Monnier *et al.*, 1994; Garcia Torres and Fernandez, 1997).

Such systems also have a major effect on soil protection against erosion, which was the main purpose for their use in the central Great Plains of the USA (Conservation Reserve Program) in the years 1930 –1940.

Adopting less energy intensive methods such as zero tillage can reduce the total emissions budget. Low-input or organic rice in Bangladesh, China, and Latin America is some 15-25 times more energy efficient than irrigated rice grown in the USA. For each tonne of cereal or vegetable from industrialised high-input systems, 3000-10,000 MJ of energy are consumed in its production. But for each tonne of cereal or vegetable from sustainable farming, only 500-1000 MJ are consumed (Pretty and Ball 2001).

Zero-till systems also have an additional benefit of requiring less fossil fuel for machinery passes. Fuel use in conventional systems (Tebruegge, 2000; Smith *et al.*, 1998) in the UK and Germany varies from 0.046-0.053 t C ha^{-1} yr^{-1}; whereas for zero-till systems, it is only 0.007-0.029 t C ha^{-1} yr^{-1} (0.007 is for direct energy use only; 0.029 includes the embodied energy in herbicides). Compared with the savings from reduced carbon loss and increased carbon sequestration in soils, these represent only a small proportion of total savings (approximately 7 percent).

Conservation agriculture (FAO concept) or agro-biological agriculture (CIRAD concept) also favour biological functioning of the soil, the most evident change being the increase in soil fauna and microflora. The function of conservation agriculture and zero-tillage systems is to protect the soil physically from the action of sun, rain and wind, and to feed soil biota. The result is reduced soil erosion and improved soil organic matter and carbon content.

Another important issue for zero-tillage (ZT) relates to herbicides. Some of the most interesting work in Brazil relates to herbicide-free ZT systems – with cover crops and green manures being used instead (Petersen *et al.* 2000). Participatory development of no-tillage systems without herbicides for family farming. Environment, Development & Sustainability, 1 (3-4) 235-252).

Increase of organic matter inputs to the soil

Increases in crop biomass can increase OM input into the soil, for example through introduction of new varieties as well as through agronomic management, such as nutrient management (especially nitrogen) and crop rotation. About 70-100 kg of N is necessary for sequestering 1 ton of C (Swift, unpublished). Increase in CO_2 content in the atmosphere due to climatic change can have a similar positive influence, the so-called "CO_2 fertilization effect"(Bazzaz and Sombroek, 1996). All these factors combined explain why in certain European countries (for example in Belgium), without input of manure and with conventional tillage practices, the organic matter content of cultivated soils has recently increased. Water management (irrigation), with an associated increase in productivity, can produce similar effects, especially in semi-arid regions. However, the development of irrigation is generally limited by other factors, such as availability of water resources and, the risk of salinisation. In certain countries, in addition to cover crops, associated crops also represent a substantial aid to increasing biomass.

The increases in biomass involve both aboveground biomass and roots. Considerable progress could be made in this connection, especially as concerns grasslands and pasture, by selection of deep-rooting species and varieties.

Crop residue management is another important method of sequestering C in soil and increasing the soil OM content. Residue-burning has negative consequences, even if they are sometimes mitigated by the great stability of the mineral carbon which is formed.

The positive effects of using crop residues to induce C sequestration have been estimated by Lal, 1997 at 0.2 Pg C yr^{-1} with transformation of 15 percent of the total C (1.5 Pg C globally). Generally, there is a linear relationship between the organic matter in the first 15 cm of soil and the quantity of crop residues applied.

Surface-applied crop residues decompose more slowly than those that are incorporated by tillage, because they have less contact with soil microorganisms and soil water. Angers *et al.* (1995) reported that conversion of maize residue C into soil organic matter in the 0 to 24 cm layer was about 30 percent of the total input; this value is higher than Lal's estimation. Evidently, there are qualitative differences between the residues: the lignin content of the residue has a highly positive effect on the accumulation. Roots are very easily transformed into stable OM.

Mulch farming and plant cover are specific land management practices allowing both coverage of the soil by specific plants, giving protection against erosion, and providing biomass residues to increase soil OM. To be completely effective, plant cover or mulch management should be carried out on site and in combination with conservation tillage (agrobiological management). The quantity of mulch should be in the range of several dozens of t ha^{-1} yr^{-1} in order to provide an important source of soil C up to 0.1 t ha^{-1} yr^{-1}, depending on the climatic zone (Lal, 1997). A great variety of plant species can be used to cover the soil. The quality of the plant residues is also an important factor (Heal *et al.*, 1997; Drinkwater *et al.*, 1998).

The soil has to be protected during the initial period of crop-growth; green manures have an important role in this connection. These have been used for millennia, mainly to increase fertility after their incorporation into the soil. Now they are considered as a crop in the rotation, which has a direct effect on soil protection during the growing period and an indirect one through their residues. Green manures can be sown during the seasonal break between the main crops or mixed in association with the crops, or perennially in areas under fallow. Some common examples of green manures are given in Table 6, which shows a prevalence of leguminous species. In the past, green manures were incorporated into the soil by ploughing. Now, conservation techniques require minimum or zero tillage and direct sowing through the vegetal cover.

TABLE 6
Different plant-based systems to increase carbon sequestration (from CIRAD, 1998)

Mulch	Associated plant cover	Green manures or cover crop
Maize	Maize/Mucuna	Avena
Sorghum	Frijol Tapado[1]	Crotalaria
Cotton	Maize and Mulch	Lathyrus
Soya	Rice and leguminous crops (*Sesbania, Crotalaria, Pueraria phaseoloides*)	Lolium, Lupinus (*angustifolius, luteus*)
Banana		Melilotus
Sugar Beet		Sesbania (cannabina, exaltata, speciosa) Mucuna (*aterrima, pruriens*) Trifolium Vicia (*angustifolia, articulata, bengalensis,* ervilia, faba, hirsuta, sativa, villosa, sinensis…)

[1] "Covered beans": Phaseolus vulgaris grown in a slash-and-mulch system of short fallows, without burning.

Several studies have shown that weed control is more efficient in cropping systems with a dead surface cover, due to the existence of a specific allopathic effect. In this case, the need for pesticides is reduced or eliminated.

Much evidence exists to demonstrate the effectiveness of soil cover, by living plants or by plant residues, in preventing erosion, by wind or by water. The direct impact of raindrops is prevented, with consequent protection of the soil structure and porosity.

The soil cover provided by plants during their growth cycle is often not always enough to prevent erosion. In Parana, Brazil, the following order was established for erosion intensity under different crops: coffee < maize < wheat < soybean < cotton < bare soil. Generally, crop residues in direct contact with the soil are more effective in preventing erosion than crops, and a few tons (5 to 10) per hectare, with differences between species, can prevent the soil loss and decrease runoff.

The soil cover increases the water infiltration rate by several hundred percent and prevents water evaporation; hence, soil moisture is increased. Especially in dry areas, soil cover has an important role in water economy. It also decreases the temperature, thus slowing the rate of OM mineralisation.

Green manures and cover crops can provide important contributions to soil carbon as experiences in Latin America demonstrate. There are some 45 000 farmers in central America who have adopted *Mucuna* (velvetbean) based systems, in which 150 kg N can be fixed per ha per year, and 35-50 tonnes of biomass added to the soil per ha per year. This represents a very large sequestering of carbon.

Composting or manuring are traditionally used in agriculture with proven beneficial effects on the soil. A problem in many countries is the decreasing source of such amendments, linked to animal husbandry. There is competition for plant residues or plant cover - to be used for feeding animals or for returning to the soil. But careful management associating cropping with livestock production can permit reintroduction of new sources of manure or composted manure.

Using sewage sludge or other urban residues is less effective, because of the low transformation rate, unless they are first composted. This practice has the advantage of recycling waste but presents an environmental risk of soil pollution and needs specific precautions.

Chapter 4
The different scenarios of C sequestration

Major attention is given here to the drylands and tropical zones, of interest to developing countries. As noted before, estimates must take into account the soil type and the agro-ecological region, but the main factors are the type of land use, and the specific soil and crop management. It is also important to take into account the criteria of degraded land, with reference to Oldeman *et al.* (1991) even if they cannot be related to specific soil organic matter contents.

LAND MANAGEMENT OPTIONS FOR CARBON SEQUESTRATION

A comparison is made between the latest evaluation of Lal (1999) for the FAO-IFAD project (Table 7), and the latest data of IPCC (2000), with a focus on the most beneficial practices in order to establish priorities. All the estimates are in ton ha^{-1} yr^{-1}. For this purpose, the activities or the practices are assumed to have a finite duration (20 to 50 years), corresponding to the finite capacity of the soils to store carbon (in relation with the type of soil). This is a very large range and it will be critical to tighten it up if carbon trading systems are to succeed.

Table 7
Main effects of land management practices or land use on carbon sequestration (t C ha^{-1} yr^{-1}) in drylands and tropical areas (from Lal, 1999)

	DRYLANDS (3 billion ha)	TROPICAL AREAS (humid and subhumid) (2 billion ha)	
CROPLANDS			700 million ha
Conservation tillage	0.1-0.2	0.2-0.5	
Mulch farming or plant cover	0.05-0.1	0.1-0.3	
Conservation agriculture	0.15-0.3	0.3-0.8	
Composting	0.1-0.3	0.2-0.5	
Nutrient management	0.1-0.3	0.2-0.5	
Water management	0.05-0.1		
GRASSLAND AND PASTURES	0.05-0.10	0.1-0.2	3 billion ha
AFFORESTATION		4 - 8	
AGROFORESTRY		0.2-3.1	1 billion ha

Croplands

On croplands, tillage is the most important practice, which can have a major effect on the carbon pool, either negative with conventional ploughing or positive, when conservation tillage is applied. For this latter practice, Table 8 shows the range of variation of C sequestration, expressed in t ha^{-1}, from 0.1-0.2 in semi-arid regions, to 0.2-0.5 in tropical- humid regions. The favourable effects of conservation tillage are very high during the first years, then reach a plateau; they can also be rapidly reversed if conventional tillage is reintroduced. Very often in the USA, conservation tillage is not a true no-tillage practice as is generally the case in Brazil or Argentina. No tillage or conservation tillage include crop residue management on site, which ensures the input of organic matter, and direct seeding of planting through the residue cover. Conservation tillage requires a minimum of 30 percent of crop residues, which is often not enough to cover the soil and prevent erosion. If there is a slope, 70 percent is often necessary (Benites, oral communication). Competition for residues exists for feeding animals, where equilibrium has to be found.

The second important practice - which has to be combined with the first one (no tillage) to be effective - is mulch farming. Lal gives values of 0.1-0.3 t C ha^{-1} yr^{-1}. The value depends on the quantity of mulch (1 to 6 t) and on the type of mulching. Cover crops have a very similar effect, or are even more effective than mulch if kept on the field. In this case, there is both above- and belowground organic matter with roots. The production of biomass by plant cover or mulch requires water, so the practice will depend on rainfall. Produced in rotation after harvest, the biomass obtained can be added to the C sequestration budget, which could reach 1 ton C ha^{-1} per year. Through the species, one can also influence the partition of C between above- and below- ground on the depth of the C incorporation (rooting depth). A list of the cover crop species used in different climatic conditions by CIRAD is given in Table 6 but there are no data on their specific effect on C sequestration. Organic wastes (sewage sludge ...) have a very low yield of stable soil carbon, yet may contain significant amounts of pollutants. Whenever possible such organic matter should be matured through composting. This is a valuable approach and C sequestration can be relatively high (0.2 to 0.5 t C for 20 t of compost/ha). However, finding good sources of compost is difficult.

For arid or semi-arid zones, the use of cover plants or mulching is very important in order to suppress the bare fallow or ameliorate the fallow. In these areas, the use of manure or compost can also be of fundamental importance to initiate water retention and crop production in desertified zones; one of the best examples is the development of tassa (small planting pits) in Niger to initiate vegetation development.

Fertilization, with the increase of biomass obtained, will increase the C available for sequestration in soil. But, to be effective, this sequestration implies the use of the former practices described, including no-tillage. So-called ‘agricultural intensification’ or use of irrigation (combined with good drainage) permits an increase of biomass production, but the conditions are not necessarily compatible with those required for carbon storage.

All the practices aimed at accumulating carbon in croplands will also restore degraded soils or prevent erosion: these are win-win situations. Organic matter loss by erosion is prevented and accumulation of organic matter will increase.

Forests

Besides afforestation - which depends largely on political decisions -, agroforestry represents a good technical and ecological management option. But it must be borne in mind that agroforestry is a complex system, comprising at least 18 different types of practices and with a virtually infinite number of variations (Cairns and Meganck, 1994). Trees are associated with crops or livestock or both. All the practices involve C sequestration. So crops should be grown under the practices presented before (no tillage, mulching, plant cover). The carbon uptake rate can be very high, because of sequestration both by trees and by crops: from 2 to 9 t C yr^{-1}, depending on the duration (15 to 40 years). Agroforestry can offer many advantages, especially for smallholder agriculture, be it in Africa or in South America (Sanchez *et al.*, 1999). But it will need some collective management of the space (for example for a watershed). Existing statistics indicate that some 185 million rural people use agroforestry products, and this could be developed further. The application of the Kyoto protocol or a post-Kyoto treaty will be a good opportunity to promote such initiatives, including tree planting, assuming that adequate socio-economic incentives can be provided under CDM.

Pastures and grasslands

Whatever the agroecological zone, overgrazing is the main cause of degradation but the mechanisms and their effects vary widely. In tropical areas, overgrazing induces compaction and waterlogging; in drylands it provokes mainly a decrease in soil cover and subsequent erosion (by wind or water) and desertification. If a priority has to be established, it would be for pastures and grasslands in drylands, which constitute barriers against desertification and erosion.

The technical way to achieve this is to increase soil cover and protection by above-ground-biomass and anchorage of this biomass by a well-developed root system. Other management factors involving grazing and fire control may be more difficult to apply, because of social aspects. Economic input and policy improvement can be determining factors.

SURFACE AREA CONCERNED AND CARBON SEQUESTRATION BUDGET

Many estimates or calculations are presented in IPCC (2000); Lal (2000 and 1997); and Batjes (1999), from which some data have been extracted (Table 8). A distinction is made between changes in land management and changes in land use.

For croplands, the evaluation from IPCC (2000), for developing countries (which corresponds roughly to the countries not yet included in Annex 1 of the Kyoto Protocol) is that improved management practices could involve 20 percent of the land (50 percent in 2040) with reference to an area of 700 million ha and a mean rate of carbon gains of 0.32 t ha^{-1} yr^{-1}.

For grazing land, 10 percent (and then 20 in 2040) of the 2104 million ha would be involved in the improvement of management, at a rate of 0.80 t C ha^{-1} yr^{-1}.

For agroforestry, 30 percent (and then 40 in 2040) of the 317 million ha could be better managed at a rate of 0.22 t C ha^{-1} yr^{-1} (which is a relatively low rate compared with Post and Kwon (2000) estimates).

It does not seem realistic to hope to improve (irrigated/wetland) rice fields for carbon sequestration. Priority is given to the reduction of methane emissions. The main proposals for land use change concern conversion of croplands to agroforestry or grassland, which involve very considerable areas. As for irrigated/wetlands rice fields, carbon sequestration cannot be the main motivation for wetland restoration.

Restoring or preventing soil degradation has to be the main priority, either for management practices or for changes in land use.

TABLE 8

Potential net carbon storage of additional activities under article 3.4 of the Kyoto protocol (from IPCC, 2000)

Activity (Practices)	Group*	Area (10^6 ha)	Adoption/conversion (% of area)		Rate of Carbon Gain	Potential (Mt C yr^{-})	
			2010	2040	(t C ha^{-1} yr^{-1})	2010	2040
a) Improved management within a land use							
Cropland (reduced tillage, rotations and cover crops, fertility management, erosion control and irrigation management)	AI	589	40	70	0.32	75	132
	NAI	700	20	50	0.36	50	126
Rice paddies (irrigation, chemical and organic fertilizer, and plant residue mgmt.)	AI	4	80	100	0.10	>1	>1
	NAI	149	50	80	0.10	7	12
Agroforestry (better management of trees on croplands)	AI	83	30	40	0.50	12	17
	NAI	317	20	40	0.22	14	28
Grazing land (herd, woody plant, and fire management)	AI	1297	10	20	0.53	69	137
	NAI	2104	10	20	0.80	168	337
Forest land (forest regeneration, fertilization, choice of species, reduced forest degradation)	AI	1898	10	50	0.53	101	503
	NAI	2153	10	30	0.31	69	200
Urban land (tree planting, waste management, wood product management)	AI	50	5	15	0.3	1	2
	NAI	50	5	15	0.3	1	2
b) Land-use change							
Agroforestry (conversion from unproductive cropland and grasslands)	AI	~0	~0	~0	~0	0	0
	NAI	630	20	30	3.1	391	586
Restoring severely degraded land (to crop, grass or forest land)	AI	12	5	15	0.25	>1	1
	NAI	265	5	10	0.25	3	7
Grassland (conversion of cropland to grassland)	AI	602	5	10	0.8	24	48
	NAI	855	2	5	0.8	14	34
Wetland restoration (conversion of drained land back to wetland)	AI	210	5	15	0.4	4	13
	NAI	20	1	10	0.4	0	1
c) Off-site carbon storage							
Forest products	AI	n/ae	n/a	n/a	n/a	210	210
	NAI	n/a	n/a	n/a	n/a	90	90
Totals	AI					497	1063
	NAI					805	1422
	Global					1302	2485

* AI: Kyoto Protocol Annex I countries (approx: industrial countries)
NAI: Non-Annex I countries (approx: developing countries)

Chapter 5
Main consequences and impact of carbon sequestration

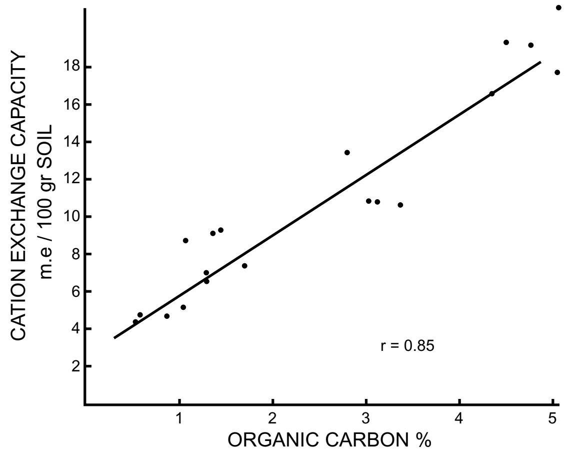
Carbon sequestration and an increase in soil organic matter will have a direct positive impact on soil quality and fertility. There will also be major positive effects on the environment, and on the resilience and sustainability of agriculture.

SOIL QUALITY AND FERTILITY

As mentioned before, organic matter has essential biological, physical and chemical functions in soils. OM content is generally considered one of the primary indicators of soil quality, both for agriculture and for environmental functions.

Organic matter is of particular interest for tropical soils (except for vertisols) with low -activity clays, i.e. having a very low cation exchange capacity. Cation exchange capacity increases in function of the increase in organic matter (Figure 12). Bio-availability of other important elements, such as phosphorus, will be improved and the toxicity of others can be inhibited by the formation of chelate or other bonds, for example, aluminium and OM (Robert, 1996a).

FIGURE 12
Relationship between organic carbon and cation exchange capacity of selected experimental soils



In agriculture with low plant nutrient inputs, recycling of nutrients (N, P, K, Ca) by gradual decomposition of plant and crop residues is of crucial importance for sustainability (Sanchez and Salinas, 1982; Poss, 1991).

With regard to physical properties, OM and living organisms associated with OM play the main role in soil aggregation at different scales of soil organization (Tisdall and Oades, 1982; Robert and Chenu, 1991) both at micro and macro level (figure 13). Aggregation and carbon sequestration processes are strongly associated (Golchin *et al.*, 1994; Angers and Chenu, 1998). Many properties depend on the soil fabric and on its stability, water retention and release to plants, infiltration rate and resilience to erosion and other physical degradation processes.

In the case of erosion, a correlation has been established between the historical decrease in soil organic matter and erosion development. All crop management for C sequestration favours soil cover and limits tillage, thus preventing erosion.

ENVIRONMENTAL IMPACTS

Carbon sequestration in agricultural soils counteracts desertification process through the role of increased soil organic matter in structural stability (resistance to both wind and water erosion) and water retention, and the essential role of soil surface cover by plant, plant debris or mulch in preventing erosion and increasing water conservation.

OM, which increases the soil quality, also protects through fixation of pollutants (both organic, such as pesticides, and mineral, such as heavy metals or aluminum) with, in general, a decrease in their toxicity.

Air quality is mainly concerned with the decrease in atmospheric CO_2 concentration, but attention has to be given to other greenhouse gases, particularly methane and nitrous oxide (CH_4 and N_2O). The main soil factor controlling their genesis is anaerobiosis (soil reduction), which is generally linked with hydromorphy. When pastures or rangelands are increased, the methane emission by cattle has to be taken into account.

In some environments and depending on climatic conditions (humid area) or soil properties (high clay content), N_2O can be formed. Hence careful balance of the different gas emissions has to be made.

Wetland rice culture represents the most complex system in relation to carbon sequestration. If OM is accumulated in wetland soil, CH_4 is also formed. The greenhouse effect of methane is far greater than that of CO_2. The usual strategy for preventing CH_4 formation is to decrease the duration of waterlogging, so that OM will be less protected from mineralization and CO_2 and N_2O or NH_4 can be emitted. In view of these various effects, it seems very difficult for the moment to jointly manage wetland rice production and carbon sequestration.

Recent developments of conservation agriculture in rice-wheat systems are very positive, however: rice yields can be maintained or improved without water saturation, puddling or soil reduction and with major water savings in the rice growing period. This new approach has been validated by farmers on several thousand ha in countries including India and Brazil.

Natural wetlands have similar anaerobic conditions with a smaller CH_4 emission than wetland rice fields and a greater potential for C sequestration, which can take the form of peat formation. They also have other important environmental advantages, so they should be protected; it would not be realistic to hope for a rapid increase.

Water quality is also improved by the decrease of erosion and runoff of water and pollutants. In the specific case of conservation tillage, strong OM mineralization with nitrate formation is avoided or minimized as well.

Changes in land use and land management also have an important effect on the partition of precipitation between runoff and storage or infiltration, with an increase of the latter under grassland, forest and conservation tillage with soil cover. Soil cover will prevent erosion. Hence, even if some runoff still occurs the water will be free of particles with associated pollutants (mineral trace elements, PO_4). Off-site pollution by soluble products will decrease also in relation with lesser runoff. This is one of the bases of the eco-conditionality in the US Farm bill since 1996. With such changes in agricultural practices the challenge for the water quality can be met. Once the changes have taken place over large areas the frequency and severity of floods will decrease as well.

The overall effect of increasing OM in soil is an improvement of soils buffer capacity and resilience to different kinds of degradation or stress.

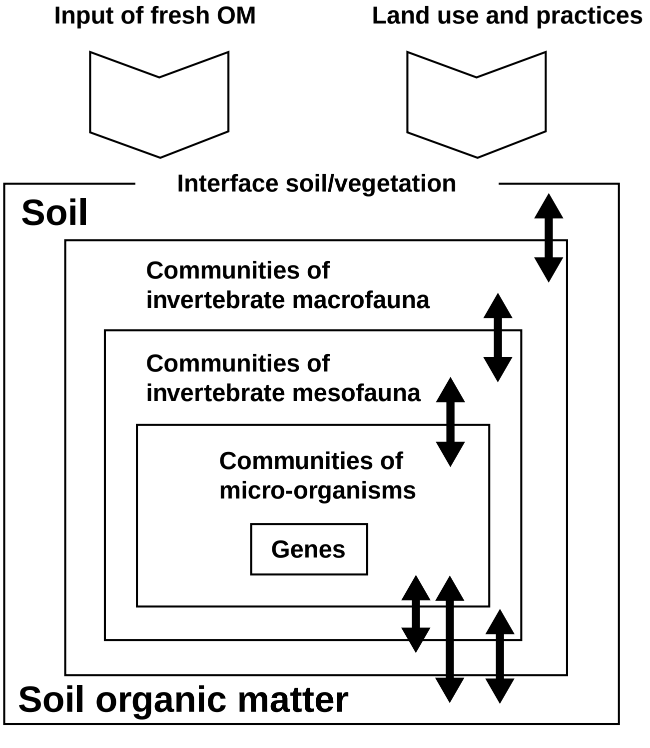
BIODIVERSITY AND SOIL BIOLOGICAL FUNCTIONING

Changes in biodiversity are evident when deforestation occurs. For afforestation, they will depend on the forest type established. Well-managed agroforestry systems also involve a wide range of biodiversity. Generally mammal biodiversity is preserved in reference to forests, but the numbers of bird species are halved and plant species decrease by a third (420 to 300), (IPCC, 2000). Likey (ICRAF) speaks of a mosaic of patches, each of them composed of many niches; a very favourable system for biodiversity.

Most intensive agriculture systems have in the past led to a strong decrease in biodiversity, parallel to the decrease in organic matter mainly through tillage and pesticide use (Rovira, 1994).

For croplands, the increase in biodiversity in relation to the increase in organic matter concerns mainly the soil biodiversity (Copley, 2000). Figure 13 presents a hierarchical organization of soil biodiversity, which depends directly on the input of fresh OM and the agronomic practices. This biodiversity ranges from genes to micro-organisms, fauna, and above ground biodiversity. The amount of bacteria can increase by several orders of magnitude, from 10^3 to 10^{12},as soon as the source of OM is abundant. No-tillage will favour development of fungi, which are very active in soil aggregation. However, only 5 to 10 percent of the soil micro-flora species are known and now, it would be possible, using new molecular techniques, to go further in the evaluation of specific or inter specific biodiversity of micro-organisms.

FIGURE 13
Hierarchical organization of soil biodiversity

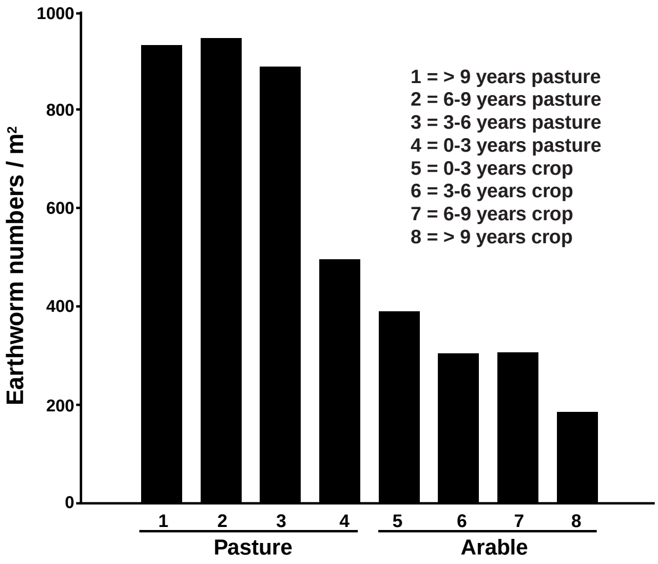


When fresh OM (mulch or plant residues) is present at the soil surface, there will be an increase in the different categories of fauna, mainly of decomposers. The detritus food webs will be stimulated (Hendricks *et al.*, 1986) (bacteria-fungi, micro arthropods-nematodes, enchytraeides- macro arthropods). Earthworms, termites and ants, which are the main groups composing the macro-fauna (> 1 cm) are often called soil engineers because of their major role in soil porosity (biopores) and structure; their number increases generally with an increase in

OM and with a decrease in soil disturbance (no-tillage) (Figure 14). They are good indicators of soil biological quality (Lavelle, 2000; Lobry de Bruyn, 1997) and they have a fundamental role to play in conservation agriculture. They are for example indispensable in ensuring the distribution throughout the soil (to more than 1 m) of OM accumulated on the surface.

An increase in carbon sequestration causes an increase in the operational biodiversity and more effective soil biological functioning, which is normally very low in most agricultural soils. Aboveground biodiversity in cropping systems (vegetation, birds...) also depends on the type of management.

Figure 14
Effect of previous cropping history on earthworm numbers on a range of farms in Canterbury. New Zealand (from Fraser in S*oil Biota*, 1994)



All the consequences and benefits of this approach should be appreciated with regard to the sustainability of agriculture even in respect of gene reservoirs and the biological control of pests.

BENEFITS FOR FARMERS

Farmers are not always sensitive to soil quality, unless there are other more tangible advantages. Soil conservation and prevention of land degradation are increasingly perceived as concrete benefits. Soil organic matter is also equivalent to a certain amount of nutrients and will retain supplementary water. All these benefits have been evaluated for US farmers (Lal *et al.*, 1998a).

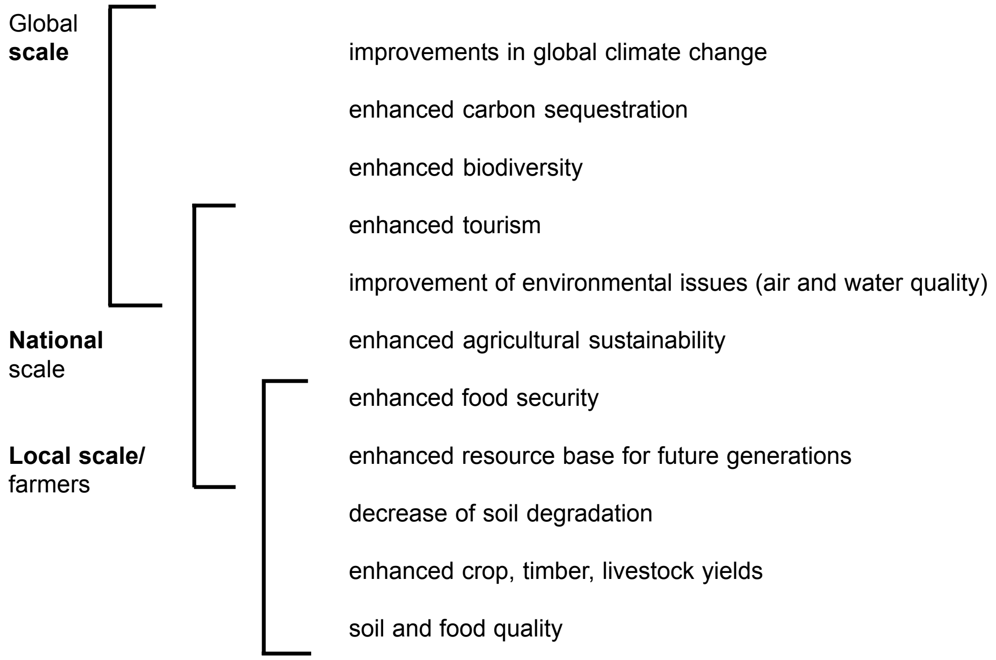
As regards conservation tillage and no-tillage, farmers can gain in terms of working time, energy and costs of materials: these are direct advantages that can be evaluated. Farmers will have to control pests in any case, but with higher soil quality, crops will generally be in better health and more resilient.

Well-managed agroforestry systems can be viable from an economic point of view. Some examples are well known, such as coffee, cacao, pepper, fruit trees or palms. These systems present advantages, but there will not always be immediate increases in yields, especially for normal crops.

Therefore, in order to achieve a win-win situation, other benefits will have to be added. These can come from various sources such as conventions or policy intervention (Izac, 1997), based on benefits such as listed in Figure15.

FIGURE 15

Principal benefits of sustainable soil carbon management at various spatial scales (from Izac, 1997)



It is essential that an economic value (as for tradable goods) be given to the quantity of C sequestered through the application of the Kyoto Protocol or a likely post-Kyoto treaty and of the Clean Development Mechanism (CDM).

Carbon 'boards of trade' or trading systems first emerged during the year 2000. There are three ways to calculate the value of carbon in such trading and exchange systems: i) the first option is to allocate a value through calculation of the external costs of each ton of carbon emitted to the atmosphere by assessing damage, mitigation and adaptation costs; ii) the second option is to calculate the cost of implementing projects that would deliver a particular policy target, such as for the Kyoto Protocol; iii) the third is to assess what businesses are currently willing to pay others as an offset for their own carbon emissions – companies are, in effect, hedging against the risk of future enforced payments to meet tougher carbon emission regulations.

The externalities of carbon have been calculated in Europe to be US$ 95 per ton according to ExternE and Open Fund models (Pearce *et al.*, 1996; Eyre *et al.*, 1997; Holland *et al.*, 1999). This is higher than the $20-28 per ton values estimated in the early 1990s (Fankhauser, 1994; Sala and Paruelo, 1997).

A number of carbon exchange or trading systems have recently been established, in which carbon credit values are being set at much lower levels than the real external costs. The range is wide – from US$1-38 per ton of carbon, though the most common values are in the $2.50-5.00 range. These per ton monetary values are considerably less than the optimistic wishes of $100 per ton of some farmers in the US.

For real impacts on climate change to occur, sinks must become permanent. If land under conservation tillage is ploughed, then all the gains in soil carbon and organic matter are lost. This raises a core challenge for trading systems, as there is clearly no such thing as a permanent emissions reduction nor a permanent sequestered ton of carbon. These can be reversed at any time. Trading and exchange systems must therefore address the issue of permanence risk – and almost certainly adopt lower bounds for both carbon sequestration potential and for allocated monetary values. The risk of reversal will be lower during the time period bound by a contract between a buyer and seller of carbon reduction credits, but permanence will only be guaranteed if there are long-term changes in behaviour and attitudes. Over time, the scientific and measurement procedures may mature too, thus bringing greater clarity to the terms of trade.

Trading and exchange systems do offer significant new options, but it is also clear that emissions trading alone cannot solve climate change problems, as substantial cuts in emissions will also be needed. Perverse outcomes are also possible in the early stages of trading systems, such as the conversion of native forests to fast-growing tree monocultures so as to obtain reward for emissions credits, or the ploughing of pastures so that they can be reconverted to qualifying zero-tillage systems.

A few of the trading systems are summarized in a recent paper (Pretty *et al.*, 2001). Most are private sector, and are unlikely to be affected by the lack of progress on Kyoto.

The so-called additional activities in Article 3.4 of the Kyoto Protocol would need to be approved by the next COP and applied to the developing countries. This is the real challenge. The system will also need specific intergovernmental, but also governmental policy development, with a participatory approach (Benites *et al.*, 1999) and technical actions. For European countries and the US, practices, which sequester carbon in soil, have to be considered for agro-environmental funding.

EFFECTS OF CLIMATIC CHANGE

While an increased content of atmospheric greenhouse gases is leading to climatic change, numerous complex, contrasting and reverse effects will occur as well (Brinkman and Sombroek, 1996; Impacts potentiels 2000).

All the experimental results demonstrate that an increase in CO_2 concentration in the atmosphere induces an increase in biomass or in the Net Primary Production (NPP) by carbon fertilization, playing a major role in plant photosynthesis and growth. The gain in CO_2 fixation could be important. The increase in productivity measured for a doubling of the CO_2 concentration (predicted for the year 2100) is about 30 percent for C3 plants. Another important effect of CO_2 increase is a decrease in transpiration from the stomata which results in increased water use efficiency (WUE), particularly in C4 plants. So far as water is concerned, the net effect of CO_2 on the reduction of plant transpiration is favourable (Gregory *et al.*, 1998). Evidently, in order to achieve an increase in yield in the field, other plants needs have to be met in the normal way, including available water and nutrients.

As far as the carbon cycle is concerned, there will be an increase in C sequestration by the aboveground biomass and a correlated increase in carbon input to the soil from plant residues and from the growth and decay of fine roots. The compounds of roots have a higher C/N ratio and are more stable.

With regard to soil C sequestration, another factor, which will play an important role, is temperature, which may increase over part of the globe. Such an increase could provoke a higher rate of OM mineralization by microbes and a higher respiration rate by roots. This effect of temperature on mineralization will be significant in cold countries, where temperature is now a limiting factor, and there, an increase in CO_2 emissions may be expected. But in most parts of the world, C sequestration will increase (van Ginkel *et al.*, 1999).

Models can be used to estimate the effect of climatic change on C sequestration. Many recent results already confirm the increasing rate of growth for forests in temperate and northern countries. For tropical forests, some measurements exist in Amazonia and an increase in biomass has been measured (Phillips *et al.*, 1998) of 0.62 t C ha^{-1} yr^{-1}, which for about 7 billion ha would mean a C sequestration of 0.44 Gt C yr^{-1}. The reason behind this is not simple, because the influence of El Niño is probably involved in the increase in humidity in this area.

Chapter 6
Proposals

WHAT ARE THE MOST REALISTIC PROPOSALS CONCERNING CARBON SEQUESTRATION?

With reference to Article 3.3 of the Kyoto Protocol, regarding afforestation, reforestation and deforestation, and to the period from 2008 to 2012 for the countries mentioned in annex 1 of the protocol, the balance between the first two activities (46 million t C yr^{-1}) and the third (deforestation –90 million t C yr^{-1}) is negative. Also the FAO forecast for deforestation in developing countries (not including China) is 90 million ha in the next ten years. Hence, forest preservation must be a priority in all countries.

If the application of Article 3.4 (Table 8) is considered, referring to both improved management and change in land use, developing countries have the greatest potential for carbon sequestration, except in forest management (100 Mt C yr^{-1} for developed, 70 for developing countries). Management of croplands (125 Mt C yr^{-1}) or grazing land (240) and change in land use with conversion to agroforestry (390) are of major interest for C sequestration. The total represents 0.53 Pg or Gt C sequestered per year, which is significant independently of the other advantages, representing 10 percent of the total emission by fuel combustion. This should be considered when both additional activities and extension of the Kyoto Protocol or an eventual post-Kyoto treaty to developed countries are discussed. If the surface area is extended, carbon sequestration in drylands and tropical areas could amount to about 1,5 Pg C yr^{-1}.

Batjes (1996) discusses carbon sequestration potential with special reference to the state of land degradation. The approach distinguishes slight and moderate degradation, which can be restored by improved land management, and strong and extreme degradation, which require specific works of restoration, implying conversion to a new land use.

Strong degradation is mainly linked to deforestation (113 million ha, Table 7). Conversion to agroforestry (Table 8) in more humid areas and to grasslands in drylands can be sustainable solutions.

For other types of degraded soils, projects can be developed using bioremediation by plants. For landfills and highly polluted soils it is possible, to use species adapted to high concentration of toxic metals. Species adapted to saline soils, such as *Prosopis juliflora* have different uses, and can sequester considerable amounts of C (12 t ha^{-1}).

Moderately degraded lands (910 million ha), where the main degradation process is erosion, have to be better managed as a priority. Wind erosion, occurring mainly in the drylands of Africa and Argentina, can be prevented by conservation agriculture or better grazing management. To prevent erosion by water, which occurs more in the central part of South America or Africa (tropical areas), both conservation agriculture and agroforestry can be used. Considering the forecasts of IPCC (Table 7), 50 million ha seems a minimum for improved management. If the incentives are strong, it could be higher. The annual rate of carbon sequestration can be higher than 0.36 t (Stewart, 1995). For grazing land, improved management of 168 million ha may be a more ambitious objective.

WHAT ARE THE MAIN IMPLICATIONS FOR AGRICULTURE?

Such proposals have considerable consequences for agriculture but it is clear that there are good options for crop management.

Croplands and the crop component of agroforestry

The first major experience was the conservation tillage developed in the Great Plains of the USA, with a continental temperate climate. This was quite successful for erosion prevention but a little less so for carbon sequestration.

Variants of conservation agriculture have become widespread: they are being applied by farmers over some 60 million ha in many countries, including Brazil, Argentina, the USA, Australia, India, and are being validated in several African countries as well. They involve the agro-biological management of soils and cropping systems (CIRAD 1996,1998,1999).

The main principles are:

- no-tillage (or minimum tillage)
- maintain permanent soil cover by vegetation (normal crop and additional plants) or plant residues
- direct sowing through a permanent soil cover of vegetation or crop residues
- produce biomass and cover the soil with vegetal mulch using adapted plants (see Table 6).

Such systems entail a high rate of carbon sequestration because they combine the effects of no-tillage with the maximum input of organic matter, in the form of crop residues or cover crops. The in situ plant cover is preferred over mulch brought from other land because of the importance of below ground organic matter derived from roots, plus possible fuel needed to transport the required biomass/mulch; this also implies C losses in other places. In agroforestry, the same practices can be used for crops. Since part of the carbon sequestration related to trees can be added, the combination makes a very effective system.

If the method is to come into more general use, some new problems which may arise will have to be solved. One of these concerns weed control in the first 1-2 years of no-tillage, where some chemical control (use of herbicides) may be needed. Glyfosate has come into general use because of its effectiveness on graminaceous or perennial species. However, a careful study on the accumulation, residence time and ecotoxicity of these products in soils is still needed (Garcia Torres, 1997).

Other technical and social and economic problems, which can limit the generalisation of these practices in Africa, are the competition for vegetal material between use by extensive livestock and use to protect the soil. A good association of crops and livestock can be established only if there is an increase in biomass production (for example, with green manures).

THE IFAD-FAO PROJECT AND THE CLEAN DEVELOPMENT MECHANISM (CDM)

In continuation of a first collaborative programme on the implementation of the Convention to Combat Desertification (CCD) within the framework of a Memorandum of Understanding (MOU), FAO and IFAD started in 1999 a second project "*Prevention of Land Degradation, Enhancement of Soil and Plant Biodiversity and Carbon Sequestration through Sustainable Land Management and Land Use change*".

The first objective of the IFAD-FAO project is to interface food security, carbon sequestration and the fight against desertification, and to show that the application of the Kyoto Protocol or of a post-Kyoto treaty is related to the conventions on Biodiversity and Desertification. An expert consultation was held in Rome in 1999 and papers by Koohafkan, Mansuri and Young show a clear relationship between carbon sequestration and biodiversity, the prevention of land degradation and desertification (FAO/IFAD, 1999).

The second objective of the project is to encourage monitoring and measurement in the field. A large range of carbon sequestration rates have been reported for the different land use systems. The project is analyzing quantified scenarios for different agroecological zones of Latin America and the Caribbean (2 sites in Mexico, 1 site in Cuba), including the benefits for the farmers (yield, cost reductions, labour savings, other benefits), for different land use conversions. One of the most important conversions concerns the alternatives to shifting agriculture. The use of different models, mainly Century (Parton, W.J., *et al.* 1988,1994), and Roth-C 26 (Coleman, K. and Jenkinson, D.S.,1995), allows estimation of the carbon dynamics and the quantity of organic matter necessary to ensure sustainable production with the optimisation of other objectives (minimum land degradation, maximum biodiversity conservation).

As a follow-up to this project, a Letter of Agreement was signed between FAO and GM in August 2001 on a normative Programme for “Carbon Sequestration Incentive Mechanisms to Combat Land Degradation and Desertification”. The central objective of the programme is the collection, assessment and elaboration of information materials produced by the numerous projects and case studies implemented in different dryland areas of the world. The Kyoto Protocol also provides different opportunities to finance concrete projects, for example through the Clean Development Mechanism (CDM) or through project-based activities (LULUCF). These latter projects are mainly devoted to forestry. Other subjects are the economic benefits of reduced tillage (Canada) or of agroforestry (Mexico, Guatemala).

A few projects concern monitoring the forest biomass and two methods have been developed. The first one is based on permanent plots which give statistically good results (see the proposal below). The second uses remote sensing in different ways, from satellite imagery to aerial photographs from low-flying air planes using GPS. Possibilities also exist to develop projects with funding by the Global Environmental Facility (GEF) or the World Bank.

A PROPOSAL ON A LAND MONITORING SYSTEM FOR VERIFICATION OF C SEQUESTRATION

If an extension of the Kyoto Protocol or a post-Kyoto treaty is decided upon, tools for monitoring, verification or certification will be needed in order to ascertain the changes in carbon pools in relation to the type of soil, climatic conditions, land occupation and different land management practices. European countries, such as France and Great Britain, are establishing monitoring systems. But for the requirements of Kyoto 3.4 to be fulfilled (“uncertainties, transparency, verifiability”) it will be necessary for soil/land resource survey organization of developing countries to undertake soil monitoring systematically.

So long ago as 1991 it was argued that they should do so (Young, 1991); but to date they have not done so. The proposal is to set up a land monitoring network which represents the most permanent component of the ecosystem, with a choice of a systematic geographical grid. The scale is open to discussion, taking into account financial aspects and land heterogeneity. In Europe, the preference was for grids of 16 by16 km (France) or 8 by 8 km (Great Britain) which take into account both the diversity of soils and land occupation.

The geo-referenced permanent plots are the support for profile description, sampling for analysis and conservation of the samples. Present and past land occupation and agricultural practices have to be documented. It should be realized that a five to ten year period is the minimum timescale to monitor changes in carbon pools. The network should be linked to a relational digital database with soil and land occupation data but also other biophysical or socio-economical conditions which enable the determination of the spatial distribution at different scales (national, regional) and the different implications (geographic information system). The specific problems of baseline determination of reference plots, which are specific questions raised by IPCC, can easily be solved.

A similar monitoring process, on a 16 by 16 km grid, has been developed for the European Forest Health Network and was recently used to estimate carbon storage by the French forest ecosystem. In this case, both the carbons present in the biomass and that in the soil was determined with a breakdown of their different components (litter, roots). Such a monitoring system can be put to many uses: soil carbon sequestration, soil quality and degradation, soil and water pollution, forest health, changes in biodiversity, etc. Therefore, in parallel to the measurements of changes in carbon sequestration, some benefits other than variations of yield can be evaluated in relation to decrease of soil degradation (erosion, desertification) or increase in biodiversity.

A few sites can be selected by eco-region and land occupation with different practices, to be monitored with more equipment for a more detailed evaluation of stocks (for example, using carbon isotopes which permit the identification of the OM source (in case of land use conversion from C3 to C4 plants or vice versa) or to measure the carbon fluxes. Thus, links have to be established with networks such as Euro flux (in forests) or the Terrestrial Observation Initiative (TOC terrestrial carbon observation).

Remote sensing will be a very useful tool to extrapolate the results and map the vegetation cover and land use, but it cannot replace the need of real, measured data on the changes in soil C stocks.

A set of analytical methods can be proposed (ISO standards) from the most simple analyses (total organic carbon and bulk density) which permits the calculation of pools, to more elaborate ones (distinction between carbon compartments, measurements of changes in properties) which allow evaluation of causes and main effects. The use of Geostatistics will help in the spatial extrapolation of the results.

WHAT ARE THE MAIN GAPS?

Important questions have to be resolved and field data are missing concerning the effect of the different C-level controlling factors over a 20 to 50 year period: soil type, climatic conditions, land uses and agricultural practices:

- what is the maximum C sequestration obtained in these different conditions,
- what kinds of carbon compounds are sequestered, which residence time and which function
- in soil,
- how can the SOM input due to roots be evaluated (qualitatively and quantitatively),
- how can good data for validating and running C models be obtained,
- how can monitoring results be generalized to national and regional scales,
- need for economic data especially for small farmers,

- organic matter, biodiversity and soil biological functioning,
- how can the input and dynamic of organic matter be managed (Fernandez *et al.*, 1997; Heal *et al.*, 1997),
- which problems may arise after a certain period: change in physical properties, other GHG emissions, pest incidence,
- necessity to take into account the other GHG (N_2O and CH_4) fluxes,
- ecological approach and sustainable agriculture.

NEW PROJECTS AND PERSPECTIVES

Following the last FAO GTZ meeting on verification of country-level carbon stock and exchanges (FAO/GTZ, 2001) it appears necessary to establish benchmark sites in developing countries for monitoring and evaluation. Such benchmark sites will be proposed in Brazil, where there are many historical experiments (chrono-sequences) concerning deforestation and the development of grasslands or croplands. Such sites could be used to set up the methodologies and models proposed by IPCC and adapt them to the tropical countries.

Using some specific techniques (C isotopes, OM fractionation) it will be possible to obtain a better knowledge of the effect of different management practices on C sequestration. Some general and practical recommendations will be formulated and published in a “Guide for carbon stock evaluation in soils”.

On the same sites the effects of C sequestration on soil properties and soil biodiversity should be measured in order to evaluate the full benefits of the system.

In 2000 a new international network was created, the DMC (Direct sowing, Mulch based systems and Conservation tillage) which now includes 60 international and national institutions.

CIRAD joined this network and with different French cooperation fundings set up a plan of action in several developing countries (Brazil, Madagascar, Mali, Laos, Tunisia), where different agricultural practices are tested with measurement of stocks and fluxes of CO_2 and N_2O emissions at benchmark sites.

The German government through GTZ (Deutsche Gesellschaft fuer Technische Zusammenarbeit) has established a partnership with the African tillage network. The World Bank is strongly involved in many diffusion and extension programmes on direct sowing and associated practices , especially in Brazil. A meeting was held in Pakistan, February 2001, on conservation agriculture in rice-wheat system. Another one was held in Spain on conservation agriculture, October 2001.

The Dryland Land Degradation Assessment (LADA) is a project to be implemented by FAO under the UNEP Global Environmental Fund (GEF). The project is intended to assist in the development of drylands through provision of better information on land degradation.

CONCLUSION

The development of agriculture during the past centuries and decades has entailed consumption of soil carbon stocks created during a long-term evolution. In most of cultivated lands in the arid and semi arid regions in particular this has led to reduced land productivity due to land degradation and desertification. It is time now to reverse this trend. This has been shown feasible, but only if the type of agriculture is changed. The Kyoto protocol and anticipated post-Kyoto agreements favouring C sequestration in soils are good opportunities to facilitate this process. Soils can sequester around 20 Pg C in 25 years, more than 10 percent of the anthropogenic emissions. At the same time, this provides other important benefits for soil, crop, and environment quality, for the prevention of erosion and desertification, and for the enhancement of biodiversity.

Farms, grasslands, and savannahs have the potential to store carbon in the soil and the people have a great need for the land practices that improve soil carbon storage and productivity.

Carbon sequestration holds the promise of bringing win-win options and new benefits into dryland farming communities. The attention of Governments need to be drawn to these potential benefits and the need to initiate a process for data collection and analysis of carbon stock and fluxes under different selected sites on a pilot scale.

These benefits result from the fact that organic matter is a key factor in soils which determines a cascade of properties or functions relative to soil properties, buffer effect, resilience and sustainability. Biodiversity depends on OM content, and its increase in the soil will enable new functions. 'Soil engineers' (macrofauna) will, for example, ensures some functions of tillage. This concept implies the development of specific land use and land management practices. Some priorities can be defined for degraded lands with adapted measures for croplands, pastures and agroforestry. Development of conservation agriculture will be the key.

It will be easier to develop conservation agriculture for crops in developing countries because of the severity of land degradation in these regions. This is the case of Brazil and Argentina where the development of new practices, especially no-till and direct drilling is very rapid. In Asia the rice - wheat rotation without tillage is now beginning to expand and such practices could be generalized very rapidly. Improvement of degraded pastures and the expansion of agroforestry will need more effort and more time. Europe seems to be the most difficult to convince even though the consequences of conservation agriculture for water quality have now become clear.

Evidence from low-income countries, in particular, is that farming communities face many obstacles in adopting improved practices, even when they know of the potential benefits. There are also knowledge and data gaps associated with practically all the regional and global extrapolations underpinning the quantitative analysis, as well as problems in measuring and interpreting field data on carbon fluxes. Data are missing on different ecosystems or agrosystems. Criticisms have also been levelled at soil carbon sequestration analyses that overstate potential benefits by not fully accounting for the total flux of carbon associated with fertilizer production, irrigation, and the application of organic manure. There are also important issues of the trade-offs between the use of available sources of organic resources as well as soil organic matter for carbon storage versus exploitation for crop growth which should be addresseed.

A good first step to addressing these problems will be the development of a measurement and monitoring Manual. The Manual should build upon the existing work of the Intergovernmental Panel on Climate Change, be drafted by a small group of experts, then widely circulated to experts and stakeholders for review.

It is imperative that at this stage some pilot projects should be developed through the Global Environmental Facility (GEF), the Global Mechanism (GM) and the World Bank to test different approaches to enhance carbon sequestration in the drylands, through adoption of techniques that can promote soil fertility and productivity. Such pilot projects would provide the mechanisms to generate more accurate data on carbon stock and fluxes under different farming systems, at the same time these pilot projects can prepare the ground for large-scale applications that can eventually permit certified emission reductions to be traded with industrialized countries when the ratification process for the Kyoto Protocol or a post Kyoto treaty is completed. A demonstration pilot project would help create monitoring and measuring protocols for soil carbon, illustrate the economic benefit of such efforts to landowners, and the carbon benefits of such projects to potential investors.

More awareness is required to bring the decision makers to realize the opportunities that exist in dryland agriculture to decrease carbon emissions and increase carbon sequestration and storage in soils and vegetation. Therefore, an important activity to be included in the design of the proposed pilot activities would be directed at building more awareness at all levels to the prospects and potential benefits for carbon sequestration at local, national, regional and global levels.

In this context, FAO will have important roles to play: in validation and promotion of concepts, secondly to help to measure, monitor, model, and then organise networks in order to assist small farmers to develop and adapt practical solutions. USA is devoting considerable resources to the issue. Benchmark sites in tropical areas, on existing land management chrono-sequences, can be of interest to improve the methodologies and models for C dynamics and to measure all the effects.

While the majority of land use projects to date have been in the forest sector, soil carbon projects in semi-arid and sub-humid regions provide the following unique opportunities:

The land has relatively low opportunity cost relative to humid tropical forests, where in many cases climate mitigation may not be able to compete with logging or agricultural land demands. Large areas of degraded and desertified lands are in need of technical assistance and capital for restoring farmlands, grasslands, and savannahs. While exact estimates of desertification are difficult to obtain, estimates range from 3.47 to 3.97 billion hectares of desertified land (Lal et al 1998a).

Therefore, while the tons of carbon per hectare is relatively small relative to forests, the overall potential for cost effective climate mitigation is quite large. Arid regions of the tropics have very low rates of energy emissions, so they do not present great opportunities for reductions in their energy sector, nor do they have large areas of humid tropical forests, so they do not qualify for many forest-based projects. Soil carbon projects offer an opportunity for semi-arid and sub-humid regions to meaningfully participate in climate mitigation, while improving human well being.

To be successful soil sequestration projects and activities will need to have a strong sustainable development component, such that the projects improves the livelihood of farmers by improving agricultural productivity, reducing the risk of crop failure, providing access to better agricultural inputs. Soil carbon sequestration efforts are more likely to succeed if they build upon existing institutions, initiatives and organizations.

Opportunities exist to build partnerships with industrial country institutions to initiate soil carbon sequestration activities through pilot projects involving local communities and networking with the global networks on carbon sequestration. Capacity building and training of farmers will represent an important component of such projects. The GEF also has the potential to consider co-funding such activities within the context of its support to the implementation of the UN-FCCC. The interface between the three Conventions UN-CCD, the UN-FCCC, and the

UN-CBD in respect of the development of the dryland areas should constitute the main thrust of Dryland Development Programmes.

There is a need to initiate studies to evaluate the potential impact of some of ongoing projects, such as green belts, afforestation programmes, and rangeland rehabilitation programmes to assess their potential contribution to carbon sequestration. Moreover, planned activities to produce organic manure and convert plant residues (paddy straw in particular) into organic manure, instead of burning it, need to be carefully assessed with respect to carbon. The development of alternative renewable energy sources such as biogas, wind energy and solar energy should also be considered.

The current projected major change in agriculture is a true green revolution, even more widely applicable and sustainable than the earlier one.

References

Alexandratos, N. (ed). 1995. World Agriculture towards 2010. FAO and John Wiley and Sons. 488 pp.

Andreux, F., Choné, T. 1993. Dynamics of soil organic matter in the Amazon ecosystem and after deforestation: basis for efficient agricultural management. 51 pp. Centre National de la Recherche Scientifique, Nancy.

Angers, D.A., Carter, M.R., Gregorich, E.G., Bolinder, M.A., Donald, R.G., Voroney, R.P., Drury, C.F., Liang, B.C., Simard, R.R, Beyaert, R.P. 1995. Agriculture management effects on soil carbon sequestration in Eastern Canada. pp. 253-264. *In* Beran, M.A. ed. *Carbon Sequestration in the Biosphere, NATO ASI Series. Vol 1 33* Springer-Verlag, Berlin and Heidelberg.

Angers, D.A., Chenu, C. 1998. Dynamics of soil aggregation and C sequestration. In: Soil processes and the carbon cycle. Lal, R., J.M. Kimble, R.A. Follett, and B.A. Stewart eds. CRC Press, Boca Raton, FL. Chapter 14, pp.199-206

Arrouays, D. , Pélissier, P. 1994. Changes in carbon storage in temperate humic loamy soils after forest clearing and continuous corn cropping in France. *Plant Soil* 160. 215-223.

Arrouays, D., Deslais, W. Daroussin, J., Balesdent, J., Gailland, J., Dupoucy, J.L., Nys, C., Badeau V., Belkacem, S. 1999 Stocks de carbone dans les sols de France: quelles estimations? C.R. *Acad Agric. Fr* 85. 278-292.

Baldy, C. 2000. Conservation du milieu naturel tropical avec des plantes de couverture et des arbres d'ombrage. *Cahiers Agricultures* 9 (4) : 267-278.

Balesdent, J. 1996. Un point sur l'évolution des réserves organiques des sols de France. *Etude et Gestion des sols* 3 (4) : 245-260.

Balesdent, J., Arrouays, D. 1999. Usage des terres et stockage du carbone dans les sols du territoire francais (1900-1999) *C.R. Acad. Agric. Fr* 85 (6): 265-277.

Balesdent, J., Chenu, C., Balabane, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and Tillage Research* 53: 215-220.

Balesdent, J., Arrouays, D., Gaillard J. 2000. MORGANE : un modèle de simulation des réserves organiques des sols et de la dynamique du carbone des sols. *Submitted to Agronomie.*

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47: 151-163.

Batjes, N.H. 1999. Management options for reducing CO_2- concentrations in the atmosphere by increasing carbon sequestration in the soil. ISRIC. Wageningen, The Netherlands. 114 pp.

Bazzaz, F., Sombroek, W.G. (eds) 1996. Global Climate Change and Agricultural Production. FAO and Wiley, Chichester.Benites,J., Dudal,R., Koohafkan, P. 1999. Land, the platform for local food security and global environmental protection. *In World Soil Resources Report 86*. FAO, Rome. p.37-42

Bilan et gestion des gaz à effet de serre dans l'espace rural. 1999. Comptes Rendus Académie Agriculture de France Vol 85 n. 6, 392 pp.

Brinkman, R., Sombroek, W.G. 1996. The effects of global change on soil conditions in relation to plant growth and food production. *In* F. and W.G. Sombroek eds. *Global Climate Change and Agricultural Production.* Bazzaz FAO and Wiley, Chichester, UK. p 49-63.

Buyanovski, G.A., Wagner, G.H. 1998. Changing role of cultivated land in the global carbon cycle. *Biology and Fertility of Soils* 27: 242-245.

Cairns, M.A., Meganck, R.A. 1994. Carbon sequestration, biological diversity and sustainable development: integrated forest management. *Environmental Management* 18 (1): 13-22.

Cambardella, C. 1998. Experimental verification of simulated soil organic matter pools. *In* Lal L., Kimble J.M., Follett R.A., Stewart B.A. eds. *Soil processes and the carbon cycle.* CRC Press, Boca Raton FL. p 519-526

Cerri, C., Feller, C., Balesdent, J., Victoria, R., Plenecassagne, A. 1985. Application du traçage isotopique naturel 13C à l'étude de la dynamique de la matière organique dans les sols. *C.R. Acad. Sc. Paris*, Ser 2, 300: 423-428.

Chauvel A., Grimaldi, M., Tessier, D. 1991. Changes in soil-pore-space distribution following deforestation and revegetation: An example from the Central Amazon Basin, Brazil. *Forestry Ecology and Management* 38: 259-271.

Choné, T., Andreux, F., Correa, J.C., Volkoff, B., Cerri, C.C. 1991. Changes in organic matter in an Oxisol from the Central Amazonian forest during eight years as pasture determined by ^{13}C isotopic composition. *In* Berthelin, J. ed. *Diversity of environmental biogeochemistry.* Elsevier, Amsterdam. p. 397-405.

CIRAD. 1996 Agriculture au Brésil. Agriculture et Développement, 12 décembre 1996, Cirad, France. 76 pp.

CIRAD. 1998 Gestion agrobiologique des sols et des systèmes de culture. *Actes de l'Atelier International* 23-28 mars 1998. Antsinabe, Madagascar, ed F. Rasolo M. Raunet 658 pp.

CIRAD. 1999 Ecosystèmes cultivés : l'approche agro-écologique. Agriculture et Développement, 21 mars 1999, Cirad, France. 109 pp.

Coleman, K. & Jenkinson, D.S. 1995. RothC-26 3. A model for the turnover of carbon in soil: model description and users guide. ISBN 0951 4456 69.

Coleman, K. & Jenkinson, D.S. 1995. RothC-26 3. A model for the turnover of carbon in soil. *In* D.S. Powlson, P. Smith & J.U. Smith eds. *Evaluation of soil organic matter models using existing long-term datasets.* NATO ASI Series I, Volume 38, Springer-Verlag, Heidelberg: p 237-246.

Copley, J. 2000. Ecology goes underground. *Nature* 406: 402-454.

Dao, T.H. 1998. Tillage system and crop residue effects on surface compaction of a Paleustoll. *Agronomy Journal* 88: 141-148.

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

De Moraes, J.F.L., Volkoff, B., Cerri, C.C., Bernoux, M. 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondonia, Brazil. *Geoderma* 70: 63-81.

Diaz, S., J.P. Grime, J.P., Harris, J., McPherson, E. 1993. Evidence of a feedback mechanism limiting plant response to elevated carbon dioxide. *Nature* 364: 616-617.

Dick, W.A., Blevins, R.L. Frye, W.W. Peters, S.E. Christenson, D.R., Pierce, F.J., Vitosh, M.L. 1998. Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt. *Soil & Tillage Research* 47: 235-244.

Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gas? *Agroforestry systems* 31: 99-116.

Dregne, H.E. (ed) 1992. Degradation and restoration of Arid Lands. Texas Tech. Univ. Lubbock.

Drinkwater, L.E., Wagoner, P. & Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* 396: 262-265.

Dupouey, J.L., Siguand, G., Bateau, V., Thimonier, A., Dhole, J.F., Nepveu, G., Bergé, L. Augusto, L., Belkacem, S., Nys, C. 1999. Stocks et flux de carbone dans les forêts françaises. *C.R. Acad. Agric. Fr* 85 (6): 293-310

El Titi A. and Landes H. 1990. Integrated farming system of Lautenbach: a practical contribution toward sustainable agriculture in Europe. *In* Edwards, C. *et al.* eds. *Sustainable Agricultural Systems*. Soil and Water Conservation Society, Ankeny, Iowa.

Eyre N., Downing T., Hoekstra R., Rennings K., and Tol R S J. 1997. *Global Warming Damages.* ExternE Global warming Sub-Task, Final Report, European Commission JOS3-CT95-0002, Brussels.

Eswaran, H., Van Den Berg, E., Reich, P. 1993. Organic carbon in soils of the world. *Soil Sci Soc Am J* 57: 192-194

FAO. 1993. Forest Resources Assessment 1990, Tropical Countries. *FAO Forestry Paper* 112. Rome.

FAO. 2000. Sistemas de uso de la tierra en los trópicos húmedos y la emision y secuestro de CO_2. *World Soil Resources Reports* 88. Rome. 98 pp.

FAO/IFAD. 1999. Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean. *World Soil Resources Reports* 86.

FAO/IIASA. 1999. World Agro-Ecological Zoning. FAO, Rome.

FAO. 2000. Manual on integrated soil management and conservation practices. *Land and water bulletin* 8, FAO, Rome. 204 pp.

FAO/GTZ. 2001. Meeting on verification of country-level carbon stocks and exchanges in non-annex I countries. FAO, Rome.

Fassbender, H.W., Beer, J. Henveldop, J., Imbach, A., Enriquez, G. el Bonnemann, A. 1991. Ten year balance of organic matter and nutrients in agroforestry systems at CATIE Costa Rica *Forest Ecology and Management* 45: 173-183.

Feller, C. 1979. Une méthode de fractionnement granulométrique de la matière organique des sols : application aux sols tropicaux à texture grossière, très pauvres en humus. *Cahiers ORSTOM*, série Pédologie 17 : 339-346.

FiBL. 2000.. Organic Farming Enhances Soil Fertility and Biodiversity. Results from a 21 year field trial. FiBL Dossier 1 (August). Research Institute of Organic Agriculture (FiBL), Zurich.

Field, C.B., Fung, I.V. 1999. The not-so-big U.S. carbon sink. *Science* 285: 544-545.

Fisher, M.J., Rao, I.M., 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: 236-237.

Fisher, M.J., Rao, I.M., Ayarza, M.A., Lascano, C.E., Sanz, J.I., Thomas, R.J. & Vera, R.R. 1995. Pasture soils as carbon sink. *Nature* 376: 472-473.

Frankhausen, S. 1994. *Valuing Climate Change*. Earthscan, London.

Garcia Torres, L., Gonzalez Fernandez (eds). 1997. Agricultura de Conservación: Fundamentos agronómicos, medioambientales y economicas. Asociación Española Laboreo de conservación/suelos vivos, Córdoba, Spain 372 pp.

Gaston, C.G., Kolchugina, T., Vinson, T.S. 1993. Potential effect of no-till management on carbon in the agricultural soils of the former Soviet Union. *Agriculture*, *Ecosystems and Environment* 45: 295-309.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P. 1994. Soil structure and carbon cycling. *Aust. J. Sci. Res*. 32: 1043-68.

Greenland, D.J. 1994. Long term cropping experiments in developing countries: The need, the history and the future. *In* Leigh, R.A., Johnston, A.E. eds. *Long-term experiments in Agricultural and Ecological Sciences.* p 187-209. CAB International, Wallingford 428pp.

Greenland, D.J. 1995. Land use and soil carbon in different agroecological zones. In*: Soils and global Change*. Lal, R., Kimble, J., Levine, E., Stewart, B.A. (eds). CRC & Lewis Publishers, Boca Raton, FL. p 1-24

Greenland, D.J., Gregory, P.J., Nye, P.H. (eds). 1998. Land resources: on the edge of the Malthusian precipice. CAB. International and Royal Society, London. 173 pp.

Gregorich, E.G., Greer, K.J., Anderson, D.W. , Liang, B.C. 1998. Carbon distribution and losses: erosion and deposition effects. *Soil & Tillage Research* 47: 291-302.

Gregorich, E.G., Drury, C.F., Ellert, B.H., Liang, B.C. 1996. Fertilization effects on physically protected light fraction organic matter. *Soil Sci Sc Am J* 60:472-476.

Gregory, P.J., Simmonds, L.P., Warren, G.P. 1998. Interactions between plant nutrients, water and carbon dioxide as factors limiting crop yields. *Philosophical transactions of the Royal Society of London, Series B*, 352: 987-996.

Gregory, P.J., Simmonds, L.P., Lal, R. 1990. Soil erosion and land degradation: the global risks. *Adv.* In: *Soil Sci.* 11: 129-172.

Heal, O.W., Anderson, J.M., Swift, M.J. 1997. Plant litter quality and decomposition: an historical overview. In: *Driven by nature: plant litter quality and decomposition.* Cadisch, G., Giller, K.E. (eds). CAB International, Wallingford, UK. pp 3-30.

Hendricks, P., Parmelee R., Cressley, D., Coleman, D., Odum, E., Groffman, P. 1986. Detritus food webs in conventional and no-tillage. *Agrosystems Biosciences* 36 (6):374-380.

Holland M., Forster D., Young K., Haworth A. and Watkiss P. 1999. Economic Evaluation of Proposals for Emission Ceilings for Atmospheric Pollutants. *Interim report for DG X1 of the European Commission.* AEA Technology, Culham, Oxon.

Houghton, R.A. 1995. Changes in the storage of terrestrial carbon since 1850, In: (eds). *Soils and Global Change*. Lal, R., Kimble, J., Levine, E., Stewart, B.A. CRC & Lewis Publishers, Boca Raton, FL. p. 45-65.

Houghton, R.A., Hackler, J.L., Lawrence, K.T. 1999. The U.S. carbon budget: contributions from land-use change. *Science* 285: 574-577.

Houghton, R.A., Skole, D.L., Lefkowitz, D.S. 1991. Changes in the landscape of Latin America between 1850 and 1985. *Forest Ecology and Management.* 38: 173-199.

Howard, P.J.A., Loveland, P.J., Bradley, R.I., Dry, F.T., Howard, D.M., Howard, DC. 1995. The carbon content of soil and its geographical distribution in Great Britain. *Soil Use and Management*. 11: 9-15.

Impacts potentiels du changement climatique en France au XXI^e siècle 2000. Ministère de de l'aménagement du territoire et de l'environnement, Paris. 128pp.

International Geosphere biosphere program 1998. The terrestrian cycle: implications for the Kyoto protocol. *Science* 280:1393-1394.

IPCC. 2000. Land use, land-use change, and forestry special report. *Cambridge University Press* 377 pp.

Izac, A.M.N. 1997. Developing policies for soil carbon management in tropical regions. *Geoderma* (special issue) 79 (1-40: 261-276.

Jenkinson, D.S., Rayner, J.H. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Sci* 123: 298-305.

Johnston, A.E. 1973. The effects of ley and arable cropping systems on the amounts of soil organic matter in the Rothamsted and Woburn Ley arable experiments. *Rothamsted Experimental Station Annual Report for 1972 Part 2,* 131-159.

Kaetterer T., and Andrén O. 1999. Long-term agricultural field experiments in N Europe: analysis of the influence of management on soil stocks using the ICBM model. Agric. *Ecosys.and Environ.* 72, 165-179.

Kolchugina, T.P., Vinson, T.S., Gaston, G.G., Rozkov, V.A. , Shwidendo, A.Z. 1995. Carbon pools, fluxes, and sequestration potential in soils of the Former Soviet Union. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds*Soil Management and the Greenhouse Effect.* CRC & Lewis Publishers, Boca Raton, FL. pp. 25-40

Lal, R. 1990. Soil erosion and land degradation: the global risks. *Adv. In Soil Sci.*11:129-172.

Lal., R.., Kimble, J.M. 1994. Soil management and the greenhouse effect. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. Soil Processes and the Greenhouse Effect. USDA-SCS, Lincoln, NE. p. 1-5.

Lal, R. 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_{2-} enrichment. *Soil & Tillage Research* 43: 81-107.

Lal, R., Kimble, J.M., Follet, R.F., Cole, C.V. 1998a). The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. *Ann Arbor Press*, Chelsea, MI.128pp.

Lal, R., Kimble J.M., Follett R.F., Stewart B.A. (eds). 1998b). Soil processes and the carbon cycle. *Adv in Soil Science*, CRC Press 609 pp.

Lal, R., Kimble J.M., Follett R.F. (eds) 1998c) Management of carbon sequestration in soil. *CRC Press* 480 pp.

Lal, R. 1999. Global carbon pools and fluxes and the impact of agricultural intensification and judicious land use. In: Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean. *World Soil Resources Report* 86. FAO, Rome. p 45-52.

Lal, L., Kimble, J.M., Stewart, B.A. (eds) 2000. Global climate change and tropical ecosystems. CRC press & Lewis publishers, Boca Raton, FL.

Lal, R. 2000. Soil quality and soil erosion. CRC press 352 pp.

Lal, R., Kimble, I., Levine, E, Stewart, B.A. (eds) 1995. Soils and global change. CRC & Lewis publishers, Boca Raton FL

Lavelle, P. 2000. Ecological challenges for soil science. *Soil science* 165 (1):73-86.

Loby de Bruyn, L.A. 1997. The status of soil macrofauna as indicators of soil health to monitor the sustainability of Australian agricultural soils. *Ecological economics* 23: 167-178.

Lockeretz, W., Shearer, G. and Kohl, D.H. 1981. Organic farming in the Corn Belt. *Science* 211, p 540-547.

Lyon, D.J. 1998. Long-term tillage comparisons for winter wheat-fallow in the US Central Great plains. *Soils & Tillage Research* 49: 1.

Management of carbon in tropical soils under global change: science, practices and policy. 1997. *Geoderma* (Special Issue) 79 (1-4), 279 pp.

Middleton, N., Thomas, D. 1997. World atlas of desertification (second edition). UNEP. 182 pp.

Monnier, G., Thevenet, G., Lesaffre, B. 1994. Simplification du travail du sol. *Colloques INRA* n° 65, 172 pp.

Moraes, J.L., Cerri, C.C., Melillo, J.M. 1995. Soil carbon stocks of the Brazilian Amazon basin. *Soil Sci Soc Am J* 59: 244-247.

Moraes, J.L., Seyler, F., Cerri, C.C. & Volkoff, B. 1998. Land cover mapping and carbon pools estimates in Rondonia, Brazil. *Int J. Remote Sensing* 19: 921-934.

Neill, C. Cerri, C.C., Melillo, J.M., Feigl, B.J., Stendler, P.A., Moraes, J.F.L., Piccolo, M.C. 1998. Stocks and dynamics of soil carbon following deforestation for pasture in Rondônia. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. Soil processes and the carbon cycle. *Adv. In Soil Science*1. CRC Press. p 9-28.

Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G. 1991. (2^{d} ed.) World map of the status of human-induced soil degradation: an explanatory note. United Nation Environment Programme, Nairobi.

Oldeman, L.R. 1994. The global extent of soil degradation. pp 99-117 in: Greenland, D.J. and Szabolcs, I. (eds). *Soil Resilience and Sustainable Land Use.* CAB International, Wallingford, UK.

Pankhurst, C.E., Doube, B.M., Gupta, V.VSR., Grace, P.R. (eds). 1994. Soil Biota Management in Sustainable Farming Systems. SCIRO, Australia 262 pp.

Parton, W.J., Stewart, W.B. and Cole, C.V. 1988. Dynamics of C,N,P, and S in grassland soils: A model. *Biogeochemistry* 5:109-131.

Parton, W.J., Woomer, P.L. and Martin, A. 1994. Modelling soil organic matter dynamics and plant productivity in tropical ecosystems. pp. 171-188 In: P.Woomer and M. Swift (eds.). The Biological Management of Tropical Soil Fertility. TSBF/John Wiley & Sons.

Paustian, K., Elliot, E.T., Carter, M.R. 1998a) Tillage and crop management impacts on soil C storage: use of long-term experimental data. *Soil & Tillage Research* 47: vii-xii.

Paustian, K., Elliot, E.T., Killian K. 1998b). Modeling soil carbon in relation to management and climate change in some egroecosystems in Central North America. In: *Soil Processes and the Carbon Cycle.* Lal, R., Kimble, J., Levine, E., Stewart, B.A. (eds). CRC Press. Boca Raton, FL. p 459-471.

Paustian, K., Levine, E. Post, W.M., Ryzhova, I.M. 1997. The use of models to integrate information and understanding of soil C at the regional scale. *Geoderma* 79: 227-260.

Pearce D W., Cline W R., Achanta A N., Fankhauser S., Pachauri R K., Tol R S J., and Vellinga P. 1996.. The social costs of climate change: greenhouse damage and benefits of controls. In: *Climate Change (1995): Economic and Social Dimensions of Climate Change.* Bruce et al (eds). Cambridge University Press, Cambridge.

Petersen C., Drinkwater L A. and Wagoner P. 2000.. *The Rodale Institute's Farming Systems Trial. The First 15 Years*. Rodale Institute, Penn.

Phillips, O.I., Malhi, V., Higuchi, N., Laurance, W.F., Nunez, P.V., Vasquez, R.M., Laurence, S.G., Ferreirer, L.V., Stern, M., Brown, S., Grace, J. 1998. Changes in the carbon balance of tropical forests: Evidence from long-term plots. *Science* 282: 439-442.

Pieri, C. 1989. Fertilité des terres de savanes. Ministère de la Coopération. CIRAD. 444 p.

Ponce-Hernandez, R. 1999. Assessing the carbon stock and carbon sequestration potential of current and potential land use systems and the economic rationality of land use conversions. In: Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean. *World Soil Resources Report* 86. FAO, Rome. p 77-92.

Poss, R. 1991. Transferts de l'eau et des éléments chimiques dans les terres de barre du Togo. Thèse Univ. Paris VI. Editions ORSTOM. 355 pp.

Post, W.H., Kwon, K.C. 2000 Soil carbon sequestration and land use change: processes and potential. *Global change Biology* 6: 327-327.

Post, W.M., Emmanuel, W.R., Zinke, P.J., Stangenberger, A.F. 1982. Soil carbon pools and world life zones. *Nature* 258: 165-159.

Potter, P.K., Jones, O.R., Torbett, H.A., Unger, P.W. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great plains. *Soil Science* 162 (2): 140-147.

Powlson, D.S., Smith, P., Coleman, K., Smith, J.U., Glendining, M.J., Korschens, M. & Franko, U. 1998. A European network of long-term sites for studies on soil organic matter. *Soil & Tillage Research* 47: 263-274.

Pretty J. and Ball A. 2001. Agricultural Influences on Carbon Emissions and Sequestration: A Review of Evidence and the Emerging Trade Options. Centre for Environment and Society. *Occasional Paper 2001-03*. University of Essex [in pdf at URLwww2.essex.ac.uk/ces].

Puget, P., Chenu, C., Balesdent, J. 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. *European Journal of Soil Science* 46: 449-459.

Reganold J P., Elliott L F., and Unger Y L. 1987.. Long-term effects of organic and conventional farming on soil erosion. Nature 330,370-372.

Reicosky, D.C., Lindstrom, M.J. 1995. Impact of fall tillage on short-term carbon dioxide flux. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. *Soils and global change*. CRC Press.

Robert, M. 1996a). Aluminum toxicity a major stress for microbes in the environment. *In* Huang, P.M. *et al.,* eds. *Environmental Impacts*. Vol. 2, Soil component interactions. CRC press. p 227-242.

Robert, M. 1996b). Le sol: interface dans l'environnement, ressource pour le développement. Dunod/ Masson, Paris 240 pp.

Robert, M., Chenu, C. 1991. Interactions between soil minerals and microorganisms. *In* Bollag, J.M., Stotzky, G. eds. *Soil Biochemistry 7*. Marcel Dekker, New York. p 307-393.

Robert, M., Stengel, P. 1999. Sols et agriculture: ressource en sol, qualité et processus de dégradation. *Cahiers Agricultures* 8 (4): 301-308.

Rosenzweig, C., Hillel, D. 2000. Soils and global climate change: challenges and opportunities. *Soil Science* 165 (1): 45-56.

Rovira, A.D. 1994. The effect of farming practices on the soil biota. *In* Soil Biota Management in Sustainable Farming Systems, Vol.1. *In* Pankhurst, C.E., Doube, B.M. Gupta, V.VSR, Grace P.R. eds. SCIRO, Australia.

Sala O E. and Paruelo J M. 1997. Ecosystem services in grasslands. In Daily G (ed). *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington DC.

Sanchez, P.A., Salinas, I.G. 1982. Low-input technology for managing oxisols and ultisols in tropical America. Adv. Agron. 34: 279-406.

Sanchez, P.A. 1995. Science in agroforestry. *Agroforestry Systems* 30: 5-55.

Sanchez, P.A., Buresh, R.J., Leakey R.R.B. 1999. Trees, soils and food security. *Philosophical Transactions of the Royal Society of London, Series* B 353: 949-961.

Sarrailh, J.M. 1990. Mise en valeur de l'écosystème forestier guyanais (opération Ecerex). INRA Centre Technique Forestier Tropical. 273 pp.

Schindler, D.W. 1999. The mysterious missing sink. *Nature* 398: 105-107.

Schroeder, P. 1994. Carbon storage benefits of agroforestry systems. *Agroforestry Systems* 27: 89-97.

Skjemstad, J.O., Clarke, P., Taylor, J.A., Oades, J.M., McClure S.G. 1996. The chemistry and nature of protected carbon in soil. *Australian Journal of Soil Research* 34: 251-271.

Smith, P., Powlson, D S., Glendenning, A J., and Smith, J. U. 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. *Global Change Biology* 4, 679-685.

Smith, K.A. 1999. After the Kyoto Protocol: can soil scientists make a useful contribution. *Soil use and Management* 15: 71-75.

Smith, P., Fallon, P., Coleman, K., Smith, J., Piccolo, M.C., Cerri, C., Bernoux, M., Jenkinson, D., Ingram, J., Szabo, J., Pasztor, L. 1999. Modeling soil carbon dynamics in tropical ecosystems. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. Global climate change and tropical ecosystems. *Adv. In Soil Science*. CRC Press. p 341-364

Smith, P., Powlson, D.S., Smith, J.U. & Elliot, E.T.e. 1997. Evaluation and comparison of soil organic matter models using datasets from seven long-term experiments. *Geoderma* 81 (Special Issue), 225.

Sombroek, W.G., Nachtergaele, F.O. & Hebel, A. 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio* 22: 417-426.

Stewart, B.A. 1995. Soil management in semiarid regions. *In* Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. *Soils and global change.* CRC/Lewis publishers, Boca Raton, FL. p 251-258.

Swift M.J., seward P.D., Frost P.G.H., Ouresbi J.N., Muchena F. N 1994. Long term experiments in Africa: Developing a database for sustainable land use under Glabal Change. *In* Leigh, R.A., Johnston, A.E. eds Long-term experiments in Agricultural and Ecological Sciences.. p 229-251. CAB International, Wallingford, UK. 428pp.

Tavarez-Filho, J., Tessier, D., 1998. Influence des pratiques culturales sur le comportement et les propriétés de sols du Parana (Brésil). *Etudes et Gestion des sols* 5(1):61-71.

Tebruegge, F., Guring, R-A. 1999. Reducing tillage intensity – a review of results from a long-term study in Germany. *Soil and tillage research* 53:15-28.

Tebruegge, F. 2000. No-tillage visions – protection of soil, water and climate. Institute for Agricultural Engineering, Justus-Liebig University, Giessen, Germany.

Tian, H., Mellilo, J.M., Kicklighter, D.W., McGuire, A.D., Helfrich III, J.V.K., Moore III, B.,Vörösmarty, C.J. 1998. Effect of interannual climate variability on carbon storage in Amazonian ecosystems. *Nature* 396: 664-667.

Tilman D. 1998.. the greening of the green revolution. *Nature* 396, 211-212.

Tisdall, J.M., Oades, J.M. 1982. Organic matter and water stable aggregates. *J. Soil Sci*. 33: 141-163.

Trumbmore, S.E., Davidson, E.A., Barbosa de Camargo, P., Nepstad, D.D., Martinelli, L.A. 1995. Belowground cycling of carbon in forests and pastures of eastern Amazonia. *Global Biogeochemical Cycles* 9: 515-528.

Van Noordwijk, M., Cerri, C., Woomer, P.L., Nugroho, K., Bernoux, M. 1997. Soil carbon dynamics in the humid tropical forest zone. *Geoderma* 79: 187-225.

Wander, M., Bidart, M., and Aref, S. 1998. Tillage experiments on depth distribution of total and particulate organic matter in 3 Illinois soils. *Soil Sci.Soc.Am*. 62. 1704-11.

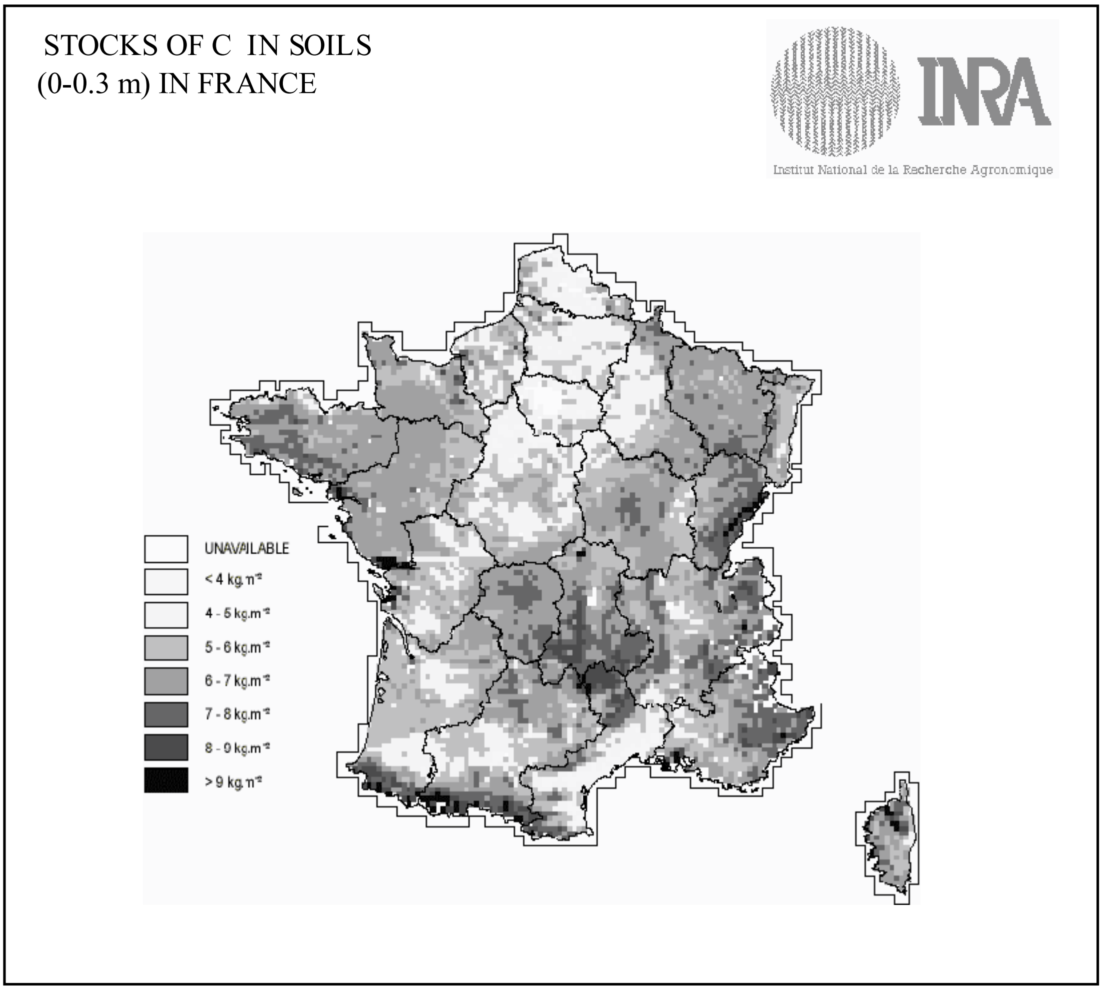
Winterbottom, R., Hazlwood, P.T. 1987. Agroforestry and sustainable development: making the connection. Ambio 16 (2-3): 100-110.

Woomer, P.L., Palm, C.A., Qureshi, J.N., Kotto-Same, J. 1998. Carbon sequestration and organic resource management in African smallholder agriculture. *In*: Lal, R., Kimble, J., Levine, E., Stewart, B.A. eds. *Soil Processes and the Carbon Cycle.* CRC Press, Boca Raton, FL. p. 153-173.

Young, A. 1991. Soil monitoring: a new basic task for soil surveys, *Soil Use and Management 7: 126-130.*

Young, A. 1997. Agroforestry for soil management, pp. 257-8.

Annex 1
Map of total carbon in soils



Source: Soil Use & Management. Arrouays *et al.*, 2000 (under press).

Annex 2
Articles 3.3 and 3.4 of the Kyoto Protocol

ARTICLE 3.3

The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8.

ARTICLE 3.4

Prior to the first session of the Conference of the Parties serving as the meeting of the Parties to this Protocol, each Party included in Annex I shall provide, for consideration by the Subsidiary Body for Scientific and Technological Advice, data to establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I, taking into account uncertainties, transparency in reporting, verifiability, the methodological work of the Intergovernmental Panel on Climate Change, the advice provided by the Subsidiary Body for Scientific and Technological Advice in accordance with Article 5 and the decisions of the Conference of the Parties. Such a decision shall apply in the second and subsequent commitment periods. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these activities have taken place since 1990.

WORLD SOIL RESOURCES REPORTS

1. Report of the First Meeting of the Advisory Panel on the Soil Map of the World, Rome, 19-23 June 1961.**
2. Report of the First Meeting on Soil Survey, Correlation and Interpretation for Latin America, Rio de Janeiro, Brazil, 28-31 May 1962**
3. Report of the First Soil Correlation Seminar for Europe, Moscow, USSR, 16-28 July 1962.**
4. Report of the First Soil Correlation Seminar for South and Central Asia, Tashkent, Uzbekistan, USSR, 14 September-2 October 1962.**
5. Report of the Fourth Session of the Working Party on Soil Classification and Survey (Subcommission on Land and Water Use of the European Commission on Agriculture), Lisbon, Portugal, 6-10 March 1963.**
6. Report of the Second Meeting of the Advisory Panel on the Soil Map of the World, Rome, 9-11 July 1963.**
7. Report of the Second Soil Correlation Seminar for Europe, Bucharest, Romania, 29 July-6 August 1963.**
8. Report of the Third Meeting of the Advisory Panel on the Soil Map of the World, Paris, 3 January 1964.**
9. Adequacy of Soil Studies in Paraguay, Bolivia and Peru, November-December 1963.**
10. Report on the Soils of Bolivia, January 1964.**
11. Report on the Soils of Paraguay, January 1964.**
12. Preliminary Definition, Legend and Correlation Table for the Soil Map of the World, Rome, August 1964.**
13. Report of the Fourth Meeting of the Advisory Panel on the Soil Map of the World, Rome, 16-21 May 1964.**
14. Report of the Meeting on the Classification and Correlation of Soils from Volcanic Ash, Tokyo, Japan, 11-27 June 1964.**
15. Report of the First Session of the Working Party on Soil Classification, Survey and Soil Resources of the European Commission on Agriculture, Florence, Italy, 1-3 October 1964.**
16. Detailed Legend for the Third Draft on the Soil Map of South America, June 1965.**
17. Report of the First Meeting on Soil Correlation for North America, Mexico, 1-8 February 1965.**
18. The Soil Resources of Latin America, October 1965.**
19. Report of the Third Correlation Seminar for Europe: Bulgaria, Greece, Romania, Turkey, Yugoslavia, 29 August-22 September 1965.**
20. Report of the Meeting of Rapporteurs, Soil Map of Europe (Scale 1:1 000 000) (Working Party on Soil Classification and Survey of the European Commission on Agriculture), Bonn, Federal Republic of Germany, 29 November-3 December 1965.**
21. Report of the Second Meeting on Soil Survey, Correlation and Interpretation for Latin America, Rio de Janeiro, Brazil, 13-16 July 1965.**
22. Report of the Soil Resources Expedition in Western and Central Brazil, 24 June-9 July 1965.**
23. Bibliography on Soils and Related Sciences for Latin America (1st edition), December 1965.**
24. Report on the Soils of Paraguay (2nd edition), August 1964.**
25. Report of the Soil Correlation Study Tour in Uruguay, Brazil and Argentina, June-August 1964.**
26. Report of the Meeting on Soil Correlation and Soil Resources Appraisal in India, New Delhi, India, 5-15 April 1965.**
27. Report of the Sixth Session of the Working Party on Soil Classification and Survey of the European Commission on Agriculture, Montpellier, France, 7-11 March 1967.**
28. Report of the Second Meeting on Soil Correlation for North America, Winnipeg-Vancouver, Canada, 25 July-5 August 1966.**
29. Report of the Fifth Meeting of the Advisory Panel on the Soil Map of the World, Moscow, USSR, 20-28 August 1966.**
30. Report of the Meeting of the Soil Correlation Committee for South America, Buenos Aires, Argentina, 12-19 December 1966.**
31. Trace Element Problems in Relation to Soil Units in Europe (Working Party on Soil Classification and Survey of the European Commission on Agriculture), Rome, 1967.**
32. Approaches to Soil Classification, 1968.**
33. Definitions of Soil Units for the Soil Map of the World, April 1968.**
34. Soil Map of South America 1:5 000 000, Draft Explanatory Text, November 1968.**
35. Report of a Soil Correlation Study Tour in Sweden and Poland, 27 September-14 October 1968.**

36. Meeting of Rapporteurs, Soil Map of Europe (Scale 1:1 000 000) (Working Party on Soil Classification and Survey of the European Commission on Agriculture), Poitiers, France 21-23 June 1967.**
37. Supplement to Definition of Soil Units for the Soil Map of the World, July 1969.**
38. Seventh Session of the Working Party on Soil Classification and Survey of the European Commission on Agriculture, Varna, Bulgaria, 11-13 September 1969.**
39. A Correlation Study of Red and Yellow Soils in Areas with a Mediterranean Climate.**
40. Report of the Regional Seminar of the Evaluation of Soil Resources in West Africa, Kumasi, Ghana, 14-19 December 1970.**
41. Soil Survey and Soil Fertility Research in Asia and the Far East, New Delhi, 15-20 February 1971.**
42. Report of the Eighth Session of the Working Party on Soil Classification and Survey of the European Commission on Agriculture, Helsinki, Finland, 5-7 July 1971.**
43. Report of the Ninth Session of the Working Party on Soil Classification and Survey of the European Commission on Agriculture, Ghent, Belgium 28-31 August 1973.**
44. First Meeting of the West African Sub-Committee on Soil Correlation for Soil Evaluation and Management, Accra, Ghana, 12-19 June 1972.**
45. Report of the Ad Hoc Expert Consultation on Land Evaluation, Rome, Italy, 6-8 January 1975.**
46. First Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Nairobi, Kenya, 11-16 March 1974.**
47. Second Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Addis Ababa, Ethiopia, 25-30 October 1976.
48. Report on the Agro-Ecological Zones Project, Vol. 1 - Methodology and Results for Africa, 1978. Vol. 2 - Results for Southwest Asia, 1978.
49. Report of an Expert Consultation on Land Evaluation Standards for Rainfed Agriculture, Rome, Italy, 25-28 October 1977.
50. Report of an Expert Consultation on Land Evaluation Criteria for Irrigation, Rome, Italy, 27 February-2 March 1979.
51. Third Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Lusaka, Zambia, 18-30 April 1978.
52. Land Evaluation Guidelines for Rainfed Agriculture, Report of an Expert Consultation, 12-14 December 1979.
53. Fourth Meeting of the West African Sub-Committee for Soil Correlation and Land Evaluation, Banjul, The Gambia, 20-27 October 1979.
54. Fourth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Arusha, Tanzania, 27 October-4 November 1980.
55. Cinquième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Lomé, Togo, 7-12 décembre 1981.
56. Fifth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Wad Medani, Sudan, 5-10 December 1983.
57. Sixième réunion du Sous-Comité Ouest et Centre Africain de corrélation des sols pour la mise en valeur des terres, Niamey, Niger, 6-12 février 1984.
58. Sixth Meeting of the Eastern African Sub-Committee for Soil Correlation and Land Evaluation, Maseru, Lesotho, 9-18 October 1985.
59. Septième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Ouagadougou, Burkina Faso, 10-17 novembre 1985.
60. Revised Legend, Soil Map of the World, FAO-Unesco-ISRIC, 1988. Reprinted 1990.
61. Huitième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Yaoundé, Cameroun, 19-28 janvier 1987.
62. Seventh Meeting of the East and Southern African Sub-Committee for Soil Correlation and Evaluation, Gaborone, Botswana, 30 March-8 April 1987.
63. Neuvième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Cotonou, Bénin, 14-23 novembre 1988.
64. FAO-ISRIC Soil Database (SDB), 1989.
65. Eighth Meeting of the East and Southern African Sub-Committee for Soil Correlation and Land Evaluation, Harare, Zimbabwe, 9-13 October 1989.
66. World soil resources. An explanatory note on the FAO World Soil Resources Map at 1:25 000 000 scale, 1991. Rev. 1, 1993.
67. Digitized Soil Map of the World, Volume 1: Africa. Volume 2: North and Central America. Volume 3: Central and South America. Volume 4: Europe and West of the Urals. Volume 5: North East Asia. Volume 6: Near East and Far East. Volume 7: South East Asia and Oceania. Release 1.0, November 1991.

68. Land Use Planning Applications. Proceedings of the FAO Expert Consultation 1990, Rome, 10-14 December 1990.
69. Dixième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Bouaké, Odienné, Côte d'Ivoire, 5-12 novembre 1990.
70. Ninth Meeting of the East and Southern African Sub-Committee for Soil Correlation and Land Evaluation, Lilongwe, Malawi, 25 November - 2 December 1991.
71. Agro-ecological land resources assessment for agricultural development planning. A case study of Kenya. Resources data base and land productivity. Main Report. Technical Annex 1: Land resources. Technical Annex 2: Soil erosion and productivity. Technical Annex 3: Agro-climatic and agro-edaphic suitabilities for barley, oat, cowpea, green gram and pigeonpea. Technical Annex 4: Crop productivity. Technical Annex 5: Livestock productivity. Technical Annex 6: Fuelwood productivity. Technical Annex 7: Systems documentation guide to computer programs for land productivity assessments. Technical Annex 8: Crop productivity assessment: results at district level. 1991. Main Report 71/9: Making land use choices for district planning, 1994.
72. Computerized systems of land resources appraisal for agricultural development, 1993.
73. FESLM: an international framework for evaluating sustainable land management, 1993.
74. Global and national soils and terrain digital databases (SOTER), 1993. Rev. 1, 1995.
75. AEZ in Asia. Proceedings of the Regional Workshop on Agro-ecological Zones Methodology and Applications, Bangkok, Thailand, 17-23 November 1991.
76. Green manuring for soil productivity improvement, 1994.
77. Onzième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Ségou, Mali, 18-26 janvier 1993.
78. Land degradation in South Asia: its severity, causes and effects upon the people, 1994.
79. Status of sulphur in soils and plants of thirty countries, 1995.
80. Soil survey: perspectives and strategies for the 21st century, 1995.
81. Multilingual soil database, 1995.
82. Potential for forage legumes of land in West Africa, 1995.
83. Douzième réunion du Sous-Comité Ouest et Centre africain de corrélation des sols pour la mise en valeur des terres, Bangui, République Centrafricain, 5-10 décembre 1994.
84. World reference base for soil resources, 1998.
85. Soil Fertility Initiative for sub-Saharan Africa, 1999.
86. Prevention of land degradation, enhancement of carbon sequestration and conservation of biodiversity through land use change and sustainable land management with a focus on Latin America and the Caribbean, 1999.
87. AEZWIN: An interactive multiple-criteria analysis tool for land resources appraisal, 1999.
88. Sistemas de uso de la tierra en los trópicos húmedios y la emisión y secuestro de CO_2, 2000.
89. Land resources information systems for food security in SADC countries, 2000.
90. Land resource potential and constraints at regional and country levels, 2000.
91. The European soil information system, 2000.
92. Carbon sequestration projects under the clean development mechanism to address land degradation, 2000.
93. Land resources information systems in Asia, 2000.
94. Lecture notes on the major soils of the world, 2001.
95. Land resources information systems in the Caribbean, 2001
96. Soil carbon sequestration for improved land management, 2001.

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In the framework of the Kyoto Protocol, carbon sequestration to mitigate the greenhouse effect in the terrestrial ecosystem has been an important subject of discussion in numerous recent international meetings and reports. The present synthesis focuses on the specific role that soils of tropical and dryland areas can play in carbon sequestration and on the land management strategies involved. A review is made of carbon dynamics and the fundamental role of organic matter in soil. To increase carbon sequestration in soils in the dryland and tropical areas, as a contribution to global atmospheric CO_2 mitigation, new strategies and new practices in agriculture, pasture use and forestry, including conservation agriculture and agroforestry, are essential. Such practices should be facilitated particularly by the application of article 3.4 of the Kyoto Protocol or a similar provision in the post-Kyoto treaty covering the additional activities in agriculture and forestry in the developing countries and by appropriate policies, and should be widely promoted. Some proposals are made concerning good land management practices for croplands, pastures and agroforestry in order to promote carbon sequestration – a priority being their application to degraded lands. A method for monitoring and verifying the changes both in carbon sequestration and in the degree of degradation is proposed based on a soil-monitoring network.

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