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Carbon sequestration in dryland soils

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Preface

Among the main challenges in the twenty-first century are the rapid increase in the world population, the degradation of agricultural soils and the release of greenhouse gases in the atmosphere that contribute to climate change. These three important issues are closely linked as land-use management options that prevent soil degradation can also decrease the emission of greenhouse gases, enhance carbon sequestration (CS), and improve food security. While the growing population is leading to a higher demand for food, the agricultural land per capita is decreasing, particularly in Asia, Africa and South America, the regions with the highest demographic expansion. Human activities such as fuel consumption and land-use change are the main causes of an increase in the atmospheric carbon-dioxide concentration, which is generally recognized as a factor of climate change and global warming.

FAO has implemented several collaborative programmes to assist developing countries in the adoption of land-management practices that reverse the current land degradation, desertification and inadequate land use. At a general level, these programmes promote land-management practices that provide economic and environmental benefits to the farmers taking into account different aspects at economic, sociological and environmental levels.

As part of its activities on soil CS within the framework of its integrated land management programme, the FAO Land and Plant Nutrition Management Service, Land and Water Development Division, initiated a one-year project at the beginning of 2002. Its aim was to collect, assess and elaborate the state of the art on the use of CS to improve land-use management in dryland areas of the world. This programme is closely linked to the FAO Land Degradation Assessment in Drylands (LADA) project that aims to develop and test an effective assessment methodology for land degradation in drylands. The programme is also linked with the Convention to Combat Desertification and the Convention on Biological Diversity (CBD) with, as its final aim, the provision of up-to-date information for the formulation of policy and technical options for the development of sustainable systems in drylands. While increasing CS, sustainable land-use systems can improve the livelihood of farmers through soil conservation, enhancement and protection of agrobiodiversity.

In the current political and international framework, the implementation of the United Nations Framework Convention on Climate Change and the agreement of the Kyoto Protocol have created new possibilities to implement specific initiatives and projects that stimulate CS. For example, the Clean Development Mechanism (CDM) enables developed countries to buy carbon credits from developing countries by establishing specific projects that enhance CS in these areas. However, this mechanism is unlikely to be applicable in drylands, and other multilateral approaches need to be explored and developed where synergies between different conventions and funds are strengthened. Whereas CS may not be a priority in poor countries, land-use management options that increase CS may also be beneficial for plant production, prevention of erosion and desertification, and biodiversity conservation, which are of major interest in these regions. Therefore, actions for soil improvement through CS are a win–win situation where increases in agronomic productivity may help mitigate global warming, at least in the coming decades, until other alternative energy sources are developed. There have been important advances in the last few years at political, scientific and awareness levels and numerous projects are being implemented.

This report aims to review and summarize the current state of the art in CS in order to analyse how available resources and specific programmes can be implemented in drylands, one of the most soil-degraded regions of the world. Other FAO publications produced under this programme have considered other aspects of CS: methodological issues related to carbon monitoring and accounting, CS options to address land degradation under the CDM, general aspects of CS, and specific CS projects.

With this analysis, the document aims to highlight the current problems and uncertainties and to produce recommendations for the development of specific strategies and policies that can be implemented in dryland areas to improve land management that enhances CS.

Summary

As in many other international organizations, national governments and intergovernmental bodies, climate-change issues are high on the FAO agenda. FAO is an active partner in the international conventions on climate change, whereby FAO's mandate covers the role of agriculture in mitigating climate change.

FAO is concerned with the effect of agriculture on climate change, the impact of climate change on agriculture and with the role that agriculture can play in mitigating climate change. Historically, land-use conversion and soil cultivation have been an important source of greenhouse gases (GHGs) to the atmosphere. It is estimated that they are responsible for about one-third of GHG emissions. However, improved agricultural practices can help mitigate climate change by reducing emissions from agriculture and other sources and by storing carbon in plant biomass and soils.

The work of FAO aims to identify, develop and promote cultural practices that reduce agricultural emissions and sequester carbon while helping to improve the livelihoods of farmers, especially in developing countries, through increased production and additional incomes from carbon credits under the mechanisms that have emerged since the Kyoto Protocol.

There have been few studies on the potential of carbon sequestration (CS) under local farming conditions in rural dryland communities in developing countries. This report aims to fill this gap in knowledge. The report evaluates specific options for land-management practices by analysing some case studies carried out in several distinctive dryland areas of the world. The ultimate goal is to facilitate the dissemination of such practices in soil CS programmes in similar agro-ecological environments in other countries to improve food security and rural livelihoods.

The case studies presented here assess the effect of different management practices on soil carbon stocks in various dryland ecosystems. The effect of climate and/or land-use change can be predicted only through the use of accurate dynamic models. Given the difficulty of measuring changes in soil carbon stocks, modelling is a useful tool and it has been used as an effective methodology for analysing and predicting the effect of land-management practices on soil carbon stocks. A number of process-based models have been developed in the last two decades. The CENTURY 4.0 model was used for these case studies. Data from distinctly different dryland systems in Argentina, India, Kenya, Nigeria, Senegal and the Sudan were used in the investigations, which were carried out by the University of Essex (the United Kingdom) and Lund University (Sweden).

Some of the results predict that soil carbon can be restored to precultivation levels, and in certain circumstances to above them. The true "native soil carbon level" is often difficult to establish in systems where agricultural activity has been present for at centuries or millennia such as in Kenya and Nigeria. To achieve quantities of soil carbon in excess of the "natural level" implies that the agricultural system has a greater productivity than the native system, assuming that carbon is not being imported. The scenarios that predict the highest CS rates are often associated with the introduction of trees. The inputs of carbon from trees are more resistant to decomposition than those from herbaceous crops and consequently can cause marked increases in the level of soil carbon. The highest annual rates of sequestration (0.1–0.25 tonnes/ha) occur where zero-tillage systems also include cultivation of green manures and additions of farmyard manure. The use of inorganic fertilizers alone was generally inefficient in providing the necessary nutrients for increasing CS. The effect of inorganic fertilizers on CS is enhanced considerably by including cover crops in the rotation cycle. Cover

crops enhance soil biodiversity, which is known to increase CS. The results of the case studies conform to rates of soil CS obtained under various land-management regimes in drylands as reported in literature sources.

There are vast areas of dryland ecosystems in the world, many in developing countries, where improvements in farming systems increase carbon stocks in soils, as shown in the case studies presented here.

While CS is not a priority in poor countries, land-management options that increase CS, enhance plant production, and prevent erosion and desertification are of major interest in these regions.

Investments in CS in drylands, as less favoured areas, are needed because they are home to large numbers of poor people and because they are the custodians of globally important environmental resources at risk of degradation or depletion.

Investments in improved land management leading to increased soil fertility and CS can also be justified in many cases because they can be a win–win situation with higher agronomic productivity and contribute to national economic growth, food security and biodiversity conservation.

Enhancing CS in degraded drylands could have direct environmental, economic and social benefits for local people. It would increase farmers' benefits and help mitigate global warming, at least in the coming few decades until other alternative energy sources are developed. Therefore, initiatives that sequester carbon are among the main priorities of FAO.

While a purely carbon-market approach is unlikely to be applicable to small-scale farming systems in developing countries, a multilateral approach for mobilizing resources under existing mechanisms is required. The Global Mechanism of the Convention to Combat Desertification (CCD) of the United Nations (UN) promotes such a multilateral path to increasing the effectiveness and efficiency of existing financial resources and to exploring new and additional funding mechanisms for the implementation of the convention. Specific emphasis is given to small-scale farming systems in dryland areas of the developing countries. Multilateral approaches include sources to combat climate change with desertification funds, links with sustainable livelihoods, and provision of visible benefits to local people, mobilizing resources also from the private sector. Several UN conventions (the CCD, the Climate Change Convention, the Convention on Biological Diversity and the Kyoto Protocol) all share a common goal: the proper management of soils to increase soil carbon. There are opportunities for bilateral partnerships with industrial-country institutions to initiate soil CS projects involving local communities that are also linked to global networks on CS. FAO believes that more effort should be put into exploring and exploiting these opportunities.

Acknowledgements

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The report has benefited from contributions from the FAO Interdepartmental Working Group on Climate. It was reviewed and edited by Prof. R. Dudal and J. Plummer. L. Chalk assisted in its preparation.

List of acronyms

BIAC	Biogeochemical analysis of carbon balance
C	Carbon
CAT	Carbon accounting tool
CBD	Convention on Biological Diversity
CCD	Convention to Combat Desertification
CDCF	Community Development Carbon Fund
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
COP	Conference of Parties
CS	Carbon sequestration
CSZ	Closed–Settlement Zone
FAMOS	Farmers management options for sequestration
FCCC	Framework Convention on Climate Change
FYM	Farmyard manure
GEF	Global Environment Facility
GHG	Greenhouse gas
GM	Global Mechanism
GPP	Gross primary productivity
HECS	Household economics of carbon sequestration
JI	Joint implementation
KP	Kyoto Protocol
LULUCF	Land use, land-use change and forestry
NGO	Non-governmental organization
N	Nitrogen
N_2O	Nitrous oxide
OP	Operational programme
P	Precipitation
PCF	Prototype Carbon Fund
PET	Potential evapotranspiration
PROMIS	Project management for increasing soil carbon
SEC	Sustainability and equity criteria
SOC	Soil organic carbon
SOM	Soil organic matter
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

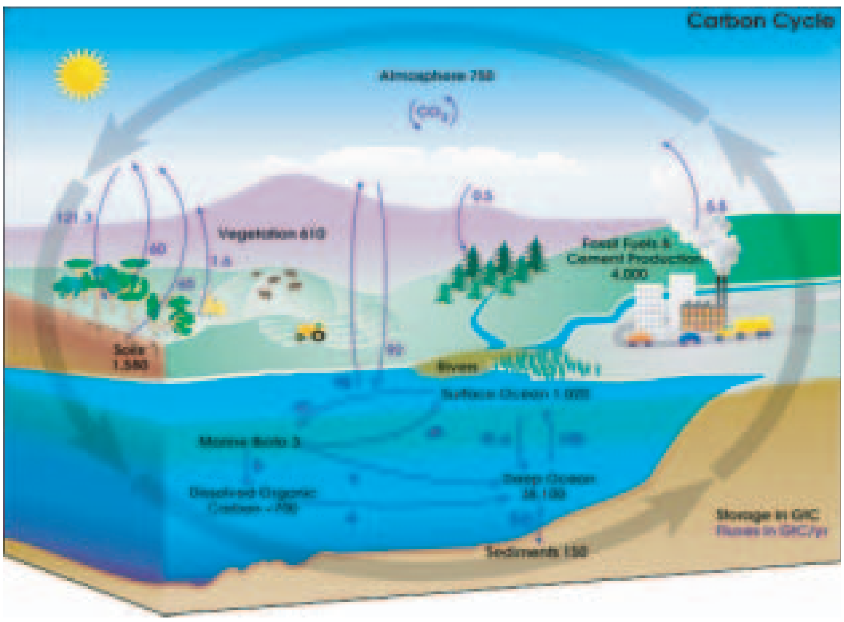
Chapter 1
Introduction

CLIMATE CHANGE

The concentration of carbon dioxide (CO_2) in the atmosphere increased from 285 ppm at the end of the nineteenth century, before the industrial revolution, to about 366 ppm in 1998 (equivalent to a 28-percent increase) as a consequence of anthropogenic emissions of about 405 gigatonnes of carbon (C) (± 60 gigatonnes C) into the atmosphere (IPCC, 2001). This increase was the result of fossil-fuel combustion and cement production (67 percent) and land-use change (33 percent). Acting as carbon sinks, the marine and terrestrial ecosystems have absorbed 60 percent of these emissions while the remaining 40 percent has resulted in the observed increase in atmospheric CO_2 concentration. Figure 1 presents the different carbon pools and fluxes of the global carbon balance.

Land-use change and soil degradation are major processes for the release of CO_2 to the atmosphere. The increase in greenhouse gases (GHGs) in the atmosphere is now recognized to contribute to climate change (IPCC, 2001). Although uncertainties remain regarding the causes, consequences and extent of climate change, it is believed that human activities are having an impact on the energy balance of the earth. Its influence on the climate is a major concern in the twenty-first century. This concern has led to the 1997 international agreement in Kyoto (the so-called Kyoto Protocol), whereby most countries are committed to reducing their GHG emissions to the atmosphere. In this context, new strategies and policies within the international framework have been developed for the implementation of agriculture and forestry management practices that enhance carbon sequestration (CS) both in biomass and soils. These activities are included in Articles 3.3 and 3.4 of the Kyoto Protocol (KP) and are known as "land use, land-use change and forestry" (LULUCF) (IPCC, 2000).

FIGURE 1
Major carbon pools and fluxes of the global carbon balance



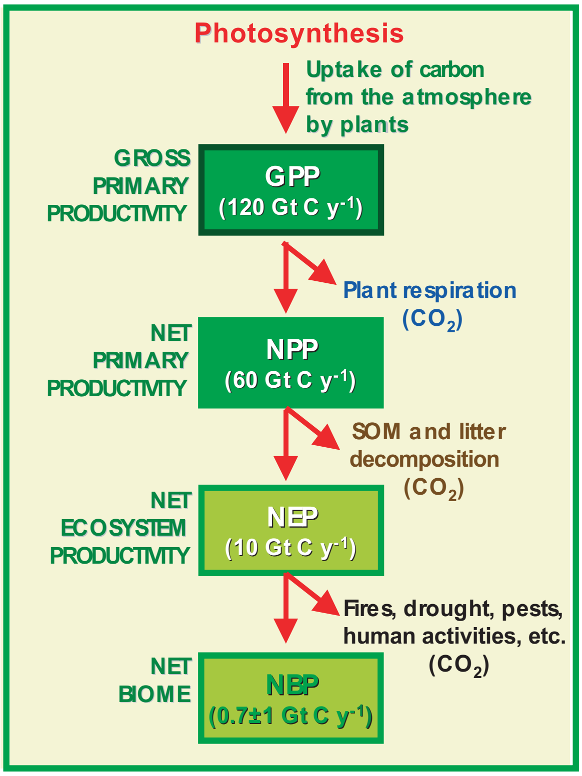
The importance of these activities is that any action taken to sequester C in biomass and soils will generally increase the organic matter content of soils, which in turn will have a positive impact on environmental, agricultural and biodiversity aspects of ecosystems. The consequences of an increase in soil carbon storage can include increases in soil fertility, land productivity for food production and security, and prevention of land degradation. Therefore, they might constitute win–win situations.

A proper analysis of the impact of climate change must also consider other global concerns such as loss of biodiversity, changes in land use, growing food demand, and soil degradation. International United Nations conventions exist regarding these problems: the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (CCD), the Ramsar Convention of Wetlands, and there are also several related United Nations programmes, e.g. the United Nations Environment Programme (UNEP), and the United Nations Development Programme (UNDP). Other initiatives, such as the Millennium Ecosystem Assessment, funded internationally by the World Bank, the United Nations Global Environment Facility (GEF), etc., aim to determine the state of the earth's ecosystems, trying to take into consideration all global problems and the interactions among them.

THE TERRESTRIAL CARBON CYCLE

To help understand the concept of CS, Figure 2 presents a simplified diagram of the carbon balance of terrestrial ecosystems. The main entry of C into the biosphere is through the process of photosynthesis or gross primary productivity (GPP), that is the uptake of C from the atmosphere by plants. Part of this C is lost in several processes: through plant respiration (autotrophic respiration); as a result of litter and soil organic matter (SOM) decomposition (heterotrophic respiration) and as a consequence of further losses caused by fires, drought, human activities, etc.

FIGURE 2
Terrestrial global carbon balance (simplified)



Source: Adapted from IPCC (2000).

Currently, the biosphere constitutes a carbon sink that absorbs about 2.3 gigatonnes of C per year, which represents about 30 percent of fossil-fuel emissions. The increasing atmospheric CO_2 concentration stimulates the process of photosynthesis (currently substrate-limited) and consequently plant growth, as extensive experimental research has shown (IPCC, 2000). The extent of this stimulation varies according to different estimates, being larger for forest (up to 60 percent) and smaller for pastures and crops (about 14 percent). Current scientific evidence suggests that managed and mature old-growth forests act as active carbon sinks sequestering C at rates of up to 6 tonnes/ha/year (for boreal and temperate forests) (Valentini, Matteucci and Dolman, 2000).

However, forests and ecosystems in general may have a limited capacity to accumulate C. First, this is because the capacity to sequester C is limited by other factors, such as nutrient availability (Oren, Ellsworth and Johnsen, 2001) and other biophysical factors. Second, photosynthesis may have a CO_2 saturation point, above which it will no longer respond to an increase in atmospheric CO_2 concentration. A third reason is that climate change may lead to ecosystem degradation, in turn, limiting the capacity to sequester C. Although much scientific progress has been made recently, these processes are still poorly understood. Therefore, predictions of more than a few decades are highly uncertain. Furthermore, forests in the absence of disturbances are expected to take up C for 20–50 years after establishment and, therefore, they should be considered as a time-buyer until other technologies are developed to reduce emissions.

Many scientific issues regarding the global carbon cycle remain unresolved or uncertain, such as the contribution of oceans to the global carbon balance (Del Giorgio and Duarte, 2002), the contribution of rivers (Richey *et al.*, 2002), and the interaction with other biogeochemical cycles (Schimel, 1998). The switch of the terrestrial biosphere from its current role as a carbon sink to a carbon source is highly controversial, as it is based on the long-term sensitivity of the respiration of soil microbes to global warming. Long-term predictions using bioclimate models yield different results depending on the temperature sensitivity function used for heterotrophic respiration. One of these simulations indicated that the absorption capacity of the biospheric carbon pool was approaching its limit, and that forests would turn into sources after 50-150 years (Cox *et al.*, 2000). Other findings suggest that, based on long-term soil warming experiments in the boreal zone, heterotrophic respiration is not very sensitive to increases in temperature, and that, therefore, the future of carbon sinks could be maintained (Falkowski, Scholes and Boyle, 2000). Global warming could lead to an increase in heterotrophic respiration and decomposition of organic matter, and consequently to a decline in the sink capacity of terrestrial ecosystems (Schimel, House and Hibbard, 2001). Further research is needed before any sound conclusions can be reached.

Although strategies to sequester C may be welcome, the use of CS options should not distract from the goal of reducing dependence on fossil fuel, the cause of the problem in the first place. CS should not be seen as a way to substitute the need and motivation to utilize energy efficiently and to use renewable energy. Rather, CS should be seen a good thing per se and as a bridge until other acceptable and environmentally friendly alternatives are found.

SOILS AND CARBON SEQUESTRATION

Soils are the largest carbon reservoir of the terrestrial carbon cycle. The quantity of C stored in soils is highly significant; soils contain about three times more C than vegetation and twice as much as that which is present in the atmosphere (Batjes and Sombroek, 1997). Soils contain much more C (1 500 Pg of C to 1 m depth and 2 500 Pg of C to 2 m; 1 Pg = 1 gigatonne) than is contained in vegetation (650 Pg of C) and twice as much C as the atmosphere (750 Pg of C) (see Figure 1). Carbon storage in soils is the balance between the input of dead plant material (leaf and root litter) and losses from decomposition and mineralization processes (heterotrophic respiration) (Figure 3). Under aerobic conditions, most of the C entering the soil is labile, and therefore respired back to the atmosphere through the process known as soil respiration or soil CO_2 efflux (the result of root respiration – autotrophic respiration – and decomposition of organic matter – heterotrophic

FIGURE 3
Soil carbon balance (simplified)

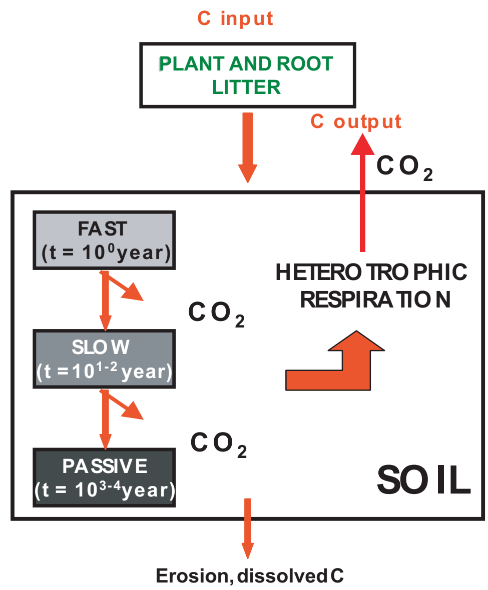


TABLE 1
Agricultural practices for enhancing productivity and increasing the amount of carbon in soils

Traditional practices	Recommended
Plough till	Conservation till or no-till
Residue removal or burning	Residue return as mulch
Summer fallow	Growing cover crops
Low off-farm input	Judicious use of fertilizers and integrated nutrient management
Regular fertilizer use	Soil-site specific management
No water control	Water management/conservation, irrigation, water table management
Fence-to-fence cultivation	Conversion of marginal lands to nature conservation
Monoculture	Improved farming systems with several crop rotations
Land use along poverty lines and political boundaries	Integrated watershed management
Draining wetland	Restoring wetlands

respiration). Generally, only 1 percent of that entering the soil (55 Pg/year) accumulates in more stable fractions (0.4 Pg/year) with long mean residence times.

The process of soil CS or flux of C into the soil forms part of the global carbon balance. Many of the factors affecting the flow of C into and out of soils are affected by land-management practices. Therefore, management practices should focus on increasing the inputs and reducing the outputs of C in soils (Table 1). The change in soil carbon stock under different management practices is modelled for specific case studies in Chapter 5.

The long-term CS potential is determined not only by the increase of C inputs into the soil but also by the turnover time of the carbon pool where the C is stored. For long-term CS, C has to be delivered to large pools with slow turnover. The partitioning between different soil carbon pools with varying turnover times is a critical controller of the potential for terrestrial ecosystems to increase long-term carbon storage. Allocation of C to rapid-turnover pools limits the quantity of long-term carbon storage, as it is released rapidly back to the atmosphere.

A proper analysis of the CS potential of a specific management practice should consider a full carbon balance of the management practice if it is to be used for carbon mitigation purposes. Another problem is the cost of agricultural practices in terms of C. Application of fertilizers, irrigation and manuring are all common practices that consume C. Therefore, full carbon accounting should take into account all activities associated with a particular practice.

Furthermore, other GHG such as methane (CH_4) and nitrous oxide (N_2O) are influenced by land use. Although emitted in smaller amounts, they have a much larger greenhouse potential. Therefore, they should be quantified explicitly and included in the total balance. One kilogram of CH_4 has a warming potential 23 times greater than 1 kg of CO_2, over a 100-year period, while the warming potential of 1 kg of N_2O is nearly 300 times greater (Ramaswamy, Boucher and Haigh, 2001). About one-third of CH_4 emissions and two-thirds of N_2O emissions to the atmosphere come from soils (Prather *et al*., 1995) and are related to agricultural practices.

THE NEED OF MODELS TO SIMULATE CHANGES IN SOIL CARBON

SOM is a key indicator for soil quality, both economically, as it enhances plant productivity, and from an environmental point of view on account of CS and biodiversity. SOM is the main determinant of soil biological activity, which in turn, has a major impact on the chemical and physical properties of soils (Robert, 1996). The increase in SOM can improve: aggregation and the stability of soil structure; infiltration rate and water retention; and resistance to erosion.

Soil carbon storage is controlled primarily by two processes: primary production (input) and decomposition (output). Measurements of C storage in an ecosystem alone reveal little about how C has changed in the past or will change in the future. The effect of climate and/or land-use change can be predicted only through the use of accurate dynamic models. Modelling has been used as an effective methodology for analysing and predicting the effect of land-management practices on the levels of soil C.

A number of process-based models have been developed over the last two decades to fulfil specific research tasks. Each model varies in its suitability for application to new contexts. A number of comparisons between models have been made, in particular by Smith *et al.*, (1997). The European Soil Organic Matter Network also provides a comprehensive description of many models currently available. Various models have been developed to simulate C dynamics in soils. SOM is very complex, formed of very heterogeneous substances and generally associated with minerals present in soils. The mean residence time of C in soils ranges from one or a few years (labile fraction) to decades and even to more than 1 000 years (stable fraction). The mean residence time is determined not only by the chemical composition of SOM but also by the kind of protection or bond within the soil. The stable carbon fraction is protected either physically or chemically. Physical protection consists of the encapsulation of SOM fragments by clay particles and microaggregates (Balescent, Chenu and Baladene, 2000). Chemical protection refers to specific chemical bonds between SOM with other soil constituents, such as colloids or clays. Different factors influence different pools. Given the complexity of the nature of SOM, most models describe soil organic carbon (SOC) as divided in multiple parallel compartments with different turnover times (Figure 3). Such compartment models are in principle conceptually simple and have been used widely. A good example is the Rothamsted SOC model that has five compartments: decomposable plant material, resistant plant material, microbial biomass, humus and SOM (Jenkinson and Rayner, 1977; Jenkinson, 1990). Another popular model is the CENTURY model (Parton *et al.*, 1987; Parton, Stewardt and Cole, 1988) which also has carbon compartments with similar parameters. Although simple conceptually, the problem of these models is that they require information on the size and turnover rate of each compartment, which is difficult to obtain from field studies. However, they have provided useful information on the effect of temperature, moisture and soil texture on the turnover of C in soils. FAO has developed a model as a methodological framework for the assessment of carbon stocks and the prediction of CS scenarios that links SOC turnover simulation models (particularly CENTURY and Rothamsted) to geographical information systems and field measurement procedures (FAO, 1999). However, the real potential for terrestrial soil CS is not known because of a lack of reliable database and fundamental understanding of the SOC dynamics at the molecular, landscape, regional and global scales (Metting; Smith and Amthor, 1999). The lack of sound scientific evidence and the difficulty of carbon accounting have probably prevented the explicit inclusion of soils in the KP.

It has been speculated that improved terrestrial management over the next 50–100 years could sequester up to 150 Pg of C, the amount released to the atmosphere since the mid-nineteenth century as a result of past agricultural conversion of grasslands, wetlands and forests (Houghton 1995; Lal *et al.*, 1998). If this figure were realistic, it would be a “buying time” for the development and implementation of a longer-term solution to the CO_2 problem. Evidence for long-term experiments reveals that soil C losses as a result of oxidation and erosion can be reversed through improved soil management such as reduced tillage and fertilization (Rasmussen, Albrecht and Smiley, 1998; Sa *et al.*, 2001). Therefore, improved land-management practices to enhance CS in soils have been suggested as a viable way to reduce atmospheric C content significantly (Cole *et al.*, 1996; Rosenberg, Izaurralde and Malone, 1999).

SOIL DEGRADATION

Soil degradation is a global problem (UNEP, 1992), particularly the desertification of drylands. Most of the drylands are on degraded soils (see Chapter 2), soils that have lost significant amounts of C. Therefore, the potential for sequestering C through the rehabilitation of drylands is substantial (FAO, 2001b). Lal (2000) estimated the magnitude of the potential for sequestering C in soils in terrestrial ecosystems at 50–75 percent of the historic carbon loss. Furthermore, Lal hypothesized that annual increase in atmospheric CO_2 concentration could be balanced out by the restoration of 2 000 000 000 ha of degraded lands, to increase their average carbon content by 1.5 tonnes/ha in soils and vegetation. The benefits would be enormous. Enhancing CS in degraded agricultural lands could have direct environmental, economic, and social benefits for local people. Therefore, initiatives that sequester C are welcomed for the improvement in degraded soils, plant productivity and the consequent food safety and alleviation of poverty in dryland regions.

The effects of soil degradation and desertification affect the global C cycle. Land-use change leads to a loss in vegetation cover and subsequent loss in organic C in soils and soil quality. The processes of plant productivity, soil degradation and CS are closely linked. A decline in soil quality leads to a reduction in the soil organic C pool, and an increase in the emission of CO_2 to the atmosphere. The decline in soil quality and structure leads to a loss in the capacity to retain water, and therefore in plant productivity.

Drylands have particular characteristics that affect their capacity to sequester C. Chapter 2 presents the main characteristics and distribution of drylands in the world. Chapters 3 and 4 describe the farming systems and the biophysical aspects of CS in drylands. Chapter 5 summarizes several case studies in various countries where several simulations have been run to estimate the change in soil C under different management options. Chapter 6 analyses the existing funds for CS projects. Conclusions are presented in Chapter 7.

Chapter 2
The world's drylands

DEFINITION OF DRYLANDS

Depending on definitions, about 47 percent of the surface of the earth can be classified as dryland (UNEP, 1992). Although there is no clear boundary, drylands are considered to be areas where average rainfall is less than the potential moisture losses through evaporation and transpiration. According to the World Atlas of Desertification (UNEP, 1992), drylands have a ratio of average annual precipitation (P) to potential evapotranspiration (PET) of less than 0.65.

Where the water deficit prevails throughout the year, drylands are classified as extremely arid or hyperarid, whereas when it occurs for most of the year they are arid and semi-arid regions. Aridity is assessed on the basis of climate variables (so-called aridity index), or according to FAO on the basis of how many days the water balance allows plant growth (growing season). The aridity index uses the P/PET to classify drylands into hyperarid, arid, semi-arid and dry subhumid (Table 2).

The negative balance between precipitation and evapotranspiration results in a short growing season for crops (usually less than 120 d). For CS purposes, drylands are also considered to include arid, semi-arid and dry subhumid areas. Hyperarid regions are not considered as there is no crop growth unless under irrigation.

Droughts are characteristic of drylands and can be defined as periods (1–2 years) where the rainfall is below the average. Droughts that persist for a decade or more are called desiccation, which can have disastrous consequences for land productivity and vegetation loss. Drought preparedness and risk mitigation are essential for the proper management of dryland areas. Populations living in these regions have been developing strategies to cope with them. These measures include: strengthening indigenous strategies to cope with drought; supporting the development and adoption of resource management practices that will protect and improve productivity, thereby increasing the resilience of agricultural systems; reducing fluctuations in prices of livestock and grains during drought periods through expanding market size and reducing transaction costs; developing a set of warning indicators; and setting aside drought grazing reserves or strategic water reserves (Øygard, Vedeld and Aune, 1999).

LAND DEGRADATION IN DRYLANDS

Desertification results from the degradation of the natural ecosystems in drylands and constitutes a major global problem (UNEP, 1992). It is defined by the CCD as "*Land*

TABLE 2
Dryland categories according to FAO (1993) classification and extension (UNEP, 1992)

Classification	P/PET (UNEP, 1992)	Rainfall (mm)	Area (%)	Area (Bha)
Hyperarid	< 0.05	< 200	7.50	1.00
Arid	0.05 < P/PET < 0.20	< 200 (winter) or <400 (summer)	12.1	1.62
Semi-arid	0.20 < P/PET < 0.50	200–500 (winter) or 400–600 (summer)	17.7	2.37
Dry subhumid	0.50 < P/PET < 0.65	500–700 (winter) or 600–800 (summer)	9.90	1.32
TOTAL			47.2	6.31

Bha = 10^9 ha.

use degradation in arid, semi-arid and dry humid areas resulting from various factors, including climatic variation and human activities". The degradation can be:

- physical — mainly driven by climate factors such as floods and droughts that cause soil erosion (by wind and water),
- chemical — generally in the form of salinization (in irrigated lands),
- biological — mainly as a result of the oxidation of topsoil organic matter in dryland.

The main consequences of land degradation are: the chemical degradation of the soil; loss of vegetation cover; loss of topsoil infiltration capacity; reduction in soil water storage; loss of SOM, fertility and structure; loss of soil resilience; loss of natural regeneration; and lowering of the water table. Soil degradation affects about one-fifth of arid zones, mostly on semi-arid margins where cultivation take place. Land degradation may have a significant impact on climate. The loss of plant cover can alter the surface energy balance. Atmospheric dusts from deserts modifies the scattering and absorption of solar radiation (Kassas, 1999). Although uncertainty exists with regard to the causes of climate change and global warming and the possible consequences, there is agreement that some impacts are probable. For example, temperature increases will affect evapotranspiration, which will be most significant in places where the climate is hot. Predictions about the quantity and distribution patterns of rainfall in these regions are uncertain, but the Intergovernmental Panel on Climate Change indicated that semi-arid regions are among those most likely to experience increased climate stress (IPCC; 1990). Furthermore, climate change may have unpredictable and perhaps extreme consequences with respect to the frequency and intensity of precipitation and temperature variability for semi-arid regions.

Table 3 indicates the extension of degraded lands according to cause. One of the problems of assessing the extent of desertification and the measures to prevent it, is the lack of reliable and easily measured land quality indicators. The Land Degradation Assessment in Drylands project, initiated by FAO, focuses on the development of a detailed methodology for the assessment of land degradation in an area that covers as much as half of the global land surface (FAO, 2002a, 2003).

Several estimates exist for the extent of desertification. According to the Global Assessment of Human and Induced Soil Degradation methodology, the land area affected by desertification is 1 140 000 000 ha, which are similar to the UNEP estimates (Table 4).

According to UNEP (1991a), when rangelands with vegetation degraded are included (2 576 000 000 ha), the percentage of degraded lands of the drylands is 69.5 percent

TABLE 3
Degraded lands per continent

Cause	Africa	Asia	Oceania	Europe	North America	South America
	(million ha)					
Deforestation	18.60	115.5	4.20	38.90	4.30	32.20
Overgrazing	184.6	118.8	78.50	41.30	27.70	26.20
Agricultural	62.20	96.70	4.80	18.30	41.40	11.60
Over exploitation	54.00	42.30	2.00	2.00	6.10	9.10
Bio-industrial	0.00	1.00	0.00	0.90	0.00	0.00
Total degraded	319.4	370.3	87.50	99.40	79.50	79.10
Total	1286	1671.8	663.3	299.6	732.4	513.0

Source: UNEP (1997).

(5 172 000 000 ha). According to Oldeman and Van Lynden (1998), the degraded areas for light, moderate and severe degradation are 489 000 000, 509 000 000 and 139 000 000 ha respectively.

Estimates of rates of current desertification vary considerably mainly because of the lack of quantitative criteria for defining degradation. UNEP (1991a) distinguished between land degradation and vegetation degradation. The degradation of vegetation in rangelands can take place with or without soil degradation. UNEP (1991) estimates the annual rate of desertification to be 5 800 000 ha or 0.13 percent of the dryland in mid-latitudes (Table 5). However, although desertification is a problem in drylands, drylands have a high degree of resilience to human interventions. Dryland populations have developed well-adapted and efficient resource management practices. Therefore, the participation of dryland communities is crucial to improving dryland management. If the policies and practices of donors are to succeed, they must be based on the knowledge, experiences, aspirations, priorities and decisions of the people living in drylands.

TABLE 4
GLASOD estimates of desertification (excluding hyper dry areas)

Land type	1. Area (Bha)	Type of soil degradation	2. Area (Bha)
Degraded irrigated lands	0.043	Water erosion	0.478
Degraded rainfed croplands	0.216	Wind erosion	0.513
Degraded range-lands	0.757	Chemical deg-radation	0.111
(soils and vegeta-tion)		Physical degra-dation	0.035
Total land area	1.016	Total land area	1.137

Bha = 10^9 ha.
Sources: 1. UNEP (1991b). 2. Oldeman and Van Lynden (1998).

TABLE 5
Rates of land degradation in mid-latitudes drylands

Land use	Total land area (Mha)	Rate of desertification	
		Mha/y	Percent of total/y
Irrigated land	131	0.125	0.095
Rangeland	3 700	3.200	0.086
Rainfed cropland	570	2.500	0.439
Total	4 401	5.825	0.132

Mha = 10^6 ha.
Source: **(UNEP, 1991a).**

Desertification can be prevented through a proper management of the land to ensure sustainable development of its resources. In 1994, the United Nations agreed on the CCD by developing specific country action plans. Strategies for desertification control include: establishment and protection of vegetation cover to protect soils from erosion, controlled grazing; improved water conservation by residue management and mulching to help decrease water losses by runoff and evaporation; supplemental irrigation; soil fertility management which enhances biomass productivity; increased water use efficiency; and improved soil quality; improved farming systems that include crop rotations; fallowing; agroforestry; and grazing management (Lal, 2001b). All these strategies increase CS in soils.

Depending on land-use, desertification is manifested in different ways:

Irrigated farmlands: Excessive irrigation and inefficient drainage leads to waterlogging and salinization;

Rainfed farmlands: Soil erosion, loss of organic matter and nutrients;

Rangelands: Reduction in plant productivity, invasion of unpalatable species.

Desertification affects more than 100 developed and developing countries in all continents (UNEP, 1997). Some 200 million people are believed to be affected directly by desertification and more than 1 000 000 000 people at risk. The future sustainability of dryland ecosystems and the livelihoods of people living in them depend directly on the actions taken for land-use management. These activities should include soil and water conservation for improved land-use management practices and farming systems, taking into account health, social and economic issues when developing strategies and policies to improve land management.

DISTRIBUTION OF DRYLANDS

Most arid land areas of the world occur between the latitudes of 20° and 35°. The main semi-arid areas occur on each side of the arid zone and include Mediterranean-type and monsoonal-type climates. Mediterranean climates are characterized by cold wet winter and dry hot summers whereas monsoonal-type climates have hot wet summers and warm dry winters. Another type of dryland is the cold desert, which generally occurs in high-altitude continental areas

Drylands occupy 47.2 percent of the world's land area, or 6 310 000 000 ha across four continents: Africa (2 000 000 000 ha), Asia (2 000 000 000 ha), Oceania (680 000 000 ha), North America (760 000 000 ha), South America (56 000 000 ha) and Europe (300 000 000 ha) (UNEP, 1992) in more than 110 countries (Figure 4). About 2 000 000 000 people live in drylands (UNEP, 1997), in many cases in poor conditions. The hyperarid zones extend mostly across the Saharan, Arabian and Gobi deserts and have only localized population around valleys such as the Nile Valley and the Nile Delta. The arid zones cover about 15 percent of the land surface. The annual rainfall in these areas is up to 200 mm in winter-rainfall areas and 300 mm in summer-rainfall areas. Interannual variability is 50–100 percent. Africa and Asia have the largest extension of arid zones, they account for almost four-firths of hyperarid and arid zones in the world (Table 6).

Semi-arid zones are more extensive and occur in all the continents, and cover up to 18 percent of the land surface. They have highly seasonal rainfall regimes and a mean rainfall of up to 500 mm in winter-rainfall areas and up to 800 mm in summer-rainfall areas. With an interannual variability of 25–50 percent, grazing and cultivation are both vulnerable, and population distribution depends heavily upon water availability.

SOIL AND VEGETATION OF DRYLANDS

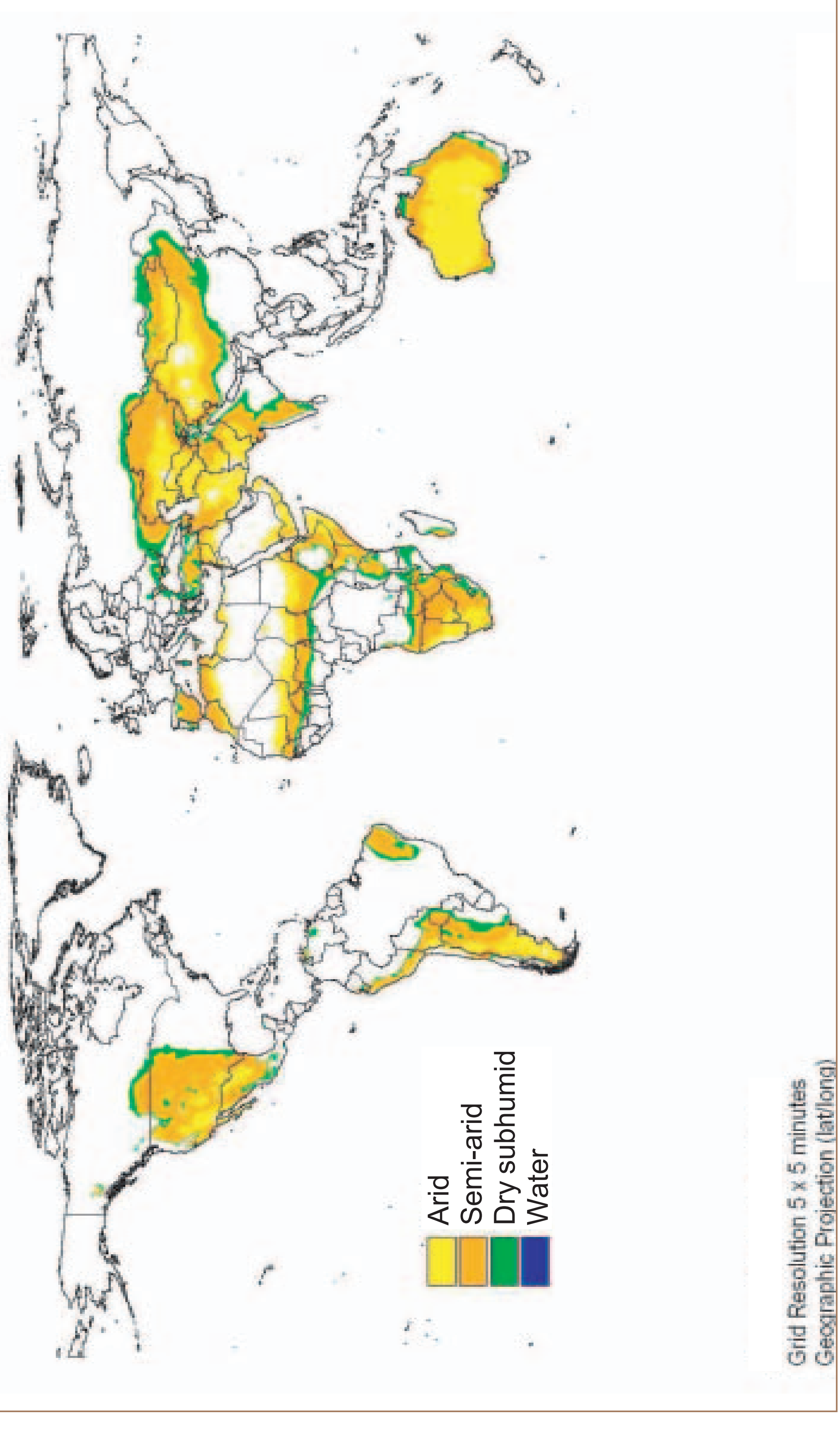
As discussed above, the soils of drylands are characterized by frequent water stress, low organic matter content and low nutrient content, particularly nitrogen (N) (Skujins, 1991). Although dryland vary considerably, they are mostly Aridisols (2 120 000 000 ha) and Entisols (2 330 000 000 ha). Other soils include: Alfisols (380 000 000 ha), Mollisols (800 000 000 ha), Vertisols (210 000 000 ha) and others (470 000 000 ha) (Dregne, 1976) (Figure 5). Whatever their type, soils are the basic resource of drylands as they provide the medium in which plants grow, and their properties, such as texture and waterholding capacity, determine the proportion of

TABLE 6
The global dryland areas by continent

Continent	Extension			Percentage		
	Arid	Semi-arid	Dry subhumid	Arid	Semi-arid	Dry subhumid
		(million ha)				
Africa	467.60	611.35	219.16	16.21	21.20	7.60
Asia	704.30	727.97	225.51	25.48	26.34	8.16
Oceania	459.50	211.02	38.24	59.72	27.42	4.97
Europe	0.30	94.26	123.47	0.01	1.74	2.27
North/central America	4.27	130.71	382.09	6.09	17.82	4.27
South America	5.97	122.43	250.21	7.11	14.54	5.97
Total	1 641.95	1 897.74	1 238.68			

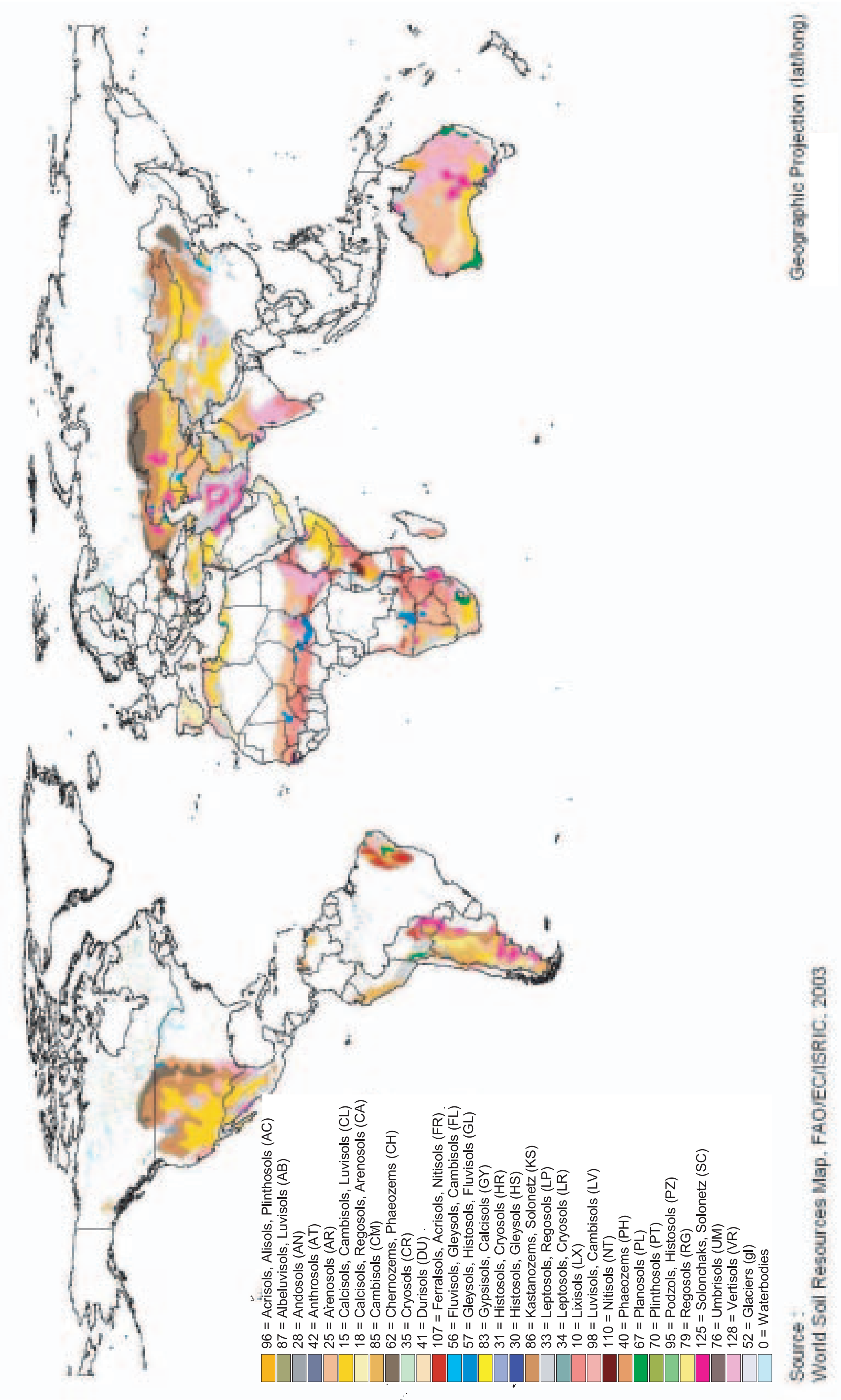
Mha = 10^6 ha.
Source: FAO (2002a).

FIGURE 4
Distribution of drylands in the world



Source: FAO (2002a).

FIGURE 5
Major soil types of drylands



rainfall available for plant growth. Low organic matter content, low germination and high seedling mortality are the main causes of very low plant productivity.

The vegetation supported by these soils ranges from barren or sparsely vegetated desert to grasslands, shrublands and savannahs, croplands and dry woodlands. Forest vegetation is usually poor, and is at low density with species adapted to arid soils and with a high water-use efficiency. Perennial vegetation varies considerably and tends to be sparse and patchy. Plants that have adapted to drylands survive irregular rainfall, high solar radiation and drought periods. Plants protect the soil surface from wind and water erosion. Removal or loss of vegetation cover results in an increased risk of soil erosion and degradation.

The predominant land uses of the drylands are pastoralism and subsistence food production (Figure 6). Cereals produced in drylands include wheat, barley, sorghum and millet and pulses such as chickpea, lentils, peas and groundnuts (Table 7). Less important are oil crops (rape and lindseed) and a wide range of fruits, vegetables, herbs and spices. Pastoralism is widespread and highly mobile (Table 8). Food production is mainly from smallholding rainfed systems for subsistence or local consumption and markets. Natural woodlands are used for fuel wood, and efforts are ongoing to extend the forested areas for fuel and for CS. Chapter 3 describes the farming systems of drylands in detail.

TABLE 7
Typical crops under rainfed conditions

Classification	Length of the growing season	Typical crops
Hyper-arid	0	No crop, no pasture
Arid	1–59	No crops, marginal pasture
Semi-arid	60–119	Bulrush millet, sorghum, sesame
Dry subhumid	120–179	Maize, bean, groundnut, peas, barley, wheat, teff (suitable for rainfed agriculture)

FAO, 1993.

TABLE 8
Percentage land uses in arid regions in 1980

Nomadic pastoralism	41
Ranching	25
Rainfed agriculture	12
Hunting, fishing, gathering	3
Irrigated agriculture	2
mostly unused	16

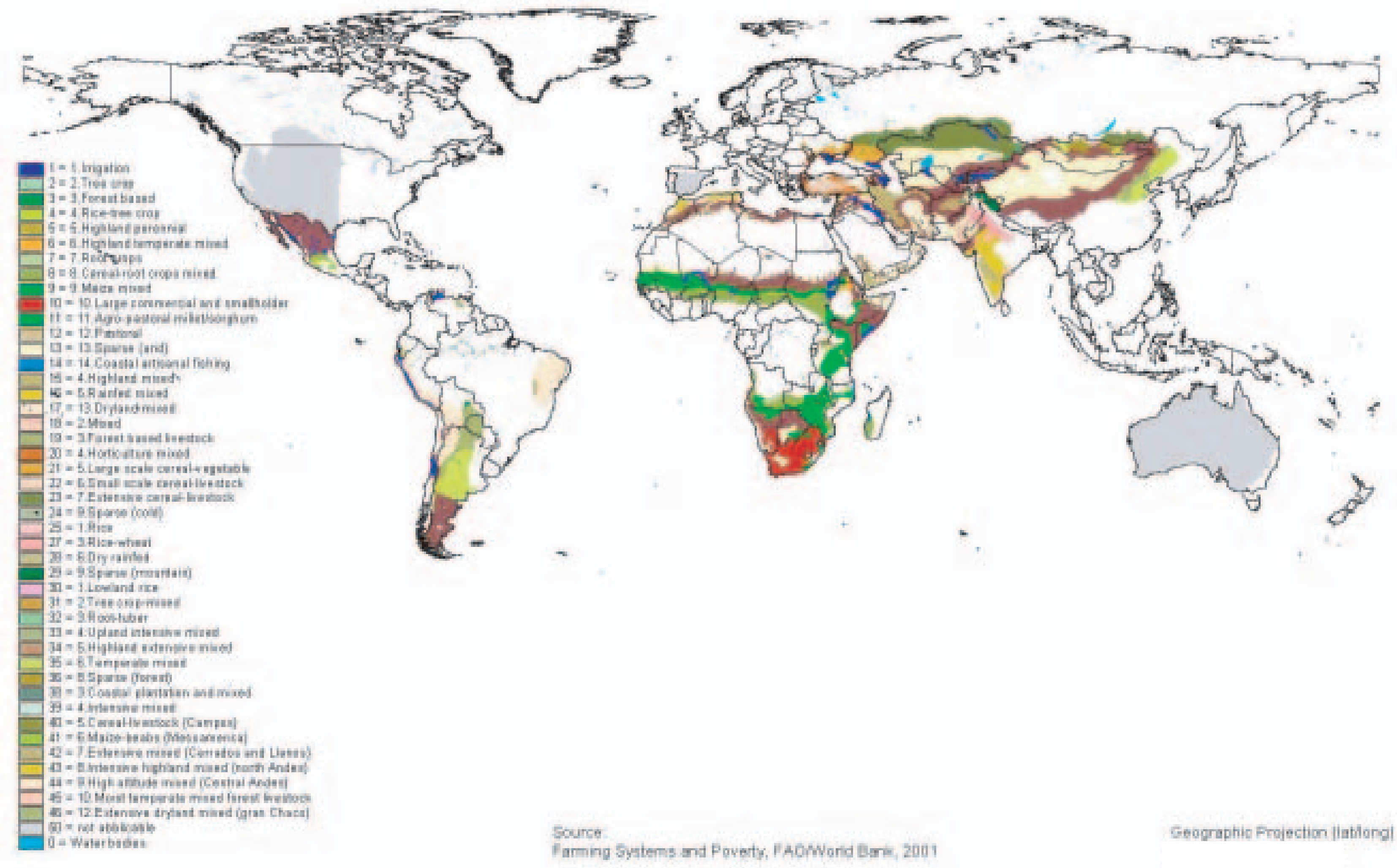
Source: Heathcote (1983).

The major constraint on agricultural development is low and highly variable rainfall and the consequent high risk for agriculture and animal husbandry. Traditional systems of rainfed cropping have evolved for thousands of years. Several general strategies have been developed to cope with low and erratic rainfall. Rainfed agriculture is generally practised in areas with a reasonable amount of rain and where soils are relatively deep. Drier regions are generally used for livestock grazing, with regular seasonal movements. Normally, several crops are sown to reduce the risk of total crop failure. Varieties that are resistant or adapted to drought are used. Long fallows are used to prevent stress on the land. During the fallow periods, soils are protected by a vegetation cover that provides nutrient and organic matter to the soils. Many pastoralists and sedentary farmers work together by exchanging crops and meat.

CHARACTERISTICS OF DRYLANDS THAT AFFECT CARBON SEQUESTRATION

Dryland environments are characterized by a set of features that affect their capacity to sequester C. The main characteristic of drylands is lack of water. This constrains plant productivity severely and therefore affects the accumulation of C in soils. The problem is aggravated because rainfall is not only low but also generally erratic. Therefore, good management of the little available water is essential. In addition, the SOC pool tends to decrease exponentially with temperature (Lal, 2002a). Consequently, soils of drylands contain small amounts of C (between 1 percent and less than 0.5 percent) (Lal, 2002b). The SOC pool of soils generally increases with the addition of biomass to soils when

FIGURE 6
Major farming systems in the drylands (arid, semi-arid and dry sub-humid) according to FAO, 2003



BOX 1
DRYLAND CHARACTERISTICS THAT AFFECT CS

- **Unfavourable**
  - Lack of water
  - Low and erratic rainfall
  - Generally high temperatures
  - Low productivity
  - Low SOM (0.5-1percent) and nutrient content
  - Prone to soil degradation and desertification

- **Favourable**
  - Residence time of SOM is long
  - They occupy more than 43 percent of the earth's surface
  - As a consequence of historic carbon loss they are far from saturation
  - Soil quality improvement through CS will have large economic and social impact

the pool has been depleted as a consequence of land uses (Rasmussen and Collins, 1991; Paustian, Collins and Paul, 1997; Powlson, Smith and Coleman, 1998, Lal, 2001a). Soils in drylands are prone to degradation and desertification, which lead to dramatic reductions in the SOC pool. A good overview of the extent of land degradation in different dryland regions of the world is given in Dregne (2002). However, there are also some aspects of dryland soils that work in favour of CS in arid regions. Dry soils are less likely to lose C than wet soils (Glenn *et al.*, 1992) as lack of water limits soil mineralization and therefore the flux of C to the atmosphere. Consequently, the residence time of C in drylands soils is long, sometimes even longer than in forest soils. The issue of permanence of C sequestered is an important one in the formulation of CS projects. Although the rate at which C can be sequestered in these regions is low, it may be cost-effective, particularly taking into account all the side-benefits resulting for soil improvement and restoration. Soil-quality improvement as a consequence of increased soil C will have an important social and economic impact on the livelihood of people living in these areas. Moreover, given the large extent of drylands, there is a great potential for CS. The potential offered by drylands to sequester C is large, not only because of the large extent, but because historically, soils in drylands have lost significant amounts of C and are far from saturation. Because of all of these characteristics, any strategy to re-establish SOM in these regions is particularly interesting (Box 1).

DESERTIFICATION AND CARBON SEQUESTRATION

The effects of desertification on soil quality include:

- loss in soil aggregation
- decrease in water infiltration capacity
- reduction in soil water storage
- increase in erosion potential
- depletion in SOM, difficulty in seed germination
- disruption of biogeochemical cycles C, N, phosphorous, sulphur alterations in water and energy balance
- loss of soil resilience

All of these effects accentuate the emission of CO_2 to the atmosphere. Lal (2001c) estimated the C loss as a result of desertification. Assuming a C loss of 8–12 Mg C/ha (Swift *et al*., 1994) on a land area of 1 020 000 000 ha (UNEP, 1991a), the total historic C loss would amount to 8–12 Pg C. Similarly, vegetation degradation has led to a C loss of 4–6 Mg C/ha on 2 600 000 000 ha, adding up to 10–16 Pg C. The total C loss as a consequence of desertification may be 18–28 Pg C. Assuming that two-thirds of the C lost (18–28 Pg) can be resequestered (IPCC, 1996) through soil and vegetation restoration, the potential of C sequestration through desertification control is 12–18 Pg C (Lal, 2001c). These estimates provide an idea about the loss of C as a result of desertification and the potential for CS through the restoration of soils in drylands.

Opportunities for improved land management as well as increasing CS should be developed in these areas. Agricultural systems contribute to carbon emissions through the use of fossil fuels in farm operations and through practices that result in loss of organic matter in soils. On the other hand, farming systems can offset carbon losses when accumulating organic matter in the soil, or when aboveground woody biomass is increased, which then acts either as a permanent sink or used as an energy source that substitutes fossil fuel. The potential for global benefits, as well as local benefits, to be obtained from increased CS in drylands should be an additional incentive for stronger support for reforestation and agriculture in drylands.

Although drylands have been studied (Heathcote, 1983; Thomas, 1997a, 1997b), the impact of desertification on the global carbon cycle and the potential impact of desertification control on CS in dryland ecosystems have not been widely investigated. There are few case studies, and little information. Consequently, there is little scientific evidence on the impact of desertification on carbon emission to the atmosphere. The aim here is to assess the state of knowledge, and the potential of different measures to increase CS.

Chapter 3
Farming systems in drylands

INTRODUCTION

According to FAO (2001a), a farming system is defined as "*a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate*". Depending on the scale of the analysis, a farming system can encompass a few dozen or many millions of households. The understanding of the major farming systems in drylands provides the necessary framework for the development of agricultural strategies and interventions. Based on the classification of farming systems of developing regions specified by FAO (2001a), most of the farming systems in drylands fall into the category of rainfed farming systems in dry low-potential areas. These systems are characterized by mixed crop–livestock and pastoral systems merging into sparse and often dispersed systems with very low current productivity or potential because of extreme aridity or cold.

Understanding the world of smallholders in dryland environments is the key to designing appropriate and successful CS activities. It is important to understand that CS for poverty alleviation must be much broader in terms of the range of both practices and benefits (i.e. not only in monetary terms) than similar schemes in commercial agriculture and forestry.

There are various potential partners, or target groups, for CS programmes in drylands. From a purely scale-driven perspective, large-scale capital-intensive agriculture might be the most attractive. However, from a biophysical standpoint, as discussed in Chapter 4, systems that use significant quantities of fertilizers or that depend heavily on fossil fuel to supply irrigation water should not generally be considered because they are usually net carbon emitters. Only if a switch from high fertilizer and fossil-fuel dependence to more carbon-friendly inputs, technologies or land use is foreseeable in the short-run, should current large-scale agriculture be considered. There are some systems of capital intensive land use, such as the mechanized farming schemes in eastern Sudan (where large areas of land have been severely degraded) that offer great potential for soil CS if rehabilitated through low-intensity land use.

Apart from these technical reasons, large-scale, capital-intensive agriculture systems are probably not potential partners for soil CS because the small additional income that sequestration might bring would be unattractive in comparison with profits from other sources, many of which depend on carbon-emissive techniques.

Thus, the main target groups of soil CS in degraded agro-ecosystems are primarily small-scale, resource-poor farmers in uncertain and risk-prone environments for whom anticipated benefits could constitute an enhancement of their livelihood. Reference to these groups of farmers is made as smallholders. They depend on low-input, subsistence-based agriculture, and they are usually characterized by diversity, variability and flexibility (Mortimore and Adams, 1999).

CHARACTERISTICS OF SMALLHOLDER AGRICULTURE

The primary characteristics of smallholder agriculture in semi-arid developing countries are its diversity in space, its variability through time, and its multidimensionality in terms of the ways it operates and survives (Mortimore and Adams, 1999). This is largely because dryland smallholders must be highly responsive to a varied, changeable and hazardous environment. Thus, their operations are very different from those of large-scale farms driven by commercial goals, equipped with credits and efficiency-oriented technologies and covered by insurance systems against hazards and losses. This diversity, variability and multidimensionality means that each particular system must be approached with careful attention to its unique mix of characteristics.

Another important characteristic of smallholders, which also differentiates them from commercial farmers, is that few are motivated solely by the goal of agricultural profit. Instead, smallholders pursue basic subsistence and survival goals, balancing daily risks and opportunities directly through their livelihood options and management practices rather than through external institutions (Collinson, 2000). Many smallholders have deep attachment to their land, which they continue to farm, even when profitability is low, for reasons such as maintaining tenure, and maintaining family ties. At the same time, many have additional, and often higher, incomes from non-agricultural sources. These include: petty trading; the gathering of wild produce, including firewood; labouring; and remittances from family members. The result is "multi-enterprise production units" (Hunt, 1991).

Smallholders are further differentiated from high-input commercial farmers by their need to manage multiple risks. Almost all of their inputs and outputs are subject to large variation and uncertainty, such as labour, which is often the most critical variable. Another critical risk arises from the high variability in rainfall, which itself has two major consequences as far as sequestration is concerned. One is variation in the timing of bioproductivity, which means that planting and harvesting (and most other agricultural and non-agricultural activities) may have to be readjusted rapidly, sometimes within a season, and often between seasons. For example, fallows that appeared secure for years may have to be cleared after a particularly poor season. The other consequence is variability between fields, some of which may receive sufficient rainfall, and some of which may not. There are other risks that have similar consequences. These include: attacks by pests (against which pesticides are too expensive); illness, resulting in the unavailability of labour at some critical point in the season; and variability regarding prices of inputs such as seed, labour, food, and of outputs, mainly crops.

According to Mortimore and Adams (1999), smallholder responses to these various constraints follow three key avenues: (i) diversification of natural, economic, technical and social resource endowments with the underlying rational to spread risks as efficiently as possible; (ii) flexibility in day-to-day management of these resources in the form of active decisions to cope with and adapt to short-term variability; and (iii) adaptability over the longer term, perceived as cumulative and purposeful decision-making that will result in new or altered systems or livelihood pathways. When spreading risks, it is important for farmers to have a mix of products where both the type of products and the price of these products are independent of each other, a criteria that potentially applies very well to CS.

A further characteristic of smallholder agriculture is variable access to resources of all kinds. Within a village, some have ready access, and others have less access, to: secure landholdings; wild produce, such as fuelwood; credit; hired labour; livestock; and markets. Access also varies between villages and between countries. The implications of such uneven access to resources for sequestration schemes are discussed below.

Finally, these agricultural systems are and have long been undergoing continual change in response to environmental and social changes. Dry environments are now widely recognized as having a complex history of change, based on non-equilibrium dynamics rather than predictable, gradual and linear change (Leach and Mearns, 1999; Scoones, 1999; Scoones, 2001), sometimes referred to as event-driven systems (Reenberg, 2001; Sorbo, 2003). Thus, agricultural systems have had to adapt continuously to environmental conditions and to changing political and economic processes. In the lifetime of a soil CS scheme, one could expect many changes in the configuration of the agricultural landscape, apart from the changes that the project itself might bring. Planning in such an environment will be challenging. Instead of simplified and standardized approaches and predefined technical solutions, CS schemes in these systems will need to offer a range of technological and management options from which farmers can choose according to their needs.

EXAMPLES OF SMALLHOLDER FARMING SYSTEMS

Within this broad description of the characteristics of dryland smallholder agriculture, there are various farming systems. These are systems such as annual croplands, plantations, forests, savannahs, natural pastures, fallow lands and vegetable gardens. Within each, there is a specific interaction between crops, livestock and trees, and between cultivated and non-cultivated land (FAO, 2000a).

Farming systems in drylands range from shifting cultivation embedded in extensive wooded grasslands to intensive smallholder farming where all land is under cultivation and the integration between cropping and animal husbandry maximized. However, these two extremes should not be understood as fixed points along an axis of agricultural development, but rather as examples of "pathways" of agricultural and environmental change (Scoones, 2001) that are possible both between and within sites. Such pathways of change reflect farmers' livelihoods, constraints and opportunities within a historical context. Figure 7 provides a schematic illustration of dryland smallholder farming systems.

Agricultural intensification

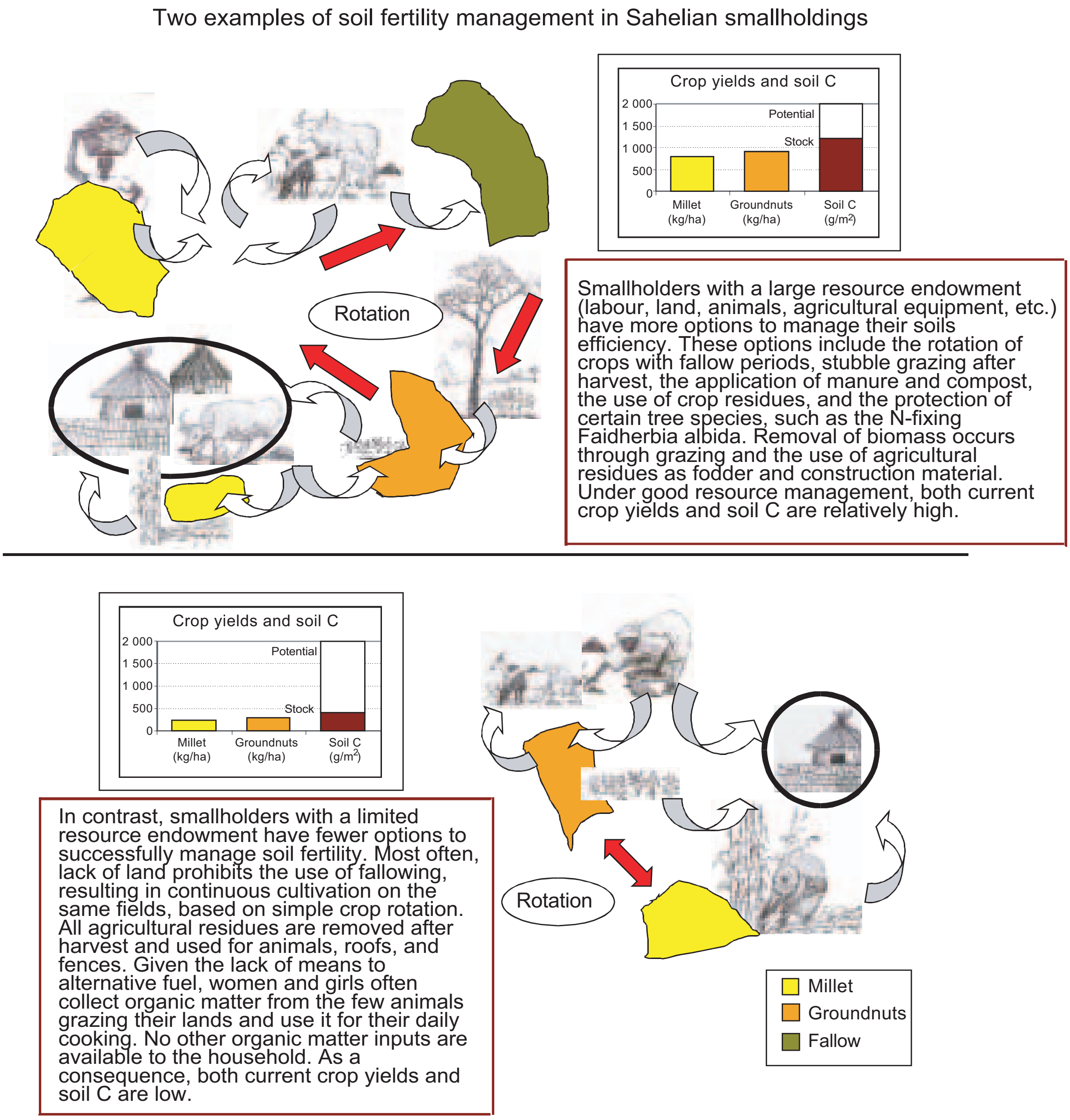
Intensification, as defined by Tiffen and Mortimore (1993), implies "increased average inputs of labour or capital on a smallholding, either on cultivated land alone, or on cultivated and grazing land, for the purpose of increasing the value of output per hectare". Intensification takes many forms, which can be classified in many ways. In the case of smallholder dryland farming systems, intensification tends to be related to increased local labour inputs per hectare and low-cost technologies rather than capital-intensive innovations. Mortimore and Adams (1999) describe such intensification as an "indigenous and adaptive process" whose path can be reconstructed through historical analyses.

There are many examples of such "indigenous" intensification. In rainfed farming systems, intensification often occurs as a consequence of growing population pressure. In many places, fallow periods have become shorter and shorter and eventually even abandoned. All fields may then be under cultivation and soil fertility is maintained by greater labour intensity. Techniques may include: intercropping with N-fixing legumes; time-intensive weeding and harvesting; the utilization of manure and mulch; and the protection of certain tree species. Crop rotation is practised where possible to ensure differential nutrient use and uptake between crops, such as millet and sorghum, and N-fixing crops, such as groundnuts and cowpeas. Trees, especially those known for their N-fixing and soil-restoring capacities, are protected. The application of manure, either from cattle or small ruminants, is a key element. In order to maintain supply in the face of increasing land scarcity, herds must be managed more intensively, e.g. feeding them with agricultural residues and weeds.

In dryland areas where sufficient surface water is available, irrigation has been a key method of intensifying land-use systems since ancient times. It requires supplies of water and of energy to take the water to the fields and gardens. The water may come from streams, rivers, springs and wells. Streams and rivers may be range from small ephemeral water courses, as in many parts of central Asia, to major rivers such the Nile, Niger, Amu-Darya, Hwang He and Indus.

Where there is a good "head" of water, as in mountainous terrain (e.g. in parts of highland Yemen and Oman), or in the large systems on floodplains, as of the Indus and Nile rivers, the water may be taken by gravity in small channels to the fields or

FIGURE 7
Smallholder farming systems in the Sahel and management strategies in the context of carbon



Source: Tschakert, field work, 2001.

gardens. Where the river flows in a gently sloping floodplain, the methods raising it to the fields of small schemes are much the same as from wells: animal or human-driven devices such as saqqias, Archimedes screws and shadufs. The qanat systems, which are particularly well developed in Iran and neighbouring areas, but are also found in other parts of Asia and in north Africa, are more elaborate, involving wells from which water is channelled underground, and fed to the fields by gravity. Another ancient system, which has seen major expansion and development in recent years, is water harvesting (or runoff agriculture). In this system, highly intermittent runoff is concentrated and then held in shallow troughs, where it is usually used for tree-crops.

Extensive land use

In areas where both population densities and rainfall are low, patterns of extensive land use predominate either as a longer-term system state or a more recent major pathway of change (Mortimore and Adams, 1999). The latter is true for some areas in central Senegal where entire compounds have migrated recently to the city of Touba, leaving relatives and neighbours with more land available than in previous decades (Tschakert and Tappan, 2004). As land scarcity does not represent a constraint in this case, fallow lands constitute an important element of the farming system, allowing for short- and medium-term soil regeneration. In general, field sizes are significantly larger than in areas under intensification. Given the amount of land available to individual households, manure is generally only used for fields that are under continuous cultivation, primarily those adjacent to the settlements and others in close proximity. Remote fields and those left fallow are accessible to grazing animals all year round. Unlike animals in intensified systems, herds are not forced to leave for transhumance and thus contribute to a continuous flux of organic matter input. Weeding and harvest activities might occur with less intensity, while more agricultural residues are left on the fields.

Agroforestry may play an important part in these extensive systems. One example is the Sudanese system of gum arabic production, where a tree that regrows on fallow land is a major source of income for smallholders (Elmqvist and Olsson, 2003). In other long fallows, trees that yield other useful products, such as fruits, nuts, fibre and medicines, are planted. Trees also provide an important source of emergency food.

The above examples of intensive and extensive farming systems illustrate that a context-specific approach based on multiple pathways of change offers useful guidelines for potential CS schemes. Project design and implementation should start with a local understanding of environmental change and its underlying processes. The next step is to identify positive pathways of change at the local level and then finally to assess opportunities to encourage such pathways on a larger scale.

Soil fertility management

The concept of CS in degraded agro-ecosystems is typically based on two assumptions. The first is that any improvement in soil fertility management and land use will result automatically in higher amounts of C sequestered from the atmosphere and stored in soils. The second is that local smallholders and herders, who are anticipated to be the prime beneficiaries of planned interventions, need to be made aware of and trained in such improved management practices.

Given the complex, diverse and dynamic world of smallholder farming in dryland environments, these two assumptions seem oversimplified. In general, proposed management practices and land-use options merely reflect the most efficient technical options, focusing on achieving an optimal agronomic situation. However, as illustrated above, smallholders are more concerned about day-to-day risk management and longer-term adaptive strategies than the achievement of an assumed new equilibrium. Opportunistic farming is all about spreading risk, an adaptive process during which both losses and gains occur, often intentionally. Pure “efficiency would leave no room for flexible maneuver” (Mortimore and Adams, 1999).

What in fact constitutes “improved” soil fertility management or land-use options might be understandable only from a holistic farming-system research approach. Farmers who have developed highly dynamic and flexible soil-fertility management practices to cope with variability and uncertainty are often in the best position to bring this holism to a development project. Although farmers often have much experience in deliberating technologies within a much broader framework of “real life”, they are most often considered as passive recipients of outside assistance rather than key resources in the process itself.

Thus, a first step towards linking soils and C to people is to investigate practices that smallholders in dryland environments currently know and use, to understand their underlying rationale as well as driving factors for change, and to identify examples of positive pathways of change that could be replicated on a larger scale (Tschakert and Tappan, 2004).

Soil fertility management practices can be grouped according to the movement of nutrients into, within, and out of a system. Here, practices are sorted into four groups (Hilhorst and Muchena, 2000): (i) adding nutrients to the soil; (ii) reducing losses of nutrients from the soil; (iii) recycling nutrients; and (iv) maximizing the efficiency of nutrient uptake. The examples below are based mainly on the Senegal and Sudan case studies.

Adding nutrients to the soil

Fallowing

Fallowing is a well-known practice for replenishing nutrients in soils. Ideally, fallow periods are rotated with cropping periods, allowing the land to recover from years of cultivation. However, in many parts of the world's drylands, both fallow area and duration have decreased over time. Most often, this decline is caused by increasing population pressure, the introduction of modern agricultural machinery, such as the plough, and periods of droughts, or a combination of all three. Some believe that this process is reaching crisis proportions. Today, in many drylands, fallow duration is reduced to only one year. In areas with severe land scarcity, it has disappeared altogether. As a consequence, farmers have shifted to other soil-fertility management practices, such as manuring and composting (see below) or they continue to farm with exceptionally low and decreasing yields. At the same time, less land in fallow also means reduced grazing possibilities or less fodder for animals, thus reducing the amount of manure that can be produced (Breman, Groot and van Keulen, 2000). Nevertheless, in areas with less population pressure, fallowing still constitutes an important option for soil-fertility management. This is particularly true for countries where structural adjustment packages have been implemented and subsidies for fertilizers removed.

Stubble grazing

Many farming systems include the grazing of animals on fields immediately after crop harvests. Animals graze stubble and stalks left on the field, while soils benefit from faeces deposition throughout the duration of the practice. Depending on the size and the forage situation of a field, as well as the overall number of animals, livestock is usually kept for 1–7 months on the same field, where it is rotated between different parts during shorter time intervals.

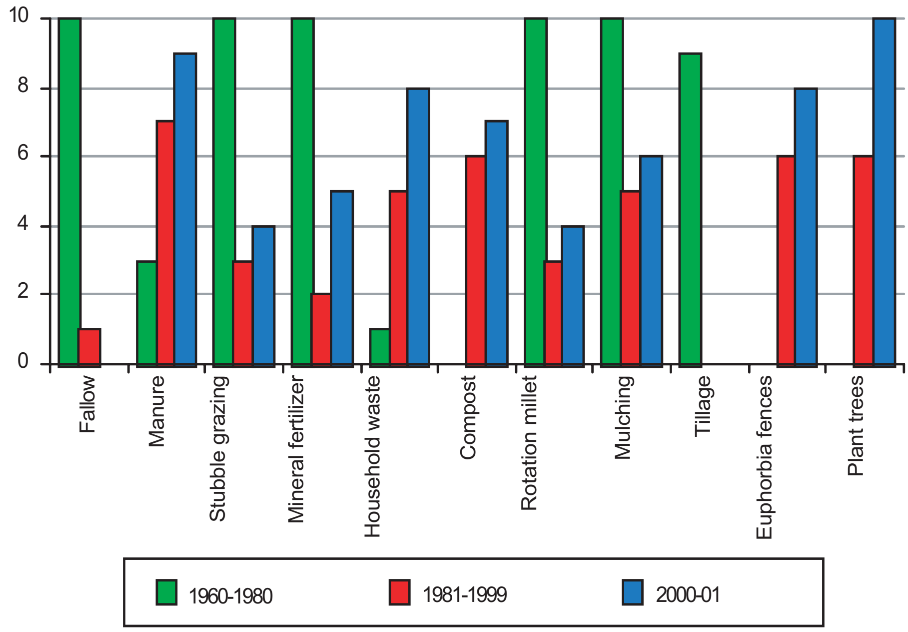
Overall, the gain in organic matter from stubble grazing can be substantial. In the Sahel, deposition of droppings ranges from 1 tonne/ha to 50 tonnes/ha depending on the time that animals are kept on the same field (Sagna-Cabral, 1989; Garin and Faye, 1990; Hoffmann and Gerling, 2001). However, direct exposure to the elements can reduce the nutrient value of dung and droppings considerably. Although stubble grazing has a long tradition in drylands, increasing land scarcity, limited purchasing power among many smallholders, and increased risks of animal theft in many areas have contributed to a general decline in herd sizes and, in some cases, led to the abandonment of stubble grazing altogether.

Inorganic fertilizers

The use of inorganic fertilizers has been one of the most widely promoted means for increasing production since the early twentieth century. In many of the drylands of the developing world, this kind of fertilizer was subsidized and made available to farmers with the aid of government and the support of non-governmental organizations

FIGURE 8

Changes in land use and soil fertility management, expressed in weighted points of importance/extent (1-10), as perceived by farmers in an intensified farming system in Senegal



Source: Tscharkert, field work, 2001.

(NGOs). Under structural adjustment programmes, subsidies were often removed and, hence, fertilizers became increasingly expensive for farmers. As is shown in the Senegal example (and illustrated in Figure 8), the use of fertilizers decreased in the 1990s. From a CS point of view, the use of synthetic fertilizers does not result in any net gain of carbon fixation (Schlesinger, 1999). The emission of CO_2 during the manufacture, transport and application of the fertilizers offsets any gain in biological production.

Crop rotation and association

The practice of crop rotation and association, especially where it involves both cereals and legumes, is well known among farmers as a soil-fertility management practice. In many places, N-fixing crops include beans and groundnuts. However, in farming systems where land scarcity has become a limiting factor, priority is often given to cereals. Moreover, the availability of seeds for legumes might be dependent on state subsidies or credits, as was the case with groundnuts in the Sahel.

Reducing losses of nutrients from the soil

Woody vegetation

Trees can be an important component in many agro-ecosystems. With their deep and extensive root systems, they can capture nutrients not accessible by crops and make them available to crop production again through litter fall. From a CS point of view, not only do the trees store C in their aboveground biomass, they also contribute to belowground biomass through their root systems and their input of litter to the soil (branches and leaves). Of particular use are leguminous (N-fixing) trees, among which *Faidherbia albida* and *Acacia senegal* are two of the most appreciated. Trees may also play a role in reducing nutrient losses from wind erosion. Special consideration must be given to the use of biofuel instead of fossil fuel.

Living hedges and fences can capture silt and clay particles suspended in the air and could, hence, locally increase the clay content of the soil, a factor beneficial for

CS (El Tahir and Madibo, in press). Litter produced by woody plants is beneficial because of its higher content of polyphenols (lignines and tannins), which decreases the decomposition rate (Abril and Bucher, 2001), when compared with grasses and annual herbs.

Erosion control

Erosion and subsequent transport and deposition have a complex relationship to soil carbon storage. Where water erosion dominates, a high proportion of soil C may be washed into alluvial deposits close to the erosion site, and stored there in forms which decay more slowly than in the parent soils. Therefore, this kind of erosion may have a positive effect on soil CS. Erosion does not always decrease productivity, but if it could be shown to do so, it would be perverse to favour decreased productivity for a medium-term and perhaps one-off gain in sequestered C. The same arguments probably do not apply where wind erosion is the main erosional process, for organic matter is usually blown great distances and dispersed to places where it may decay rapidly and release its C. Management options that increase the amount of live and dead biomass left in agricultural areas decrease erosion in general while simultaneously increasing the C input to the soil (Tiessen and Cuevas, 1994).

Field clearing and weeding

Clearing the fields from weeds before planting, as well as weeding during the cropping season, is an important practice for reducing competition between the crop and weeds. However, from the point of view of soil fertility and CS, it is important to recycle as much of the weeds back into the soil as possible. Selective clearing and weeding implies that only weeds competing directly with the crop are removed while others remain in the field.

Recycling nutrients

Manure

Spreading manure from livestock that is kept within or close to the compounds is one of the most widespread soil fertility management practices. Farmers are well aware of the fertilizing effects of manure but they also appreciate it for the fact that it stabilizes sandy topsoil and reduces wind erosion. Farmyard manure (FYM) and manure produced in pens is usually of higher quality than dung and droppings left on fields by grazing animals. It may be combined with agricultural residues, household waste and ashes accumulating within a household. The most limiting factor of the usage of manure, in addition to lack of animals, is the lack of transporting material, often resulting in well-manured fields closer to the homestead rather than on more remote fields.

Crop residue management

Crop residues such as stalks and hay can be left on or returned to the field in the form of mulch or ploughed under at the end of the cropping season. However, in most dryland farming systems, crop residues are contested and are removed after harvest either as fodder, construction material, fuel or litter for composting. What remains on the field is often burned before the next cropping season. In some cases, crop residues are also sold at the local market, generating additional income.

Management of other organic matter

Household waste, fish scales, ashes, leaf litter, prunings, and surplus crop residues are also used to increase soil fertility. Often, these additional inputs are accumulated within the homestead, sometimes added on to manure piles, and then transported to fields where they are spread according to nutrient needs. In various places, composting has resulted in improved decomposition rates. Although the use of such alternative organic matter, primarily household waste, has been increasing, overall quantities are rarely sufficient to fertilize entire fields in a sustainable manner.

Maximizing the efficiency of nutrient uptake

Reduced land tillage

Although some farmers appreciate tillage for weed control and soil aeration, there seems to be a growing recognition that tillage also destroys the protective vegetative cover and, as a result, exposes soil nutrients to the elements. In areas where ploughs and draught animals are available to smallholders, tillage is still widely practised. In other areas, such as the Senegalese Peanut Basin, farmers have replaced deep tillage by superficial tillage, primarily because of the lack of machinery (Tschakert and Tappan, 2004). For the purpose of CS, reduced or no-tillage are preferable, simply because they enhance the storage of C in the soil.

Precision agriculture

Many farmers often match crops and management practices with the fertility status of specific fields and, on a smaller scale, with specific spots within one field. Given the relative scarcity of organic and inorganic inputs, the available quantities are spread following a patch-by-patch scheme.

Fire management

Fire is a very common tool for land managers in drylands. Fire is often used to clear the fields of weeds before planting. Another important reason for preplanting fire is to kill a range of agricultural pests. The role of fire in the soil carbon balance was investigated by modelling and found to have a significant effect on SOC. When the fire-return period was increased from 3 to 15 years, the SOC level increased by 30 percent (Poussart and Ardö, 2002).

These descriptions of individual methods of soil fertility management do not capture the full complexity of the ways in which they are combined. Some of this complexity is described in more detail below.

Soil fertility management practices in the Sahel

In drylands, farmers know and use a whole range of soil fertility management practices. However, these practices may vary from farming system to farming system, from farmer to farmer, and from field to field, and even within fields, depending on differential access to and utilization of resources. To illustrate the complexity of soil fertility practices, Table 9 presents a detailed example from Senegal.

In addition to spatial variability, soil fertility management practices tend to vary over time. As farmers adapt to risks, shocks and uncertainty over the long run and new or altered systems or livelihood pathways emerge, farmers' portfolios of management practices also change. Figure 8 illustrates changes in management practices in a village that has followed a pathway of "indigenous and adaptive" intensification (Tschakert and Tappan, 2004). With increasing population pressure and land scarcity, a general shift from extensive management practices (fallowing and stubble grazing) to more intensive strategies (application of manure, household waste, compost, planting trees and fences) has occurred. This transition is overlaid with a change in governmental policies, reflected in the disengagement of the state after 1980, primarily following structural adjustment, implying reduced or no subsidies or credits for mineral fertilizer, groundnut seeds, and agricultural equipment.

TABLE 9
Example of soil fertility management practices used in the Old Peanut Basin, Senegal, 1999/2000

Practices known	Preferred crops	Preferred soils	Preferred fields	Usage in 1999/2000 [1]	General extent within villages
1. Adding nutrients to the soil[2]					
Fallowing	After millet and before groundnuts	Poorest soils, *dior*[3]	Outfields, never on infields, never in basins; in case of lack of seeds and/or manure	85%	less common
Stubble grazing with cattle	Before millet, watermelons	*Dior*	Poorest fields; closer fields, on remote fields only with surveillance	69%	less common
Applying mineral fertilizers (NPK)	Millet rather than groundnuts; vegetables	All soil types	Outfields, never infields; rare on women's fields	77%	common
Applying urea	On millet, vegetables	All soil types	Outfields, vegetable gardens, never infields	<10%	very rare
Applying phosphate rocks	All crops	All soil types, but better hard soils	Outfields	54%	rare
Rotating cereals with cowpeas	-	*Dior*, very poor fields	On fields for which no groundnut seeds are available	46%	common
Rotating millet with groundnuts	-	All soil types, soil with groundnuts	Outfields	100%	very widespread
Rotating with watermelons	-	All soil types	Infields	<10%	rare
2. Reducing losses from nutrients from the soil					
Protecting trees	-	*Dior*	Closer fields	85%	common
Planting trees	-	*Dior*	Outfields or basins	23%	rare
Living hedges/fences	Millet, cassava, mango trees, henna	*Dior*, *ban*[3]	Infields and basins	46%	rare
Selective clearing and/or weeding	Millet	All soil types	Infields and outfields	>70%	common
3. Recycling nutrients					
Applying cattle manure	Before millet, vegetables	*dior*, poorest fields	Infields and outfields	77%	common
Applying manure from small ruminants	All crops	*Dior*	Poor fields, close and remote fields	92%	wide spread
Applying horse and donkey manure	Before millet, vegetables	*dior*, poor fields	Infields, vegetable gardens; outfields if carts available	92%	wide spread

[1] Between December 2000 and December 2001, fourteen villages in the Départements de Thiès, Fatick, Bambey and Diourbel participated in a study on soil fertility management and carbon sequestration.

[2] Classification of soil fertility management practices after Hilhorst and Muchena (2000).

[3] "dior", "deck" and "ban" are Wolof names for the dominant soil types in the Old Peanut Basin. According to Badiane, Khouma and Senè (2000), "Dior" are common on former dune slopes and usually contain >95% sand and <0.2% organic C; "deck" are hydromorphic with 85–90% sand and carbon contents between 0.5 and 0.8%. "Ban" are similar to "deck", usually found along waterways and basins ("bas-fonds").

Practices known	Preferred crops	Preferred soils	Preferred fields	Usage in 1999/00[1]	General extent within villages
Applying chicken manure	Before millet, vegetables, cowpeas	*Dior*	All fields	77%	less common
Leaving millet stalks on the fields	-	*Dior*	Infields and outfields depending on availability of cart	77%	common
Incorporating household waste	Before millet, watermelon	*Dior*	Least fertile fields, project fields	100%	very widespread
Composting	Before millet, vegetables	*Dior*	Infields, outfields only if mixed with manure and taken out with cart	69%	less common
Using ashes	On millet, sorghum, cowpeas	Any soil type	Infields, closer fields, fields in fallow	85%	widespread
Using peanut shells	Before millet	Any soil type	Infields and outfields	69%	common
Using millet glumes	Before millet (decomposed), groundnuts	All soil types	All fields, fields in fallow	92%	widespread
Spacing peanut heaps	-	*Dior*	Infields and outfields (if carts available)	61%	rare
Using leaf litter	Before millet	All soil types	Infields	69%	rare
Using fish scales	On millet	*Dior*	All fields	31%	rare
Using decomposing baobab parts	Before millet, hot peppers			46%	rare
Using crop residues	All crops	*Dior*	All fields	77%	common
4. Maximizing the efficiency of nutrient uptake					
Deep tillage	-			<10%	very rare
Superficial tillage	Before millet, groundnuts	*Dior* and *deck*[3]	Outfields, fields in fallow	46%	widespread
Matching crops with soil quality and fertility	All crops	-	Infields and outfields, basins	100%	widespread
Applying patchwork schemes for nutrient applications	All crops	*Dior*	Outfields	100%	widespread

[1] Between December 2000 and December 2001, fourteen villages in the Départements de Thiès, Fatick, Bambey and Diourbel participated in a study on soil fertility management and carbon sequestration.

Source: Tschakert, fieldwork, 2000-01.

Building on local knowledge

In addition to the practices, it is important to understand farmers' theories of soil fertility, soil formation, and the processes that cause losses and gains of soil fertility over time.

For example, smallholders in the Senegalese Peanut Basin perceive soil fertility as "saletés" (dirt), a generic term for organic matter inputs (manure, decomposing plant material, household waste, etc). To farmers, this "dirt" contains nutritious elements, referred to as "vitamins" or "tasty ingredients" that determine the strength and health of a soil. Although the majority of farmers lack detailed knowledge with respect to the origin of such "vitamins", they are aware of the various processes resulting in soil degradation and fertility losses. The most frequently cited causes of fertility decline include: continuous cultivation without external inputs or crop rotation; reduction of protective vegetation cover; and exposure of SOM to the elements as a consequence of tree removal, deep tillage, and too short fallow periods; bush fires; and harmful insects. Accordingly, farmers' preferred options to restore soil fertility focus on crop rotation, increased organic matter inputs, and accumulation of vegetative cover, primarily through longer-term fallowing and increased tree density.

In parts of Niger, soil fertility is seen much more holistically by farmers than by agronomists, who disaggregate the influences on crop productivity into factors such as water supply, water uptake, individual nutrients, and soil structure (Osbahr and Allen, 2002). The farmers know that the productivity of different soils is determined by a combination of factors. In a wet year, clay-rich soils in depressions may be waterlogged and unproductive, while sandy soils, where managed adequately, yield at acceptable levels. Clay-rich soils on better-drained sites may be very productive, and very responsive to inputs of manure or fertilizer. In a dry year, the sandy soils are barren, the well-drained clay-rich soils are too hard to till, and only the clay-rich soils of the depressions yield anything at all. Hard-won experience of each subtly different village environment yields a huge variety of different "knowledge" and practices, and a soil CS project could only succeed if all this experience were tapped.

Using farmers' knowledge and practices as an entry point for CS activities offers several advantages: (i) it stimulates farmers' participation in research and project design from the outset; (ii) it facilitates the introduction of C, N and other minerals unknown to the majority of smallholders in a way that is readily understandable and easy to integrate in their own construct of soil theories; and (iii) it opens new doors for extension services to engage, together with farmers, in a more participatory and holistic approach to problem solving instead of delivering predefined agronomic packages.

REALIZING THE BIOPHYSICAL POTENTIAL FOR CARBON SEQUESTRATION IN FARMING SYSTEMS

In dryland environments, SOC in the first 100 cm soil amounts to about 4 tonnes/ha (Batjes, 1999). This is considerably lower than in other environments. Batjes' estimates for current SOC are: 7–10 tonnes/ha in the tropics; 7–13 tonnes/ha in the subtropics; 11–13 tonnes /ha in temperate regions; and 21–24 tonnes/ha in boreal, polar and alpine areas. Few reliable numbers exist for the entire Sahel, with the exception of estimates for semi-arid savannahs and dry forests in Senegal (the West-Central agricultural region) as reported by Tiessen and Feller, 1998, Ringius, 2002 and Tschakert, Khouma and Senè, 2004, ranging from 4.5 tonnes C/ha for continuously cultivated areas without manure input to 18 tonnes C/ha for non-degraded savannahs (top 20 cm soil).

There is a suite of recommended practices and land-use types that are recommended to increase both the uptake of C from the atmosphere and the duration of storage in soils. As for croplands, FAO (2001b) differentiates practices that decrease carbon losses from the soil from those that increase organic matter inputs into the soil, and considers a combination of both. The first category includes reduced/conservation/zero tillage, crop residue management, green manuring, cover crops, and integrated weed control. The second category is based on increases in biomass resulting from manure, compost, mulch farming, mineral fertilization and irrigation as well as improved crop-residue management and green manuring with leguminous species. All these practices simultaneously increase CS, improve soil fertility, and decrease erosion through soil restoration in drylands, thus offering real potential for a win–win situation for local smallholders.

However, reliable dryland estimates on how much C could be sequestered under the various management practices and farming patterns are still sparse. The most comprehensive estimates (Table 10) range from 0.05 to 0.3 tonnes C/ha/year for croplands and from 0.05 to 0.1 tonnes C/ha/year for grasslands and pastures (Lal *et al*., 1998). The estimates by Lal *et al.* for tropical areas are about twice as high as those for drylands. For the Old Peanut Basin in Senegal, Tschakert, Khouma and Senè (2004) report a possible range of 0.02–0.43 tonnes C/ha/year for improved crop-fallow systems.

TABLE 10
Effects from land management practices or land use on carbon sequestration potential in drylands

Technological options	Sequestration potential (tonnes C/ha/year)
Croplands	
Conservation tillage	0.10 – 0.20
Mulch farming (4–6 Mg/ha/year)	0.05 – 0.10
Compost (20 Mg/ha/year)	0.10 – 0.20
Elimination of bare fallow	0.05 – 0.10
Integrated nutrient management	0.10 – 0.20
Restoration of eroded soils	0.10 – 0.20
Restoration of salt-effected soils	0.05 – 0.10
Agricultural intensification	0.10 – 0.20
Water conservation and management	0.10 – 0.30
Afforestation	0.05 – 0.10
Grassland and pastures	0.05 – 0.10

Source: After Lal *et al.* (1998)

Dryland farming systems with access to adequate water resources may benefit from developing their irrigation potential. In small-scale irrigation systems, a high potential for CS arises from four characteristics:

- The supply of water allows high primary productivity, more so in some (qanat irrigation) than in others (runoff agriculture).
- In most of these systems, the soils are fine-textured, permitting high quantities and slow decay of soil C, much of which is bound closely to clay particles.
- The extensive use of manure, both from animal and crop residues.
- The generally carbon-neutral energy sources, such as animal and human power. In qanats, the large investment of human power in the early years may be drawn on for centuries, or even millennia.

Larger-scale irrigation schemes should not be dismissed outright as systems for soil CS. Some date back to times when they were no inputs of fossil energy. Therefore, their construction might be regarded as carbon-neutral. Even more recent systems, as in the vast systems in Pakistan and India, were constructed largely with animal or human power. With their high productivity, use of many fine-textured soils and sometimes large extent, these may be potentially valuable sinks of soil C. However, the total carbon budget of each, from the time of construction through to recent interventions, such as deep drains or tubewells, would have to be evaluated separately before it could be considered as suitable as a soil carbon sink. Some would almost certainly not qualify. These would be those in which large amounts of fossil energy had been used in construction, or in which large quantities of fertilizer were being used.

Chapter 4
Biophysical aspects of carbon sequestration in drylands

INTRODUCTION

As discussed in Chapter 1, the process of CS, or flux of C into soils forms part of the global carbon cycle. Movement of C between the soil and the atmosphere is bi-directional. Consequently, carbon storage in soils reflects the balance between the opposing processes of accumulation and loss. This reservoir of soil C is truly dynamic. Not only is C continually entering and leaving the soil, the soil C itself is partitioned between several pools, the residence times of which span several orders of magnitude. Nor is soil C an inert reservoir, the organic matter with which it is associated is vital for maintaining soil fertility and it plays a part in such varied phenomena as nutrient cycling and gaseous emissions. A detailed description and analysis of soil C and organic matter can be found elsewhere (Schnitzer, 1991; FAO, 2001c). Taking into account specific biophysical characteristics of dry areas, this chapter describes different biophysical aspects of CS in dryland soils.

HALOPHYTES

A special feature of many dryland soils is salinity, either through natural occurrence or increasingly as a result of irrigation. Saline soils affect large parts of the drylands (Glenn *et al.*, 1993). Such lands are often abandoned, but halophytic plants are especially adapted to these conditions and offer potential for sequestering C in this inhospitable environment. It has been estimated that 130 million ha are suitable for growing halophytes, which can be used for forage, feed and oilseed. Glenn *et al.* estimate that 0.6–1.2 gigatonnes of C per year could be assimilated annually by halophytes. Evidence from decomposition experiments suggests that 30–50 percent of this C might enter long-term storage in soil. Although irrigation would be required to achieve these figures, a complete carbon budget still suggests a carbon actual rate of 22–30 percent.

GRASSLANDS

Grasslands are the natural biome in many drylands, partly because rainfall is insufficient to support trees, and partly because of prevailing livestock management. However, grassland productivity and CS have been controversial. The productivity of tropical grasslands is now known to be much higher than was previously thought, and consequently they sequester much more C (Scurlock and Hall, 1998). Estimates for C stored under grassland are about 70 tonnes/ha, which is comparable with values for forest soils. Although many of the grassland areas in drylands are poorly managed and degraded, they offer potential for CS as a consequence.

The average annual input of organic matter into grassland is about double the 1–2 tonnes/ha that is contributed to cropped soils (Jenkinson and Rayner, 1977). This fact is borne out by the results of studies from various locations. The data have shown that grassland, even where subject to controlled grazing, generally has higher soil C levels than cropland. Chan and Bowman (1995) found that 50 years of cropping soils in semi-arid New South Wales, Australia, had on average reduced soil C by 32 percent relative to pasture. The reduction was linearly related to the number of years of cropping.

Similarly, soils of tall-grass pasture under controlled grazing had greater soil C than adjacent cropland subject to conservation tillage (Franzluebbers *et al*., 2000).

The key factor responsible for enhanced carbon storage in grassland sites is the high carbon input derived from plant roots. It is this high root production that provides the potential to increase SOM in pastures and vegetated fallows compared with cropped systems. Root debris tends to be less decomposable than shoot material because of its higher lignin content (Woomer *et al*., 1994). Consequently, the key to maintaining and increasing CS in grassland systems is to maximize grass productivity and root inputs (Trumbmore *et al*., 1995). Grasses have also been shown to sequester more C than leguminous cover crops (Lal, Hassan and Dumanski, 1999). Grasses also have the potential to sequester C on previously degraded land. Garten and Wullschleger (2000) used a modelling approach that estimated a 12-percent increase in soil C could be obtained under switchgrass (*Panicum virgatum* L.) on degraded land in ten years.

Grazing is a feature of many grasslands, natural or managed. This might be expected to decrease the availability of residues that can be used to sequester C, especially as the quantity of C returned in manure is less than that consumed. However, provided there is careful grazing management, many investigations have found a positive effect of grazing on the stock of soil C. This was found to be the case for a composite pasture (alfalfa and perennial grasses) in the semi-arid pampas (Diaz-Zorita, Duarte and Grove, 2002). Even under harsher conditions in the Syrian Arab Republic, grazing was found to have no detrimental impact on soil C (Jenkinson *et al*., 1999). Schuman, Janzen and Herrick, (2002) have calculated that with proper grazing management, rangelands in the United States of America can increase soil carbon storage by 0.1–0.3 tonnes/ha/year. For new grasslands, this can rise to 0.6 tonnes/ha/year.

The positive effect of grazing appears to result from the effect that it has on species composition and litter accumulation. Willms *et al.* (2002) found that when prairie was protected from grazing there was little effect on production but there was an increase in the quantity litter. Reeder and Schuman (2002) also found that there was an accumulation of litter in an ungrazed semi-arid system and that soil carbon levels were higher in the grazed lands. The litter acted as a store of immobilized C. The ungrazed grassland also experienced an increase in species that lacked the fibrous rooting system that is conducive to SOM formation and accumulation.

Therefore, grasslands can play a vital role in sequestering C. However, careful grazing management is essential. The historical record shows how susceptible semi-arid grasslands are to overgrazing, soil degradation and carbon loss.

BURNING

Fires form part of the natural cycle in many biomes and are especially prevalent in grassland ecosystems. However, humans have also used fire to clear areas for agriculture and to clear crop residues. The action of fire would seem to be counter to CS as it returns C fixed by vegetation directly to the atmosphere, thereby preventing its incorporation into the soil. The effect of fire is difficult to generalize because it depends upon the intensity and speed of the fire. These factors are influenced by: the state of the vegetation, i.e. its maturity and woody component; the accumulation of litter; and climate factors such as moisture level. They C in all the aboveground material that is fully combusted will be lost from the system. However, in grassland ecosystems, C lost to fires can be replaced quickly by increased photosynthesis and vegetative growth (Knapp, 1985; Svejcar and Browning, 1988). Even in savannah systems that contain woody species, it has been shown that C lost through combustion can be replaced during the following growing season (Ansley *et al*., 2002). Regarding the soil, the intensity and speed of the fire will govern the depth to which it is affected. In one study where burning was used to clear forests, 4 tonnes C/ha was lost in the top 3 cm of soil, but this was replaced within one year under a pasture system (Chone *et al*., 1991).

Not all plant material is fully combusted by fire, and a variable amount of charcoal will be produced. Charcoal is extremely resistant to decomposition; it is not cycled like most organic matter, and has a mean residence time of 10 000 years (Swift, 2001). Consequently, in severely degraded soils that have been affected by several fires, charcoal and charred material can form a substantial proportion of the remaining organic C. However, it is not known whether charcoal and other charred material have any protective effect on the native organic matter. Thus, although fires release CO_2 back into the atmosphere, the simultaneous production of charcoal can be regarded as a sequestration process that results in a substantial amount of C being accumulated within the soil for a long period.

AFFORESTATION

Forestry is recognized as major sink for C. However, as well as accumulating C aboveground, it can also make significant contributions to soil C even in drylands. A number of suitable species are available that enable viable afforestation in dryland environments (Srivastava *et al.*, 1993; Silver, Ostertag and Lugo, 2000; Kumar *et al.*, 2001; Niles, *et al.*, 2002). In particular, N-fixing trees generally lead to increased accumulation of soil C. For example, *Prosopis* and *Acacia* are adapted to subtropical semi-arid lands and are reported to increase the level of soil C by 2 tonnes/ha (Geesing, Felker and Bingham, 2000).

Some tree varieties are particularly suitable for growing on degraded lands, their deep rooting systems tapping resources unavailable to shallow-rooted crops. *Prosopis juliflora* has been grown on salt-affected soils in northwest India and increased the SOC pool from 10 tonnes/ha to 45 tonnes/ha in an eight-year period (Garg, 1998). Even where large-scale forestry is not appropriate, there is often scope for introducing trees around farmers' fields. Such is the case in semi-arid India where *Prosopis cineraria* has improved soil fertility as well as sequestering extra C (Nagarajan and Sundaramoorthy, 2000). However, natural systems are complex and trees do not guarantee improved CS. Jackson *et al.* (2002) found that soil C decreased when woody vegetation invaded grasslands. Although there was an increase in aboveground and belowground biomass, these gains were offset by losses in soil C.

RESIDUES

Plant residues provide a renewable resource for incorporation into the SOM. Production of plant residues in an ecosystem at steady-state will be balanced by the return of dead plant material to the soil. In a native prairie, about 40 percent of plant production is accumulated in the SOM (Batjes and Sombroek, 1997). However, in agricultural systems, because plants are harvested, only about 20 percent of production will on average be accumulated into the soil organic fraction. Furthermore, in some farming systems, all aboveground production may be harvested, leaving only the root biomass. Of the plant residue returned to the soil, about 15 percent will be converted to passive SOC (Lal, 1997). Schlesinger (1990) is more pessimistic, suggesting that only 1 percent of plant production will contribute to CS in soil. The actual quantities of residue returned to the soil will depend on the crop, the growing conditions and the agricultural practices. For example, for a soybean–wheat system in subtropical central India, the annual contribution of C from aboveground biomass was about 22 percent for soybean and 32 percent for wheat (Kundu *et al.*, 2001). This resulted in 18 percent of the annual gross carbon input being incorporated into the SOM. In semi-arid Canada, the conversion of residue C to SOC was reported to be 9 percent in frequently fallowed systems, increasing to 29 percent for continuously cropped systems (Campbell *et al.*, 2000).

Unless a root crop is being harvested, all belowground production is available for incorporation into the SOM. Roots are believed to be the major constituent of particulate organic matter although tillage reduces the net accumulation of C from roots substantially (Hussain, Olsson and Ebelhar, 1999). In cool climates, belowground carbon inputs from roots alone can generally maintain soil carbon levels. However, this is not the case in warmer or semi-arid regions where residues are decomposed much more readily, providing sufficient moisture is available (Rasmussen, Albrecht and Smiley, 1998). Consequently, when continuous cropping is practised in drylands, failure to return aboveground plant residue will lead invariably to a reduction in soil C. Many African soils demonstrate this phenomenon. Continuous cropping over a number of years without the recommended inputs has often halved their carbon content (Woomer *et al*., 1997; Ringius, 2002).

Both the quality and quantity of plant residues are important factors for determining the amount of C stored in soil. The quantity is highly dependent on the environmental conditions and agricultural practices. Differences between crops can be marked. A crop of maize will return nearly twice as much residue to the soil compared with soybean and, consequently, will result in a higher rate of SOM increase (Reicosky, 1997). The advantage that cereals have over legumes for achieving maximum CS rates has also been demonstrated by Curtin *et al.* (2000). They have shown that while black lentil fallow in semi-arid Canada added between 1.4 and 1.8 tonnes C/ha, a wheat crop would add 2–3 times this amount of C annually. Similarly, in Argentina, soybean, which produced 1.2 tonnes/ha of residue, resulted in a net loss of soil C, while maize, with 3.0 tonnes/ha of residue, lessened the loss of soil C from the system significantly (Studdert and Echeverria, 2000).

Even within one crop group, large differences in organic matter production occur. Abdurahman *et al*. (1998) compared dry leaf production from pigeon pea and cowpea. While the former yielded 3 tonnes/ha, cowpea produced 0.14 tonnes/ha. These examples illustrate how the choice of crop can have a major influence on how much C an agricultural system can sequester.

The importance of roots relative to shoots for providing soil C is another factor illustrated in an experiment to compare the fate of shoot- and root-derived C (Puget and Drinkwater, 2001). In this study with leguminous green manure (hairy vetch), nearly half of the root-derived C was still present in the soil after one growing season whereas only 13 percent of shoot-derived C remained. This implies that shoot residues are broken down rapidly on account of their higher N content (Woomer *et al*., 1994) and may serve as a nitrogen source for the following crop.

The chemical composition of plant residues affects their rate of decomposition. On average, crop residues contain about 40–50 percent of C but N is a much more variable component. A high concentration of lignin and other structural carbohydrates together with a high C:N ratio will decrease the rate of decomposition. For example, measurement of CO_2 evolution from tree leaves of African browse species and goat manure showed a significant correlation with initial nitrogen content and a negative correlation with lignin content (Mafongoya, Barak and Reed, 2000). Legume residues such as soybean are generally of high quality (low C:N ratio) and so decompose rapidly (Woomer *et al*., 1994). Although the chemical composition of the plant residue affects its rate of decomposition, there is little effect on the resulting SOM (Gregorich *et al*., 1998).

Where residues accumulate on the soil surface, their physical presence affects the soil. Mulches reduce water loss and soil temperature (Duiker and Lal, 2000), both important factors for drylands, especially where the soil temperature is above the optimum for plant growth. The ability of soil to assimilate organic matter is not clear-cut. A linear relationship between application and accumulation of SOM is often quoted. However, measurement of CO_2 flux in central Ohio, the United States of America, showed this flux to increase with added application of wheat straw (0, 8 and 16 tonnes/ha). However, the SOC was 19.6, 25.6 and 26.5 tonnes/ha after four years, suggesting that CS was reaching saturation (Jacinthe, Lal and Kimble, 2002).

Care must be taken when applying residues, as large losses of C can still occur under certain conditions. For example, in western Kenya, 70–90 percent of the added C was lost within 40 d when green manure from agroforestry trees was applied during the rainy season (Nyberg *et al.*, 2002). In Niger, the addition of millet residue and fertilizer for five years had no significant effect on the carbon level in the sandy soils (Geiger, Manu and Bationo, 1992). Termite activity may have contributed to the low levels of soil C here because entire surface mulches can be consumed within one year.

The potential amount of residues available for applying to soils can be large. Gaur (1992) estimated that in India about 235 million tonnes of straw/stover are produced annually from five major cereals (not only from drylands). Even if half of this were used for feeding livestock, there would be more than 1 million tonnes available for adding to the soil. However, availability of sufficient plant residues is often a problem, especially where they are required for livestock feed. This conflict of requirement occurs frequently in many dryland farming systems. In West Africa, crop residues are either removed or burnt. Consequently, the amount of soil C has declined steadily. Continuous cultivation and manure application can raise soil carbon levels by 40 percent but this frequently involves mining C from neighbouring areas to support the livestock (Ringius, 2002). Where plant and animal residues are in short supply, possibilities may exist for alternative organic inputs to the soil. For example, in India, waste products from a plant processing coir dust have been incorporated successfully into soil (Selvaraju *et al.*, 1999), and other experiments with industrial glue waste (Dahiya, Malik and Jhorar, 2001) have increased soil carbon levels successfully.

With regard to the complete carbon budget, where plant residues accumulate *in situ*, there is no extra carbon cost involved. Consequently, the C fixed by plants in photosynthesis is available as a net gain to the soil. The situation becomes more complex where machinery is required to separate the residue from the harvestable components. Where plant residues are transported between fields the energy cost would need to be included.

Perhaps the major issue regarding residue application and carbon accounting is the question of whether C is simply being transferred from one place to another rather than being truly sequestered. If organic material from industrial processes or other sources were to be used for incorporation into the soil, then any C used in transport would have to be accounted for. However, where the material is truly a waste product, there should be no need to consider the C used in its production. In this case, the C available for sequestration should be viewed no differently from the CO_2 emitted from a fossil fuel source that is subsequently fixed by plants in photosynthesis and returned to the soil via crop residues.

APPLIED MANURES

The application of FYM has long been treated as a valuable source of organic matter to enhance soil fertility. One of the key characteristics of manure application is that it promotes the formation and stabilization of soil macroaggregates (Whalen and Chang, 2002) and particulate organic matter (Kapkiyai *et al.*, 1999). Manure is more resistant to microbial decomposition than plant residues are. Consequently, for the same carbon input, carbon storage is higher with manure application than with plant residues (Jenkinson, 1990; Feng and Li, 2001). Following five years of application, soil receiving manure had 1.18 tonnes/ha more C present than soil receiving plant residues. Even after 15 years, there was a still a difference of 0.37 tonnes C/ha as calculated by the RothC soil carbon model. In the field, Gregorich *et al.* (1998) found that manured soils had large quantities of soluble C with a slower turnover rate than in control or fertilized plots.

The composition and, therefore, decomposition of manure varies between the species from which it originates and also within species according to their diet (Somda and Powell, 1998). Many field trials have found that manure is the best means for incorporating organic matter into soils and promoting carbon storage. For example, Li *et al.* (1994) found that manure yielded the largest amount of C sequestered over a range of soils and climate conditions, although soil texture was important, and the greatest rate of sequestration occurred where there was a high clay content. However, many traditional agrosystems add manure in combination with fertilizers (Haynes and Naidu, 1998).

Depending on the system, the application of even relatively high amounts of FYM does not guarantee an increase in soil C. A long-term study in Kenya has shown that SOM declined even when manure was applied and maize residue returned (Kapkiyai *et al*., 1999). It has been estimated that in order to maintain soil C in this system, 35 tonnes/ha of manure or 17 tonnes/ha manure with 16 tonnes/ha of stover would be required annually (Woomer *et al*., 1997). Consequently, there is a carbon shortfall in this case, but it is difficult to see how the present system could remedy it. In addition, high application rates of manure can sometimes cause problems in the soil through the accumulation of K^+, Na^+ and NH_4^+ and the production of water-repellent substances by decomposer fungi (Haynes and Naidu, 1998). An additional problem in drylands that restricts the quantity of manure that can be applied is "burning" of the crop when insufficient moisture is available at the time of application. Consequently, farmers often wait until the rains have come before making an application, especially as precipitation is often erratic in arid regions.

The production of sufficient manure for application to fields is a real problem for many smallholder farming systems. In Nigeria, direct manure input onto land from dry-season grazing is about 111 kg/ha of dry matter (Powell, 1986). This quantity will have little effect on the soil. More useful is the practice of night-parking cattle as manure production is usually greatest at dawn and dusk. When 50 cattle were penned in an area of 0.04 ha for five nights, they produced the equivalent of 6.875 tonnes/ha of manure (Harris, 2000). Normally, cattle will be penned in fields for 2–3 nights in northern Nigeria and this can supply manure at a rate of 5.5 tonnes/ha. Alternatively, in densely populated parts such as the Kano closed-settlement zone, cattle and crop production are fully integrated. Cattle are kept permanently in pens and fed using feed grown on neighbouring fields. Their manure is collected and spread onto the croplands. Although an efficient system, some C will be lost as a consequence of the respiratory and growth requirements of the cattle. An additional problem associated with cattle rearing is that ruminants produce significant quantities of CH_4, which is a potent GHG.

There has been some debate as to the usefulness of animal manure in CS. Schlesinger (1999, 2000) has calculated that providing 13.4 tonnes/ha would require 3 ha of cropland in order to produce sufficient cattle feed. This means that manure production requires mining of C from neighbouring lands. Although this is a generalization, it is argued that the 3:1 differential makes it unlikely that manure production per se could be used as a means of providing a net carbon sink in soils. However, in many dryland smallholder cropping systems, manure application rates are much lower, and fodder production is also less efficient. Smith and Powlson (2000) have made the case that keeping cattle is part of many agricultural systems and, hence, that manure should be considered as a byproduct that can be added to arable land without necessarily including the carbon cost of its production. Part of the disagreement with Schlesinger on the usefulness of manure depends on where the system boundary for carbon accounting is drawn. However, when conducting such a carbon audit, it is essential to remember that the purpose of agriculture is to feed people; offsetting GHGs can only be evaluated as a secondary activity.

INORGANIC FERTILIZERS AND IRRIGATION

Fertilization and irrigation are primary means for increasing plant production and crop yield. Any increase in biomass also offers increased scope for CS. Consequently, irrigation and fertilization have been recommended as, and proved to be, successful methods of increasing CS (Lal, Hassan and Dumanski, 1999). Rasmussen and Rohde (1988) have shown a direct linear relationship between long-term nitrogen addition and accumulation of organic C in some semi-arid soils in Oregon, the United States of America. However, these technologies provide no additional organic matter themselves but do carry a carbon cost. Schlesinger (1999, 2000) has pointed out that pumping water requires energy and that the process of fertilizer manufacture, storage and transport is energy intensive. Consequently, Schlesinger (2000) has estimated that the gains in C stored using either fertilization or irrigation are offset by losses elsewhere in the system. Irrigation can also lead to the release of inorganic C from the soil.

Izaurralde, McGill and Rosenberg (2000) have argued that the calculations used by Schlesinger are based on very high rates of fertilizer application. For many dryland agriculture systems in the developing world, farmers do not have sufficient funds to apply large quantities of fertilizer even if they were available. With regard to the energy costs incurred in pumping water, solar-powered systems are being developed (Sinha *et al*., 2002) and dryland environments with frequently clear skies would be able to make the best use of solar radiation.

These examples serve to illustrate how important it is to consider the whole system when CS is being considered to offset CO_2 emissions. The exact carbon cost of irrigation and fertilization would require calculation for each system, but the carbon deficits associated with both technologies make their incorporation into net CS systems difficult to achieve. Water conservation, the growing of legumes and careful nutrient cycling are more likely to yield a positive carbon balance.

TILLAGE

Pretty *et al.* (2002) consider tillage to be one of the major factors responsible for decreasing carbon stocks in agricultural soils. Research and experimentation with reduced tillage practices are most prevalent in the Americas. The mould-board plough and disc harrow are believed to be the causes of the loss of soil C through the destruction of soil aggregates and the acceleration of decomposition by the mixing of plant residues, oxygen and microbial biomass. Soil aggregates are vital for CS (Six, Elliott and Paustian, 2000), a process that is maximal at intermediate aggregate turnover (Plante and McGill, 2002). Of the organic matter fraction, the particulate organic matter is the most tillage sensitive (Hussain, Olsson and Ebelhar, 1999).

It is difficult to quantify the effects of tillage on soil C because the effect are very site dependent, e.g. coarse-textured soils are likely to be more affected by cultivation than are fine ones (Buschiazzo *et al*., 2001). However, reducing tillage should be most effective in hot, dry environments (Batjes and Sombroek, 1997).

Reicosky (1997) conducted an experiment that used measurements of CO_2 efflux to investigate tillage-induced carbon loss from soil. The flux of CO_2 was monitored for 19 d following different forms of tillage practice. The mould-board plough buried most of the crop residue and produced the maximum CO_2 flux. The C released by the different treatments as a percentage of C in the crop residue was: 134 percent with mould-board plough; 70 percent with mould-board plough and disc harrow; 58 percent with disc harrow; 54 percent with chisel plough; and 27 percent with no-tillage. This demonstrates the correlation between CO_2 loss and tillage intensity, and demonstrates why farming systems that use mould-board ploughing inevitably lose soil C. Very large amounts of organic matter would be required to replace the loss incurred by such heavy tillage. Reicosky *et al.* (1995) estimate that 15–25 tonnes/ha manure plus crop residue would be needed annually in North America to offset these losses.

The flux of CO_2 from soil generated directly by the tillage process may not always reflect the overall release of CO_2 and hence carbon storage of the system. This is illustrated by a comparison of conventional disc tillage and no-tillage in central Texas, the United States of America, by Franzluebbers, Hons and Zuberer (1995). Here, seasonal evolution of CO_2 was up to 12 percent greater in the no-tillage system after 10 years. This was despite the fact that more C was sequestered by the no-tillage system. The authors suggest that a change in the dynamics of CS and mineralization have occurred under the no-tillage system. Similarly, Costantini, Cosentino and Segat (1996) found that more CO_2 was released from no-tillage or reduced-tillage compared with conventional tillage despite there being increased levels of soil C. They ascribe this difference to an increase in the microbial biomass.

Rates of carbon loss through tillage depend considerably on the site and cropping system. Ellert and Janzen (1999) measured the flux of CO_2 following the passage of a heavy cultivator on a semi-arid Chernozem soil in the Canadian prairies. They found that although tillage increased rates of CO_2 loss by two to four times, values returned to normal after 24 hours. They calculated that even with ten passes of the cultivator, only 5 percent of crop residue production would be released from this cropping system. In another situation, ploughing of a wheat–fallow cropping system near Sydney, Australia, reduced soil C by 32 percent after 12 years. Elimination of ploughing and adopting a no-tillage approach was unable to prevent a decrease in the carbon stock, although the loss was reduced to just 12 percent (Doran, Elliott and Paustian, 1998). The authors suggest that a fallow period would be required to halt the decline in soil C at this site.

There are many different types of tillage system. Conservation tillage covers a range of practices – no-tillage, ridge-tillage, mulch-tillage (Unger, 1990). Mulch-tillage maintains higher levels of residue cover. With mulches, only a small fraction of the residue is in contact with the soil surface and the microbes it contains. Decomposition is slow, especially as oxygen availability is limited. The physical presence of crop residues on the soil surface also alters the microclimate of the upper soil layer, which tends to be cooler and wetter compared with conventional tillage (Doran, Elliott and Paustian, 1998).

The accumulation of residues also reduces the loss of CO_2 from the soil surface. Alvarez *et al*., (1995) reported an increase in labile forms of organic matter under no-tillage in the Argentine rolling pampa, indicating a decrease in the mineralization of the organic fraction. This study also noted that although organic C increased by 42–50 percent under no-tillage compared with ploughing and chisel tillage, there was also a marked stratification in the distribution of C under the no-tillage regime that was not evident in the ploughed system.

Stratification of organic C is common with reduced or no-tillage. Zibilske, Bradford and Smart (2002) in semi-arid Texas, the United States of America, demonstrated that the organic carbon concentration was 50 percent greater in the top 4 cm of soil of a no-tillage experiment compared with ploughing, but the difference dropped to just 15 percent in the 4–8-cm depth zone. This is typical of organic carbon gains observed with conservation tillage in hot climates. Bayer *et al.* (2000), working on a sandy clay loam Acrisol, also found that the increase in total organic C was restricted to the soil surface layers under no-tillage but that the actual quantity depended on the cropping system. An oat/vetch – maize/cowpea no-tillage system produced the largest quantity of crop residues and sequestered the most C: 1.33 tonnes C/ha/year in 9 years.

Reicosky (1997) has compared the results from many no-tillage trials. The data emphasize the effect that crop rotation and quantity of crop residue has on organic matter accumulation. Overall, rates of organic matter accumulation can be expected to be lower in the hotter climates. Nevertheless, even in the very sandy soils of in north of the Syrian Arab Republic, it has been possible to make modest increases in SOM with no-tillage (Ryan, 1997). In western Nigeria, no-tillage combined with mulch application had a dramatic effect, increasing soil C from 15 to 32.3 tonnes/ha in 4 years (Ringius, 2002).

Although no-tillage systems are an excellent tool for combating the carbon losses associated with conventional cultivation, they do have their own special problems. In temperate lands, the reduction in soil temperature commonly associated with plant residue accumulation on the soil surface can retard germination. However, in drylands, where soil temperatures are frequently above the optimum for germination and plant establishment, such cooling is likely to be beneficial (Phillips *et al*., 1980). No-tillage systems frequently suffer from an increased incidence of pests and diseases; the mouldboard plough and disc harrow are efficient weed controllers (Reicosky *et al*., 1995). Consequently, no-tillage systems generally rely upon extra herbicides and pesticides. These inputs have an economic price and they also incur a carbon cost. However, in many dryland farming systems of the developing world, purchasing such products is not feasible, and quite often there is plentiful labour available for weeding. Application of N fertilizer can also be problematic when used on undisturbed, no-tillage soils. Where the soil is poorly drained, denitrification can occur and the reduced rate of evaporation increases the risk of nitrate leaching. In addition the native soil N has a lower rate of mineralization in undisturbed soil.

Not all soils are suited to a reduced-tillage approach. Some soils in the Argentine pampa may actually lose more C under no-tillage (0.7–1.5 tonnes C/ha/year) compared with conventional ploughing (Alvarez *et al*., 1995) and periodic ploughing is required to avoid soil compaction (Taboada *et al.*, 1998). Where no-tillage is used on the pampas, the physical status of the soil is a critical factor for the success of the system (Diaz-Zorita, Duarte and Grove, 2002). Similarly, in the West African Sahel, the highest crop yields are obtained with deep ploughing, which is required to prevent crusting and alleviate compaction. In general, the success of reduced-tillage systems is often dependent on soil texture (Needelman *et al*., 1999).

A particular advantage of the no-tillage system is that it favours multicropping; harvesting can be followed immediately by planting (Phillips *et al*., 1980). Any cropping system that allows for continuous or near continuous plant growth should yield the maximum capacity to produce plant biomass and, consequently, has the potential to provide the greatest amount of organic mater for inclusion into the soil.

Considering the overall carbon budget, no-tillage systems have a lower energy requirement because tillage is very energy intensive. Phillips *et al.* (1980) have calculated that no-tillage systems in North America reduce the energy input into maize and soybean production by 7 and 18 percent, respectively. Improved water-use efficiency means that the energy, and hence carbon, cost of irrigation are reduced. However, the impact of energy savings is frequently offset by additional herbicide requirements (Phillips *et al*., 1980). Kern and Johnson (1993) estimated that the manufacture and application of herbicides to no-tillage systems of the Great Plains is equivalent to 0.02 tonnes C/ha.

Reduced-tillage systems were adopted originally to help combat soil degradation. They were not intended as a means of sequestering C, which is a fortunate side-effect. Although the effectiveness of no-tillage at sequestering C will depend on the specific agricultural system to which it is introduced, there is no doubt that, as the intensity of tillage decreases, the balance between carbon loss and gain swings toward the latter.

ROTATIONS

The importance of rotation in agricultural systems has long been known and the procedure now forms an intricate part of many conservation tillage practices. The inclusion of rotations has many benefits such as countering the buildup of crop-specific pests and, thereby, lessening the need for “carbon costly” pesticides and herbicides. Different crop species have a variety of rooting depths and this aids in distributing organic matter throughout the soil profile. In particular, deep-rooting plants are especially useful for increasing carbon storage at depth, where it should be most secure. The inclusion of N-fixing varieties in a rotation increases soil N without the need for energy-intensive production of N fertilizers.

The beneficial effects that rotations have for CS have been proved in many long-term field experiments. For example, Gregorich, Drury and Baldock (2001) made a comparison of continuous maize cultivation with a legume-based rotation. The rotation had a greater effect on soil C than did fertilizer. The difference between monocultured maize and the rotation was 20 tonnes C/ha while the effect of fertilization was 6 tonnes C/ha after 35 years. In addition, the SOM present below the ploughed layer in the legume-based rotation appeared to be more biologically resistant. This demonstrates that soils under legume-based rotations tend to preserve residue C. A positive effect on SOC (an increase of 2-4 tonnes/ha) was also found with legumes and alternate cattle grazing in semi-arid Argentina (Miglierina *et al*., 2000).

Rotations, especially legume-based ones, are generally regarded as extremely valuable for maintaining soil fertility and have a very good potential for sequestering C in dryland systems. Drinkwater, Wagoner and Sarrantonio (1998) estimate that their use in the maize/soybean-growing region of the United States of America would increase soil CS by 0.01–0.03 Pg C/year The effectiveness of rotations for sequestering C is likely to be greatest where they are combined with conservation tillage practices.

FALLOWS

The role that fallows play in CS is varied. Where cropping is not taking place, it is important that vegetation cover is preserved. This is especially so in drylands where exposed soil is most likely to suffer from erosion and degradation. In addition to protecting the soil, cover crops can utilize solar energy that would otherwise be wasted. The CO_2 fixed is then available for sequestering into the soil as the plants senesce. The importance of vegetation cover can be illustrated with the results from an experiment conducted at a semi-arid site in Mediterranean Spain (Albaladejo *et al*., 1998). Four and a half years after the vegetation cover was removed from one site, the SOC had decreased by 35 percent compared with the control plots.

The type of fallow is important. In Nigeria, forest clearance caused a decline in soil C from 25 to 13.5 tonnes/ha in seven years, but 12–13 years of bush fallow restored the carbon content (Juo *et al*., 1995). Conversely, pigeon pea fallow was unable to sequester sufficient C on account of its low biomass production and rapid degradation.

However, fallows can have a negative effect on carbon storage in many situations. The frequency of summer fallows in semi-arid regions has been suggested as one of the major factors influencing the level of soil C in agricultural systems (Rasmussen, Albrecht and Smiley, 1998). Reducing the summer fallow in the semi-arid northwest United States of America is reported to have had a more positive effect on soil carbon retention than that achieved by decreasing tillage intensity. The loss of C in this region is believed to reflect the high rates of biological oxidation that occur here, which can only be offset by very large applications of manure (Rasmussen, Albrecht and Smiley, 1998). Consequently, yearly cropping and the associated organic additions is the recommended practice. Miglierina *et al.* (2000) also found that reducing summer fallow increased soil C, a consequence of the additional crop residue that was added. Using the CENTURY agro-ecosystem model, Smith *et al* (2001) predicted that reducing summer fallow in wheat cropping systems (wheat–fallow to wheat–wheat–fallow) in the semi-arid Chernozems of western Canada would reduce carbon losses by 0.03 tonnes/ha

Elimination of fallows can be highly beneficial for soil C simply because most fallows are associated with small inputs of plant residue. The significance of fallows for CS in a given system will depend on whether or not the cropping cycle adds significant quantities of organic matter to the soil. Where it does, then the presence of fallows is unlikely to enhance carbon storage within the system. Conversely, where the cultivation practice is poor and little or no organic matter is added, fallow periods will serve to counter this situation.

SOIL INORGANIC CARBON

Not all soil C is associated with organic material; there is also an inorganic carbon component in soils. This is of particular relevance to drylands because calcification and the formation of secondary carbonates is an important process in the soils of arid and semi-arid regions where, as a result, the largest accumulations of carbonate occur (Batjes and Sombroek, 1997). The dynamics of the inorganic carbon pool are poorly understood although it is normally quite stable. Sequestration of inorganic C occurs via the movement of HCO^-_3 into groundwater and closed systems. According to Schlesinger (1997) accumulation of calcium carbonate is quite low at 0.0012–0.006 tonnes/ha. However, Lal, Hassan and Dumanski (1999) believe that the sequestration of secondary carbonates can contribute 0.0069–0.2659 Pg C/year in arid and semi-arid lands.

Although soil inorganic C is relatively stable, it will release CO_2 if the carbonates become exposed through erosion (Lal, Hassan and Dumanski, 1999). In addition, irrigation can cause inorganic C to become unstable if acidification takes place through inputs of N and sulphur. The release of CO_2 through carbonate precipitation is seen as a major problem if irrigation waters are used in any system that is trying to store C. Furthermore, Schlesinger (2000) has pointed out that the groundwater of arid lands often contains up to 1 percent calcium and CO_2. This concentration is much higher than that which occurs in the atmosphere. Consequently, when these waters are applied to arid lands, CO_2 is released to the atmosphere and calcium carbonate precipitates. Schlesinger's calculations suggest that irrigation of some cropping systems would yield a net transfer of CO_2 from the soil to the atmosphere.

TRACE GASES

An important aspect of agricultural systems in relation to the global carbon balance is the production of trace gases, particularly CH_4 and N_2O. When CS by soils is being considered as a mechanism for offsetting greenhouse gas emissions, it is necessary to consider all the interacting factors that can influence global warming. Both CH_4 and N_2O are radiatively active gases and, like CO_2, contribute to the greenhouse effect. Although they are present in the atmosphere at much lower concentrations than CO_2, they are much more potent. CH_4 and N_2O are, respectively, 21 times and 300 times more active GHGs than CO_2.

Ruminants, composting, biomass burning and waterlogging produce CH_4, while N_2O is released from soils when N fertilizer or manure is applied (Vanamstel and Swart, 1994). Manure usage is considered to be the major problem with regard to trace-gas emissions in agriculture. This is a potentially serious problem because the application of manure is a major tool for increasing soil C in drylands. Smith *et al* (2001) calculated that, for European soils, the effect of trace gases is sufficient to reduce the CO_2 mitigation potential of some no-tillage and manure-management practices by up to a half. Moreover, climate change is likely to amplify the problem as increased temperature is predicted to promote N_2O emissions (Li, Narayanan and Harriss, 1996).

CLIMATE CHANGE

Climate is a major factor involved in soil formation. Consequently, climate change will influence soils. Photosynthesis and decomposition will be affected directly and, hence, have an impact on soils. Whether soil carbon levels increase or decrease will depend on the balance between primary production and decomposition (Kirschbaum, 1995). Overall, productivity is predicted to increase as a consequence of rising CO_2 concentration and temperature, and this will lead to increased amounts of residue available for incorporation into the soil. However, higher temperatures can be expected to increase mineralization of SOM because this process is more sensitive to temperature increases than primary production. Kirschbaum (1995) predicts that SOC stocks will decline overall with global warming. However, Goldewijk *et al.* (1994) suggest that the effects of temperature and water availability on soil respiration will be smaller than those attributable to the CO_2 fertilization effect. The direction of change is not certain but the balance of change will most probably operate at the regional level.

It has been argued that agricultural systems are to some extent buffered from environmental effects, while decomposition is not protected (Cole *et al*., 1993). Hence, increased rates of mineralization might be more significant than any enhancement of production. However, the quality of plant organic matter is expected to decrease under elevated CO_2 owing to an increase in the C:N ratio. This would slow the rate of degradation (Batjes and Sombroek, 1997). Globally, the drylands are expected to become moister (Glenn *et al*., 1993), which should lead to an increase in productivity and decomposition. However, shifts in climate zones are dependent upon a complex array of variables. Predictions based on the CENTURY agro-ecosystem model suggest that, overall, grasslands will lose soil C except in tropical savannahs, which should show a small increase (Parton *et al*., 1995). Experiments at elevated CO_2 have also shown that changes in soil C in agro-ecosystems are particularly dependent upon the crop species grown (Rice *et al*., 1994).

The full extent of the global rise in temperature associated with climate change may not be felt in many of the drylands because warming is predicted to be greatest at higher latitudes. With regard to the vegetation, some of the best-adapted plants for dryland regions use the C_4 photosynthetic pattern. Because these species already have a CO_2-concentrating mechanism, they show little or no increase in productivity at elevated CO_2. However, they are still likely to receive some benefit from the increased water-use efficiency that accompanies a rising CO_2 concentration.

Chapter 5
Case studies on drylands

Most of the research and case studies on soil CS have been conducted in temperate zones. Much less work has been done in developing regions, including drylands (Lal, 2002b). In order to realize the great potential for CS offered in drylands, efforts are needed to identify soil-specific practices that restore SOC in degraded soils. This chapter reviews specific case studies in different representative agrosystems in drylands, where the potential for carbon storage is assessed under different land-use and land-management practices involving irrigation and biofertilizers.

MODELS FOR ANALYSING TROPICAL DRYLAND AGRICULTURAL SYSTEMS

RothC (RothC-26 3) (Coleman and Jenkinson, 1995; Jenkinson and Rayner, 1977) and CENTURY 4.0 (Parton *et al*., 1987; Parton, Stewardt and Cole, 1988) are the most extensively used SOC simulation models. They have been tested against a variety of long-term agricultural field trials and have also been used in a variety of climate zones, including dryland regions. Both have also been adopted for use in major carbon-assessment projects. The two models vary in their complexity. RothC requires fewer data inputs and so is easier to parametize. However, it only deals with soil processes and, consequently, plant residue C is a required input. The CENTURY agro-ecosystem model has similar SOC pools to RothC but has the advantage of additional submodels. Although it is able to handle a great many more land-management options than RothC, it requires an increased array of input variables that require parametization. This is important because the ability of any model to predict accurately depends on the accuracy and trustworthiness of the data used to parametize it.

APPROACH ADOPTED FOR PARAMETIZING ROTHC AND CENTURY

Data for parametizing the models can be divided into three areas: climate, soil and land management. Studies that contain data that are sufficiently detailed for modelling are few, particularly in dryland regions. Where investigations have been undertaken and detailed information collected, the primary data that are vital for modelling are often not readily available.

Climate parameters may be referred to by investigators reporting the effects of land management on soils, but complete data sets are rarely given. However, climate data are available independently, as from FAOCLIM 2 (2000), which contains a database of more than 28 000 weather stations worldwide.

The literature contains the results from many investigations analysing soil properties and the effect of various treatments and practices upon soils. However, there are far fewer studies that combine soil analysis with examination of land management, especially over the longer term. In particular, there has been little research on dryland systems.

For the case studies examined here, CENTURY was parametized and run to equilibrium for between 2 000 and 5 000 years. Scenarios reflecting the recent past and present were then applied. Although CENTURY can run many varied cropping practices, it can only handle one crop at a time. Consequently, intercropping, which is commonly practised in dryland farming systems, could not be incorporated into the scenarios.

RothC was run to equilibrium using the current soil carbon status after initially being run in reverse mode to calculate the necessary plant carbon inputs. In order to model some of the future scenarios for analysing the effects of land management on soil C, the appropriate plant residue inputs were obtained from the CENTURY plant submodel and then used to parametize the RothC land-management files. The results in RothC frequently predict higher levels of soil C than CENTURY. This has been noted before and has been attributed to the fact that SOC tends to turnover faster in CENTURY than in RothC, and, consequently, that RothC requires lower carbon inputs to maintain the same organic carbon content (Falloon and Smith, 2002). The CENTURY plant submodel is quite basic. Therefore, where accurate estimations of plant production and crop yield are required, then alternative models, such as the fully mechanistic plant productivity model WIMOVAC, should be used (Humphries and Long, 1995).

CHOICE OF SYSTEMS AND SOURCES OF DATA

Data from four distinctly different dryland systems in Argentina, India, Kenya and Nigeria were used to model changes in soil C with a variety of farm practices and technologies. These systems had different precultivation stocks of soil C, and had lost different amounts during cultivation (Table 11). Additions of organic matter to the soil through use of FYM, green manures, legumes in rotations, vermicompost, or use of fallows in rotations, all increased soil C and increased agricultural yields. Trees as part of agroforestry systems further increase soil carbon stocks. Inorganic fertilizer used alone to increase nutrient supply for crops results in declines in soil C in all systems, or only small increases if used with no-tillage. No-tillage increases soil C, although again the accumulation is greatest where organic matter is added to the soil.

The scenarios show that CS in tropical drylands soils can be achieved at the different sites. The land-management practices have been chosen to be in accordance with the current farming systems. Thus, for example, application rates of organic matter are commensurate with quantities that should be available to local farmers. However, at the field level, important trade-offs may occur, preventing adoption of the best strategies for CS. Crop residues may be required for livestock feed or fuel rather than be returned to the fields, or may be sold in difficult times. Animal manures may be

TABLE 11
Summary of findings on carbon stocks and rates of accumulation and/or loss in four dryland agrosystems

	Nigeria	India	Kenya	Argentina
Stocks of soil C before cultivation (tonnes/ha)	8-23	15-20	33-41	50-70
Current stocks of soil C after cultivation (tonnes/ha)	6-12	13-22	18-28	37-41
Effect of conventional tillage practices on soil C (tonnes/ha/year)	- 0.05 to - 0.01	- 0.07 to +0.06	- 0.3 to - 0.1	- 0.17 to - 0.19
Effect of FYM, organic additions, retained plant residues and fallows in rotations (tonnes/ha/year)	+ 0.1 to + 0.3	+ 0.2 to + 0.4	+ 0.4 to + 0.9	-
Effect of trees (tonnes/ha/year)	+ additional 0.05 to 0.15	+ additional 0.5 to 0.7	-	-
Effect of using inorganic fertilizers as sole source of nutrients on soil C (tonnes/ha/year)	- 0.12 to + 0.08	- 0.01	- 0.3	-
Effects of no-tillage (NT)				
NT alone				+ 0.02
NT + green manures or FYM				+0.1 to 0.25
NT + inorganic fertilizers				+0.04

[1] Effects of conventional tillage are averages for the last 100 years for each site except Kenya where rates are calculated from when each settlement commenced (30 – 50 years).

burnt for fuel. Many socio-economic factors will interact to determine which scenario or combination of scenarios is implemented in each growing season.

Some of the results predict that soil C can be restored to precultivation levels, or in certain circumstances to above them. The true "native soil carbon level" is often difficult to establish in those systems where agricultural activity has been present for several centuries or millennia such as in the Nigeria and Kenya cases. To achieve quantities of soil C in excess of the "natural level" implies that the agriculture system has a greater productivity than the native system, assuming that C is not being imported. The scenarios that predict the highest CS rates are often associated with the introduction of trees to the system. The inputs of C from trees are more resistant to decomposition than those from herbaceous crops and, consequently, can cause marked increases in the level of soil C (Falloon and Smith, 2002).

Case study 1

Nigeria – Kano Region

Nigeria includes some of the most densely inhabited areas of semi-arid West Africa. This is not a recent phenomenon as indications of human activity can be traced back well over a thousand years. Consequently, the soils of this region have been subjected to long periods of cultivation. However, in the last 40 years the cultivated area of northern Nigeria has increased from 11 percent to 34 percent of the total land area (Harris, 2000). In particular, the level of agricultural intensity in the Kano Closed–Settled Zone (CSZ) is among the highest in semi-arid West Africa.

Investigations into the farming systems of this region and their effect on soil fertility have been conducted by the organization Drylands Research, the United Kingdom. Its studies have found a close correlation between the intensity of farming and the adoption of soil-fertility management techniques. Plant production in the Sahel is generally limited by rainfall or nutrients (Breman and De Wit, 1983). However, the economy and infrastructure of northern Nigeria is unsuited to high external inputs such as fertilizers. Consequently, the smallholder farming units operate as low-input systems, with cattle manure being the most common form of organic input.

PHYSICAL ASPECTS

This semi-arid region has a rainy season from May–July until September. However, rainfall is erratic (Mortimore, 2000) and makes crop cultivation particularly difficult. The soils are principally ferruginous tropical soils that are sandy, with poor waterholding capacity and low levels of nutrients and organic matter (Harris, 2000). Nutrient balances can vary between years as crop growth fluctuates with rainfall. The natural vegetation is open forest savannah with a trend towards increasing open grassland where rainfall is lowest.

FARMING SYSTEMS

Northern Nigeria has been classified into three categories of farming system: intensive, less intensive and extensive (Mortimore, 1989). The intensive systems use permanent annual or biannual cultivation with a cropping intensity of more than 60 percent. The low-intensity systems operate a shrub/short-bush–fallow regime and the cropping intensity is 30–60 percent. The extensive system is one of long-bush–fallow and uncultivated areas, where the cropping intensity is typically less than 30 percent.

The major crops grown are millet, sorghum, groundnut, sesame and cowpea. As the systems are low input, grain yields are about 1 tonne/ha. Ridging ploughs are primarily used for cultivation and hoeing is commonplace. Applications of manure have to be made carefully to avoid "burning" the crops, and additions are 1–7 tonnes/ha. Crop residues are collected for fodder or left to be grazed in the fields.

Fallowing is practised in the less intensive systems although the land is still "harvested" through grazing and the collecting of wood and other products. Night-parking (or folding) of livestock is the most effective method of providing manure. Legumes such as cowpea are grown, primarily in higher-intensity systems, to provide nitrogen inputs. Inorganic fertilizers are scarce and seldom available at the optimal time.

STUDY SITES

The study sites cover a range of population density and include the three categories of farming intensity. The soils and crops grown are similar across all categories (Harris, 2000). Initially, CENTURY was parametized with a natural system of grass, woodland and grazing. A medium-intensity fire was scheduled for every 10 years and a high-intensity fire event occurred every 30 years. One thousand years ago, slash and burn episodes were commenced and two seasons of millet cultivation incorporated, repeated every 60 years. In the nineteenth century, the frequency of cultivation events was increased to a 30-year cycle, and then once every 15 years by the commencement of the twentieth century.

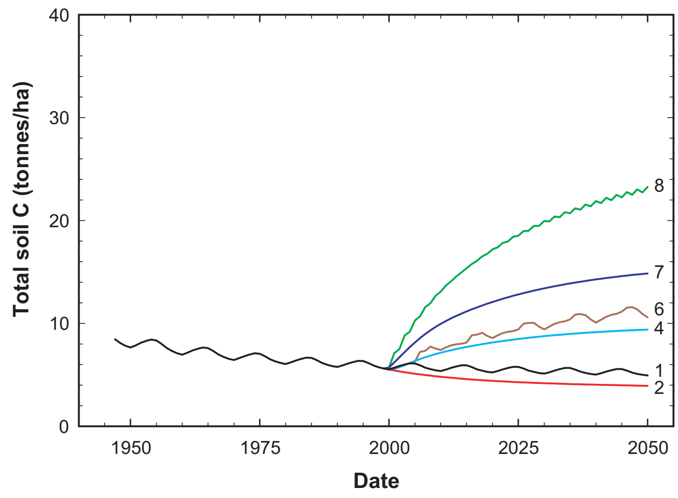
i. Futchimiram, Borno State

This is a low-intensity, or extensive, agropastoral system practising shifting cultivation. Some land has now become degraded. CENTURY was run for the last 60 years with alternate five-year cycles of grazing and millet cropping. Crop residues are grazed and there are no other inputs. This current practice produces a gradual and persistent decline in soil C (Figure 9). The estimated level is slightly above the measured value of soil C for cultivated soils that range between 3.5 and 4.4 tonnes/ha. RothC also predicts that the current practice will decrease soil C slightly over the next 50 years (Table 12). The scenarios in Figure 9, detailed in Table 13, compare current practices with additions of inorganic fertilizer, FYM, plant residues, fallow removal, retained plant residues and grazing. Figure 10 illustrates the predicted average annual change in soil C over a 50-year period.

Effect of loss of fallow

Removing the fallow period only (Scenario 2) results in a greater decline in soil C over subsequent years, with both models predicting similar reductions (Figure 9 and Table 12). Preventing grazing of the crop residues under these conditions

FIGURE 9
Total soil carbon for Futchimiram settlement (CENTURY)



Scenarios described in Table 13.

TABLE 12
Total soil carbon for Futchimiram settlement

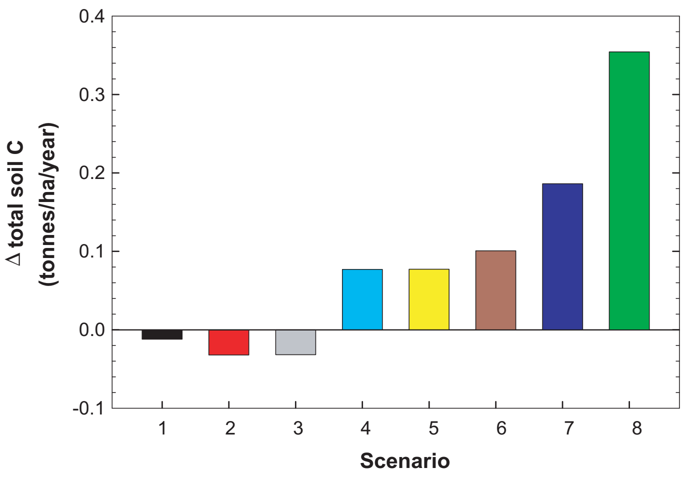
Scenario[1]	CENTURY 2000 (tonnes/ha)	CENTURY 2050 (tonnes/ha)	CENTURY % change	RothC 2000 (tonnes/ha)	RothC 2050 (tonnes/ha)	RothC % change
1	5.54	4.94	-10.8	5.38	5.18	-3.7
2		3.93	-29.1		3.72	-30.9
5		9.40	69.7		9.70	80.3
6		10.57	90.8		12.45	131.4

[1] Scenarios described in Table 13.
Source: CENTURY and RothC

TABLE 13
Scenarios for modelling land management practices, Futchimiram settlement

Scenario	Land management
1	Current practice
2	Continuous cultivation
3	Continuous cultivation, no grazing of residues, harvest only grain
4	Inorganic fertilizer only (100 kg/ha urea), no grazing
5	Plant residues average 0.5 tonnes/ha/year, no grazing of residues
6	5-year fallow, 5-year cultivation, 2 applications FYM 3 tonnes/ha, graze residues
7	Continuous cultivation, FYM 1.5 tonnes/ha/year, graze residues
8	Continuos cultivation, FYM 1.5 tonnes/ha/year Plant residues 0.5 tonnes/ha/year, no grazing

FIGURE 10
Average annual change in total soil carbon for Futchimiram settlement (CENTURY)



Scenarios described in Table 13.

(Scenario 3) has very little effect on soil C (Figure 10).

Effect of organic inputs

The addition of FYM (two applications of 3 tonnes/ha in each five-year cropping cycle, average 0.6 tonnes/ha/year) has a positive effect on soil C, the two models indicating an increase of 5–7 tonnes C/ha over the next 50 years (0.08 tonnes C/ha/year). Figures 9 and 10 show the outcome of further scenarios using different combinations of fallow and organic inputs. The gradual increase in soil C occurs with FYM, retaining plant residues and no grazing after harvest. In this case, soil stocks rise from 6 to 24 tonnes C/ha over 50 years.

Effect of inorganic fertilizer

The use of inorganic fertilizer with no other organic inputs, and no grazing or fallow (Scenario 4), leads to a modest increase in CS (0.08 tonnes C/ha/year).

Summary

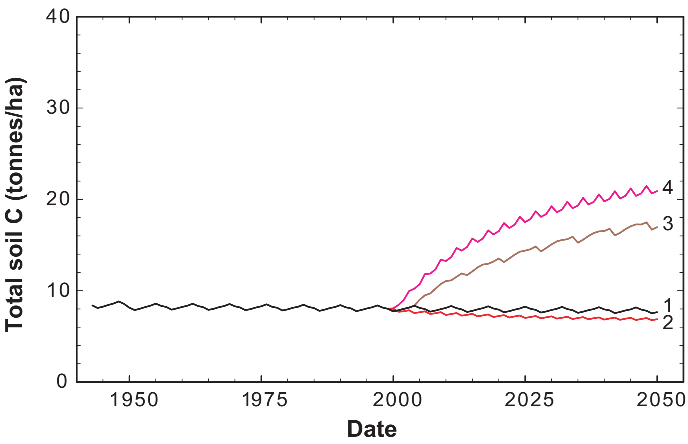
This system will not yield a positive soil carbon balance without increased organic inputs. Although inorganic fertilizers can lead to CS, they bring with them a carbon cost that will result in an overall negative balance of the complete carbon budget.

ii. Kaska, Yobe State

This is a low-intensity agropastoral farming system covering lowland, upland and some wetland areas. Only the lowland soils are modelled here. There is intercropping of legumes and grains, and crop residues are fed to livestock. Manure application to fields is low and long bush fallows are used.

CENTURY was parametized for the last 50 years with a seven-year cycle of 4 years of grazing and 3 years of millet–cowpea–millet cropping. FYM (0.75 tonnes/ha) was added in the first year of each cropping cycle. Cultivated soils have carbon contents of 4.5–7.0 tonnes/ha. The CENTURY model calculates a current carbon content of 7.7 tonnes/ha (Figure 11), and RothC gives a similar result (Table 14). Both models suggest that with current practice the system is close to steady state.

FIGURE 11
Total soil carbon for Kaska settlement (CENTURY)



Effects of fallows and organic inputs

Removing the fallow from the current practice (Scenario 2) leads to a slight decline in soil C in subsequent years (Figures 11 and 12). Applying 3 tonnes/ha FYM to each millet crop (average 1.3 tonnes/ha/year over seven-year cycle) will produce a marked increase in soil C (Tables 14 and 15) representing a CS rate of 0.18 tonnes/ha/year (Figure 12). This increase will be further enhanced if the fallow is removed, because the manure application rate will now average 2 tonnes/ha/year (Figures 11 and 12).

TABLE 14
Total soil carbon for Kaska settlement

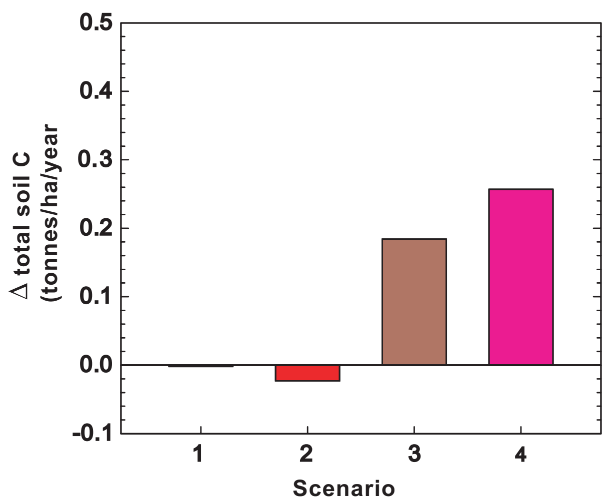
Scenario[1]	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	7.73	7.64	-1.2	7.33	7.87	7.4
3		16.94	119.1		15.57	112.4

[1] Scenarios described in Table 15.
Source: CENTURY and RothC.

TABLE 15
Scenarios for modelling land management practices, Kaska settlement

Scenario	Land management
1	Current practice
2	Continuous cultivation, millet-cowpea
3	Cultivation-fallow, FYM 3 tonnes/ha, to millet
4	Continuous cultivation, FYM 3 tonnes/ha, to millet

FIGURE 12
Average annual change in total soil carbon for Kaska settlement (CENTURY)



Scenarios described in Table 15.

Summary

The scenarios for Kaska illustrate the effect of fallow periods on stocks of soil C. Where the cropping regime is adding very little organic matter to the soil, fallows will often have a positive effect if correctly managed. However, if the cropping practice is accumulating significant organic matter in the soil, any interruption, such as fallowing, will decrease the overall potential for CS.

iii. Dagaceri, Jigawa State

This is a region undergoing rapid intensification. It is an agropastoral system with shrub or short-bush fallowing. The length of fallow has decreased as the area of arable land has expanded. Both legumes and grains are grown, but land degradation is a problem. As the fallow period shortens, farmers rely increasingly upon manures to maintain soil fertility.

The parametization for CENTURY was initially the same as for Kaska but then, 30 years ago, cropping was increased to five years out of seven. Millet and cowpea are cropped alternately with 1.5 tonnes/ha manure added to each millet crop (average 0.64 tonnes/ha over a seven-year cycle).

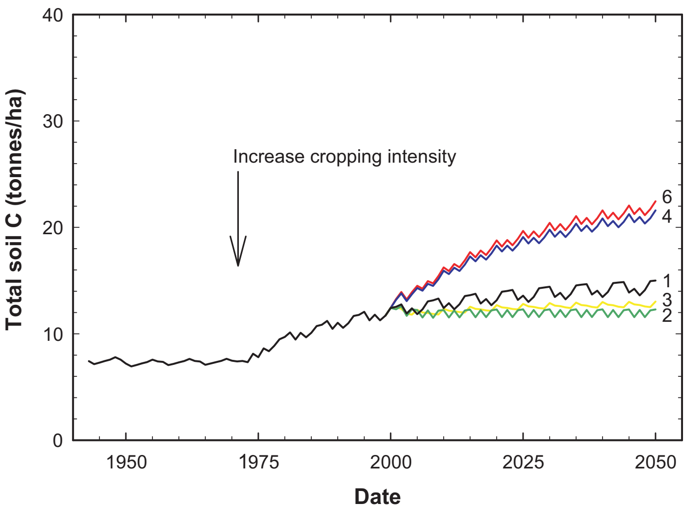
The additional manure input associated with the increase in cropping intensity results in an increase in soil C, predicted by both models, and this rise continues in subsequent years (Figure 13 and Table 16). Field measurements vary according to previous cropping intensity and range from 3 to 17 tonnes C/ha.

TABLE 16
Total soil carbon for Dagaceri settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
	(tonnes/ha)			(tonnes/ha)		
1	12.43	15	20.7	14.69	20.43	39.1
5		22.22	78.8		29.55	101.2

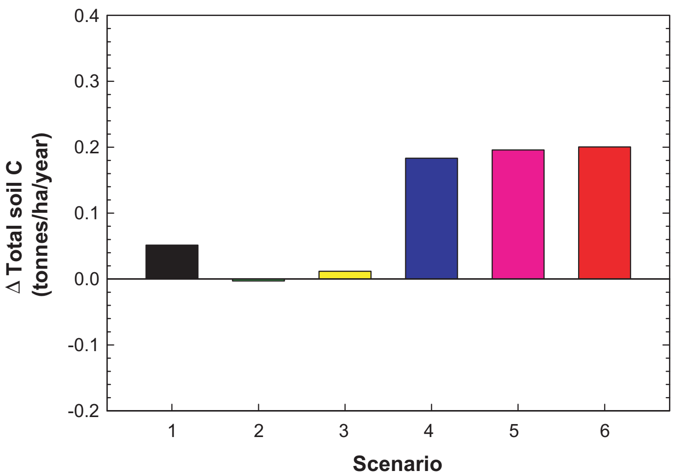
[1] Scenarios described in Table 17.

FIGURE 13
Total soil carbon for Dagaceri settlement (CENTURY)



Scenarios described in Table 17.

FIGURE 14
Average annual change in total soil carbon for Dagaceri settlement (CENTURY)



Scenarios described in Table 17.

Effects of fallows and organic inputs

The manure input to each millet crop is increased to 3 tonnes/ha in all scenarios (2–6). Carbon sequestration rates of 0.18–0.20 tonnes/ha can be achieved, with slight differences depending on whether the fallow is retained and crop residues grazed or ungrazed (Scenarios 4–6, Figures 13 and 14, Table 17). However, if fallow elimination is accompanied by harvesting all aboveground material (Scenario 3), CS is virtually halted even if manure application is maintained.

The complete removal of trees from the system results in a net loss of soil C in spite of the increased application of manure.

Summary

This system shows that SOM can be maintained and increased even with intensification of cropping, provided there are legumes in the rotation. However, careful management of crop residues is vital as is the preservation of trees.

iv. Tumbau, Kano Closed–Settlement Zone

This is a highly intensive agricultural area. All the land is cultivated although degradation reportedly affects less than 10 percent of the land area. There is a highly integrated crop and livestock production system with intercropping of legumes, intensive manuring and inorganic fertilizer application. There is virtually no grazing land so animals have to feed on crop residues and fodder from nearby fields.

CENTURY was run for the last 50 years with a millet–cowpea rotation, 6 tonnes/ha of manure applied to the millet (average 3 tonnes/ha/year) and all aboveground plant material harvested. This system is now close to steady state with soil C stocks at 9.8 tonnes C/ha (Figure 15). This compares with an average of 10.5 ± 1.7 tonnes C/ha measured at cultivated sites. RothC calculates a value of 11.3 tonnes/ha for 2000 but predicts that a higher soil carbon level will be reached by 2050 (Table 18).

Effects of organic inputs
Additional FYM inputs have a marked impact on soil C, especially when they approach the maximum (7 tonnes/ha) normally applied in this region, i.e. an annual input of 6.75 tonnes/ha (Table 19) will result in the sequestration of 0.20 tonnes C/ha/year over the next 50 years (Figure 16). Although adding N-fixing trees and plant residues to the fields will further increase soil C, the requirement of the former for livestock feed may exceed the capacity of the current farming system.

Effect of inorganic fertilizer
Replacing the manure input to this system with inorganic fertilizer (urea 100 kg/ha, Scenario 2) results in a large reduction in soil C, with stocks falling by more than 0.1 tonnes C/ha/year.

Summary
Provided that adequate organic matter is returned to the soil, these intensive-farming systems should maintain soil C and there is also scope for CS. These results are in agreement with findings in the field that provide no evidence for a decline in SOM in spite of increased cultivation pressure. However, the ability to realize future CS will depend on a careful balance between cropping and livestock husbandry and the overall capacity of the system. Maintaining crop yields through the application of inorganic fertilizer alone will probably result in substantial losses of SOM.

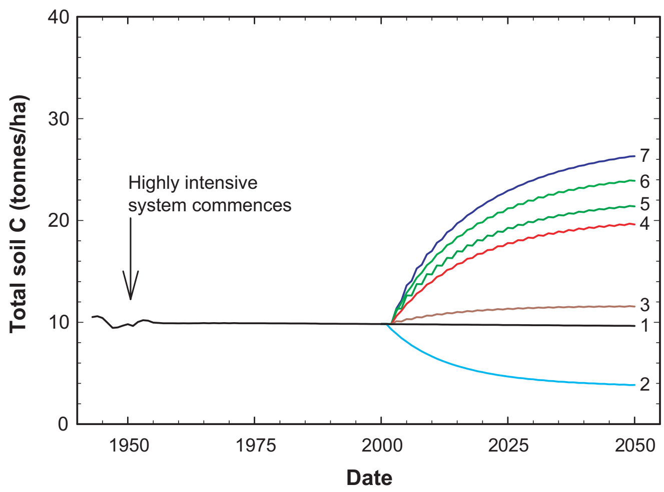
Conclusions from northern Nigeria cases

The modelling of farm data for the drylands of northern Nigeria shows that soil carbon stocks can be increased from a low base with a

TABLE 17
Scenarios for modelling land management practices, Dagaceri settlement

Scenario	Land management
1	Current practice
2	Remove trees
3	No grazing of residues, harvest all aboveground
4	Continous cultivation, millet–cowpea
5	FYM average 1.29 tonnes/ha/year,fallow, graze residues, harvest only grain
6	No grazing of residues, harvest only grain

FIGURE 15
Total soil carbon for Tumbau settlement (CENTURY)



Scenarios described in Table 19.

TABLE 18
Total soil carbon for Tumbau settlement (CENTURY and RothC)

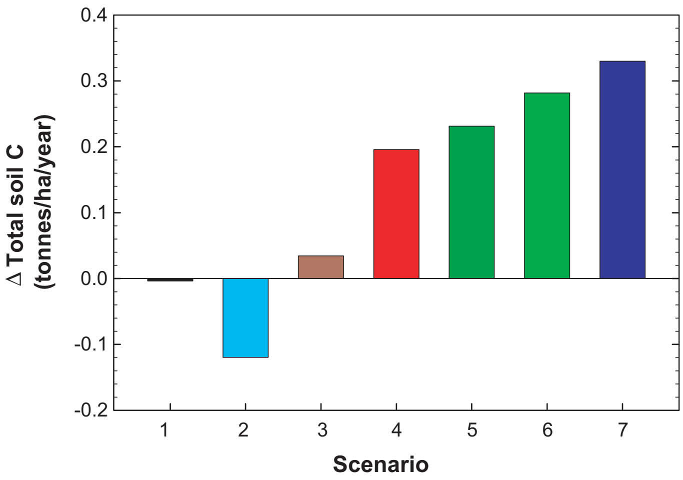
Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	9.82	9.64	-1.8	11.3	13.39	18.5
3		11.54	17.5		14.96	32.4
6		23.9	143.4		31.7	180.5

* Scenarios described in Table 19.

TABLE 19
Scenarios for modelling land management practices, Tumbau settlement

Scenario	Land management
1	Current practice
2	Inorganic fertilizer (110 kg/ha urea)
3	FYM 3.75 tonnes/ha/year
4	FYM 6.75 tonnes/ha/year
5	FYM 3.75 tonnes/ha/year, add nitrogen-fixing trees
6	FYM 6.75 tonnes/ha/year, plant residues 2 tonnes/ha
7	FYM 6.75 tonnes/ha/year, harvest only grain

Figure 16
Average annual change in total soil carbon for Tumbau settlement (CENTURY)



Scenarios described in Table 19.

variety of technologies and practices already available to farmers.

The total amounts of C that can be sequestered with the use of legumes, fallow periods, FYM and retention of plant residues varies between 0.1 and 0.3 tonnes C/ha/year. This amount rises when trees are also cultivated.

Soil C is lost when only inorganic fertilizers are used to maintain soil fertility – some 0.1 tonnes C/ha/year in the intense systems of the Kano CSZ. Continuous cultivation results in small year-on-year losses of C where there are no additional inputs of organic matter. In spite of considerable intensification of current systems (shortening of fallow periods), farmers are maintaining carbon stocks. The benefits of maintaining trees in the landscape are shown in these modelled scenarios.

Case study 2

India – Andhra Pradesh and Karnataka States

More than half of India's farmers of India live in climate regions that can be described as semi-arid. Recent decades have seen increases in crop yields that have been attributed to the green revolution. However, the associated technologies, e.g. irrigation and inorganic fertilizer are expensive, and not readily accessible to the rural poor. These practices may lead to declines in soil fertility, and are also dependent upon fossil-fuel energy (Butterworth, Adolph and Satheesh, 2002). In fact, nearly two-thirds of the arable land in India remains dependent solely upon rainfall for agricultural production. The Natural Resources Institute (the United Kingdom), the Deccan Development Society and the BAIF Institute for Rural Development (India) have studied soil fertility management in Medak District in Andhra Pradesh and in Tumkur District in Karnataka. They have shown that there is an increasing awareness about technologies for maintaining and improving soil fertility, identifying at least 14 different practices from legume cultivation to vermicompost production. Most involve maintaining and increasing the organic matter content of the soil. These studies provide an opportunity to investigate the effect that these soil-fertility improvement techniques may have on CS.

PHYSICAL ASPECTS

Medak District forms part of the tableland of the Deccan Plateau that extends from Andhra Pradesh into Karnataka. The climate consists of a mild winter period (rabi, November–February), a hot and dry summer (March–May) and the southwest monsoon, when more than 80 percent of rainfall occurs (kharif, June–October). Average rainfall is slightly less than 900 mm. The hottest month is May, just before the onset of rains, when the maximum daytime temperature can reach 40 °C. Conversely, night temperatures can drop to 6 °C in December. Moisture availability for crop growth ranges from 120 to 150 d.

The major soil types are Alfisols and Vertisols. The former include red lateritic soils comprising loamy sands, sand loams and sandy clay loams and are usually non-saline. The Vertisols, black cotton soils, are potentially more productive with a higher waterholding capacity, moderately alkaline and with a highly soluble salt content. They comprise clay loams, clays and silty clays. The organic carbon content of soils in the area is usually 0.5–1 percent. The land lies between 500–600 m above sea level, and very little natural vegetation remains. The tropical dry deciduous forest has mainly been felled except on protected government land.

FARMING SYSTEMS

The farming systems in this region have a high degree of integration between livestock, crops and trees (Pound, 2000). There is a huge agrobiodiversity that is combined with off-farm activities, particularly in Medak District. This situation makes for an efficient use of the limited land resources and acts as insurance against unpredictable weather conditions, a frequent problem in drylands. The average farm size is 2.6 ha (Butterworth, Adolph and Satheesh, 2002). The small and marginal farmers can grow at least eight varieties of crops per half hectare. The cattle population has been falling continuously since the 1980s. This has important implications for agriculture, not only because animal wastes are an important source of organic matter for soils, but also because bullocks make a vital contribution as draught animals, not least in the transport of FYM. Tillage is commonly performed with very basic implements. The greatest shift towards mechanized cultivation has been in Karnataka.

The predominant crops grown in Medak District are paddy, sorghum and maize while irrigated sugar cane is an important cash crop. The major crops grown in Karnataka are paddy, sorghum, finger millet, pearl millet, pigeon pea, green gram, and groundnut (Reddy, 2001).

Farmers attach a high priority to maintaining soil fertility while inorganic fertilizers are ranked poorly in terms of maintaining soil quality. However, many farmers use them because organic alternatives are often unavailable and because the inorganic fertilizers are subsidized. The importance attached to soil fertility can have unforeseen consequences such as the sale of FYM by the poorest farmers to their more affluent counterparts. The ultimate effect of this will be an increase in the fertility and carbon content of some soils while degrading neighbouring areas.

MODELLING SOIL CARBON IN THE STUDY VILLAGES

The CENTURY agro-ecosystem model was parametized using climate and soil data and run to equilibrium commencing with a grass/woodland system to represent the natural vegetation of this region. Low-intensity grazing and fires occurring every 30 years were included in the cycle. One thousand years ago, the effects of human interference were introduced with slash and burn events together with the cultivation of a grain crop. The frequency of these events was increased slowly and by the start of the twentieth century, cultivation periods of four years out of ten were introduced. In the mid-twentieth century, one year of grazed fallow was followed by four years of cropping (sorghum–kharif, and cowpea–rabi). Cultivation consisted of hand or bullock ploughing and hand hoeing. Average annual applications of FYM were 2.1 tonnes/ha over the five-year cycle and all aboveground material was harvested. For the final 30 years of the twentieth century, cultivation was adjusted to reflect current practices. The RothC model was run to equilibrium in the mid-twentieth century, and then parametized using current practice and plant residue quantities calculated by CENTURY.

Data on five types of farm and location are presented below:

i. large mixed dryland farm (Lingampally);
ii. small dryland farm, no livestock (Lingampally);
iii. large farm using irrigation (Yedakulapaly);
iv. small mixed drylands farm (Metalkunta);
v. small mixed drylands farm (Malligere);

i. Analysis of land management by a large mixed farm, Lingampally village, Medak District

This is a holding of slightly more than 5 ha on predominantly Vertisols. Livestock are fed fodder and plant residues from the fields. Consequently, no plant material is returned to the soil. The animals are also grazed on local common land. The livestock provide manure (2–3 tonnes/ha/year). In addition, inorganic fertilizer has been used in recent years (30–45 kg/ha of di-ammonium phosphate). Crops modelled are sorghum (kharif May–September) and cowpea (rabi October–January).

CENTURY predicts that the current farming practice is resulting in a nearly stable soil carbon content of about 19 tonnes/ha declining to 2050 by nearly 1.5 tonnes/ha (Figure 17). RothC shows a lower total soil carbon content of 16 tonnes/ha in 2000, declining to 15 tonnes/ha by 2050 (Table 20). The scenarios in Figure 17 (detailed in Table 21) compare current practices with additions of inorganic fertilizer, FYM, green manure, vermicompost, retained plant residues and cultivation of trees. Figure 18 indicates the average annual change in soil C in a 50-year period.

Effect of inorganic fertilizer

If the application of inorganic fertilizer were halted and the quantity of FYM increased to replace the nitrogen input and maintain yields (increase manure application by 0.6 tonnes/ha, Scenario 3), soil C would increase by only 0.85 tonnes/ha by 2050 (Figure 17) and there would be no net gain in soil C (Figure 18). Conversely, replacing all organic additions with inorganic fertilizer would result in a decrease in soil C of more than 4 tonnes/ha by 2050, a loss of 0.09 tonnes/ha/year (Scenario 2). Thus, inorganic fertilizer results in a fall in soil C.

Effect of farmyard manure

Doubling the current annual input of FYM to 4–6 tonnes/ha (Scenario 4) without applying inorganic fertilizer has a marked effect on soil C: 0.27 tonnes/ha/year is sequestered in the next 50 years (Figure 18), with the system still not at a steady state (Figure 17). Similarly, RothC shows a continuing rise, reaching 28.3 tonnes/ha by the same date (Table 20).

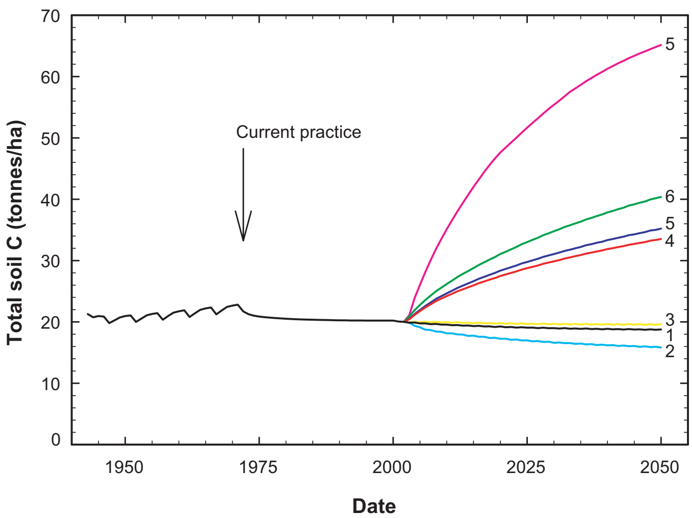
Effect of other organic inputs

Adding only modest amounts of vermicompost (100 kg/ha) and green manure (250 kg/ha) in addition to the doubled FYM (Scenario 5) has a limited effect, while 2 tonnes/ha plant residues makes a bigger contribution, 0.4 tonnes/ha/year (Figure 18).

Effect of trees

This farm has a capacity for introducing N-fixing trees such as *Glyricidia*, which creates Scenario 7 when added to the manure and plant residues. After 10 years, the trees are cut annually for wood. The result is a very large increase in soil CS of 0.4 tonnes/ha/year (Figure 18). This increase exceeds that which would be obtained by increasing the manure application by four times.

FIGURE 17
Total soil carbon for a large farm (5 ha), Lingampally village (CENTURY)



Scenarios described in Table 21.

TABLE 20
Total soil carbon for a large farm Lingampally village

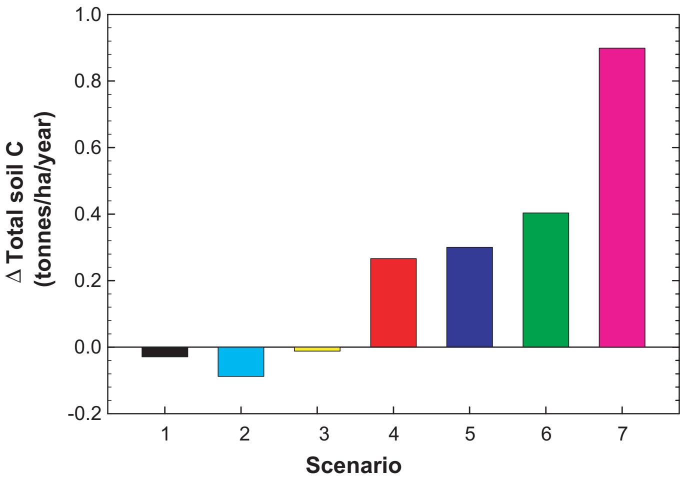
Scenario[1]	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	20.2	18.8	-7.2	18.3	17.9	-2.3
4		33.5	65.9		28.3	54.2
6		40.4	100		31.0	68.8

[1] scenarios described in Table 21.
Source: CENTURY and RothC

TABLE 21
Scenarios for modelling land management practices, large farm Lingampally village

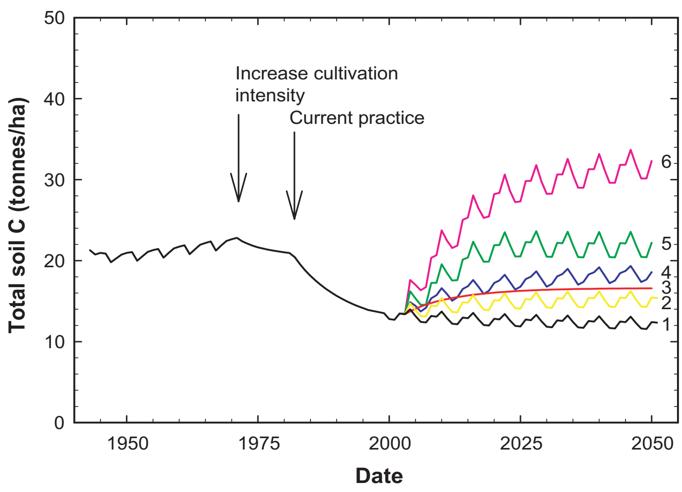
Scenario	Land management
1	Current practice
2	FYM 3 tonnes/ha/year
3	FYM 3 tonnes/ha/year, green manure 500 kg/ha/year, vermicompost 250 kg/ha/year
4	As current practice but incorporate crop residues into soil
5	FYM 3 tonnes/ha/year, leave plant residues
6	FYM 3 tonnes/ha/year, plant residues, green manure, vermicompost
7	FYM 6 tonnes/ha/year, plant residues, green manure, vermicompost

FIGURE 18
Average annual change (over 50 years) in total soil carbon for a large mixed farm, Lingampally village (CENTURY)



Scenarios described in Table 21.

FIGURE 19
Total soil carbon for a small rainfed farm, Lingampally village (CENTURY)



Scenarios described in Table 23.

Summary
The two soil carbon models are in fairly close agreement for this farming system. The current practice is nearly sustainable with only a small decline (< 2 percent) in soil C predicted over the next 50 years. However, cattle are currently being grazed on other land and, consequently, some C is effectively being mined from elsewhere.

A modest increase in organic material would be required to replace the inorganic fertilizers currently used. Further organic inputs could increase soil CS substantially. Introducing trees is likely to have a marked effect on soil C and would simultaneously increase aboveground carbon storage. However, a greater proportion of trees may have been introduced to the model than would be feasible and, therefore, the degree of CS that is practicable for this farming system may be overestimated.

ii. Analysis of land management by a small rainfed farm, Lingampally village, Medak District

This holding is less than 1 ha and the Vertisol has become very degraded. Animals were kept in the past but have been sold and currently sorghum is the only major crop grown. All aboveground material is harvested and removed. Some FYM is applied at different times, equivalent to 3.9 tonnes/ha/year.

The CENTURY model shows how current practices have produced a marked decline in soil C, reaching some 13 tonnes/ha in 2000 (Figure 19). However the system is reaching steady state and the current land-management practice is not predicted to cause much further decline in soil C in the next 50 years. RothC yields a slightly higher carbon content in 2000 but predicts a slightly greater decline (1.8 tonnes/ha) by 2050 (Table 22).

Effect of retained residues
Harvesting only the grain and the returning crop residues to the soil would produce a positive carbon balance, sequestering 0.05 tonnes/ha/year (Figure 20 and Scenario 2, Table 23).

Effect of farmyard manure

Increasing the input of FYM by 50 percent to 6 tonnes/ha/year would increase soil C by 3.8 tonnes/ha by 2050 (Figure 20 and Scenario 3). RothC predicts a rise of 3.0 tonnes/ha.

Effect of legume crops

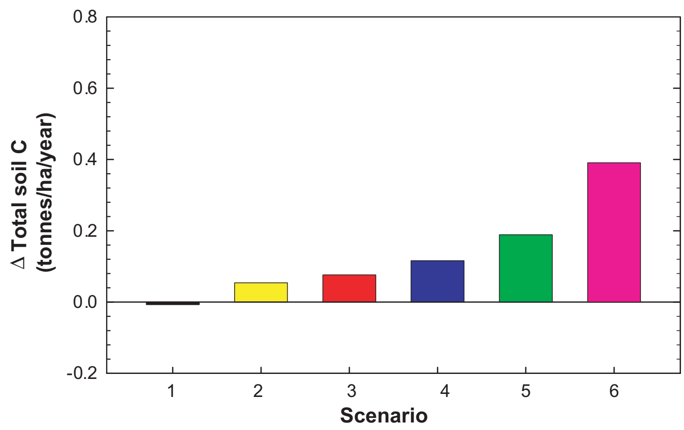
Adding cowpea the rotation (FYM 4 tonnes/ha, harvesting only grain, Scenario 4) would sequester 0.12 tonnes/ha/year. Introducing N-fixing trees (cut every 2 years after an initial 10 years) to the sorghum-only system with FYM at 4 tonnes/ha, would yield a sequestration rate of 0.19 tonnes/ha/year (Scenario 5).

Combining all treatments would lead to a soil CS rate of 0.39 tonnes C/ha/year (Scenario 6, Figure 20).

Summary

The modelling suggests that the loss of soil C can be reversed for this type of farm, even on degraded soil. In addition to direct organic inputs, this example illustrates the importance of a leguminous crop, and the inclusion of trees such as *Glyricidia*.

FIGURE 20
Average annual change in total soil carbon for a small rainfed farm, Lingampally village (CENTURY)



Scenarios – described in Table 23.

TABLE 22
Total soil carbon for a small rainfed farm, Lingampally village

Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	12.77	12.41	-2.8	16.07	14.92	-7.2
3		16.58	29.8		19.11	18.9

*Scenarios described in Table 23.
Source: CENTURY and Roth C.

TABLE 23
Scenarios for modelling land management practices, for a small rainfed farm, Lingampally village

Scenario	Land management
1	Current practice
2	Harvest only grain
3	FYM 6 tonnes/ha/year
4	Add legume (cowpea)
5	Add trees, e.g. *Glyricidia*
6	All additions

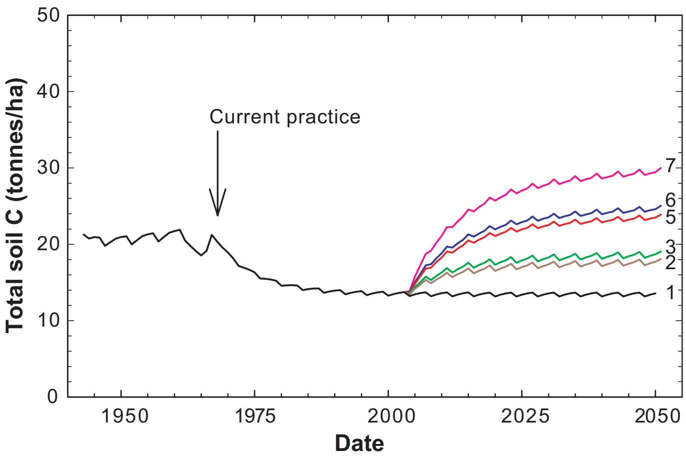
iii. Analysis of land management for a large farm using irrigation, Yedakulapaly village, Medak District

The farm comprises 4.5 ha of irrigated Vertisol. Water is pumped from a borehole. For the purposes of modelling, 5 cm of water is applied when the soil waterholding capacity is < 25 percent during the vegetative growth stage of the crop. Livestock were originally kept but were sold some years ago because there was insufficient labour to collect fodder and tend to the cattle during grazing. Only inorganic fertilizers are now used – 650 kg/ha di-ammonium phosphate and 150 kg/ha of urea annually. Crops are grown in all three seasons (summer – sorghum, kharif – legume, rabi – legume) and all aboveground material is harvested and removed. For the purposes of modelling, cowpea is used for the legume crop.

CENTURY calculates that current practices have depleted soil C to 13.26 tonnes/ha and predicts no further reduction in the next 50 years (Figure 21).

FIGURE 21

Total soil carbon for a large farm using irrigation and cultivating three crops per year, Lingampally village (CENTURY)



Scenarios described in Table 24.

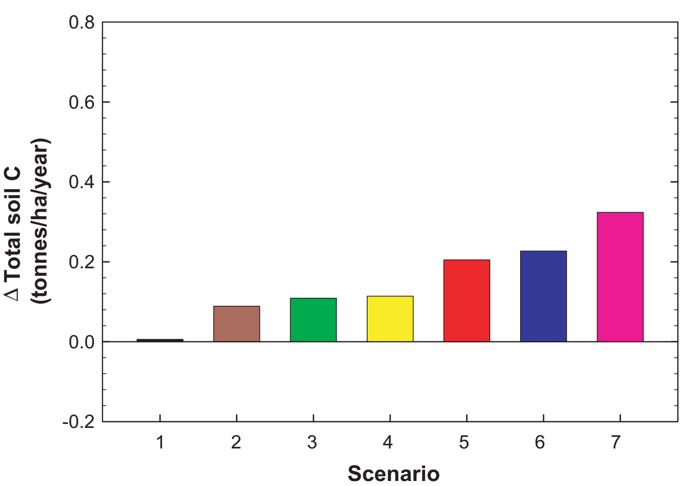
TABLE 24

Scenarios for modelling land management practices, large farm using irrigation Lingampally village

Scenario	Land management
1	Current practice
2	FYM 3 tonnes/ha/year
3	FYM 3 tonnes/ha/year green manure 500 kg/ha/year, vermicompost 250 kg/ha/year
4	As current practice but incorporate crop residues into soil
5	FYM 3 tonnes/ha/year, leave plant residues
6	FYM 3 tonnes/ha/year, plant residues, green manure, vermicompost
7	FYM 6 tonnes/ha/year, plant residues, green manure, vermicompost

FIGURE 22

Average annual change in total soil carbon for a large farm using irrigation, Lingampally village (CENTURY)



Scenarios described in Table 24

Effect of organic inputs

Adding 3 tonnes FYM/ha/year as per Scenario 2 (Table 24) would increase soil C by 4.4 tonnes/ha to 2050, sequestering 0.09 tonnes/ha/year (Figure 22). Including 500 kg/ha/year of green manure and 250 kg/ha/year of vermicompost (Scenario 3) would increase soil organic C by a further 1 tonne, sequestering 0.11 tonnes/ha/year (Figure 21). A similar increase in soil C can be obtained with no extra organic additions if only the grain is harvested and the crop residues are returned to the soil (Figure 22). When 3 tonnes FYM/ha/year is applied and only the grain harvested (Scenario 5), soil C increases by more than 10 tonnes/ha by 2050, equivalent to 0.20 tonnes/ha/year. Applying all the organic inputs and increasing the FYM component to 6 tonnes/ha would sequester 0.32 tonnes/ha/year.

Summary

A combination of leaving crop residues and adding manure could make a significant contribution to soil C in this kind of farming system, in which current practices have already caused a significant decline in soil carbon stocks. However, inorganic fertilizer and irrigation continue to have a carbon cost, resulting in smaller increases under the various scenarios. Additions of FYM can offset the nutrients applied in inorganic fertilizers. For example, removing inorganic fertilizer from Scenario 6 maintains yield without affecting soil C. Removing irrigation from the above scenario does not have a detrimental effect on soil C, but nor is there an apparent effect on yield.

iv. Analysis of land management for a small mixed crop and livestock farm, Metalkunta village, Medak District

This landholding of 2.7 ha has a very large variety of crops on lateritic red soil. Livestock are kept, a good cultivation pattern is practised and there are also many trees present around the farm. All aboveground produce is harvested so that crop residues can be fed to the animals. Cattle are also grazed on nearby land and fodder is brought in. The average yearly manure application is 2 tonnes/ha, and vermicompost is added to the land.

CENTURY was parametized with a sorghum–cowpea–millet–cowpea–maize–cowpea rotation to reflect the varied cropping pattern. The model was run with this scenario from the late 1960s. The model suggests that this system of land management would have approximately doubled the soil carbon content to nearly 25 tonnes/ha by 2000 and would reach 26 tonnes C/ha by 2050 (Figure 23). RothC predicts 25 tonnes C/ha in 2000 rising to 29.1 tonnes/ha in 2050 (Tables 25 and 26). This mixed cropping and livestock system has a substantial positive impact on soil C.

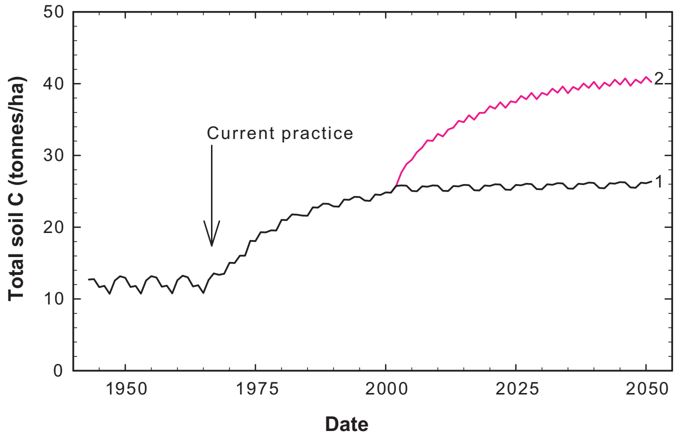
Effects of retaining crop residues

Returning crop residues to the soil (Scenario 2) would greatly increase the carbon content, sequestering 0.3 tonnes C ha/year in the next 50 years (Figure 24), with the soil carbon content reaching 40.9 tonnes/ha by 2050. RothC calculates that leaving crop residues would increase soil C to 49.2 tonnes/ha (Table 25).

Summary

The farmer is currently practising very good land management, and the models calculate that the soil carbon content has already been substantially increased. However, this is being accomplished in part by grazing cattle on other lands and bringing in fodder. This means that C is effectively being mined from elsewhere. Thus, although returning crop residues to the soil makes a further significant contribution to soil C, this would require importing

FIGURE 23
Total soil carbon for a small mixed crop and livestock farm, Metalkunta village (CENTURY)



Scenarios described in Table 26.

TABLE 25
Total soil carbon for a small mixed crop and livestock farm, Metalkunta village

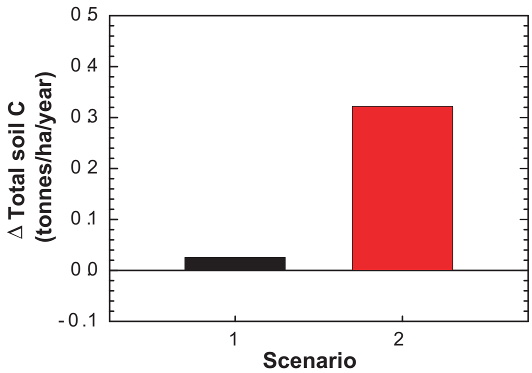
Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	24.9	26.1	5.2	25.0	29.2	16.7
2		40.9	64.7		49.2	96.6

* Scenarios described in Table 26.
Source: CENTURY and RothC.

TABLE 26
Scenarios for modelling land management practices, small mixed crop and livestock farm, Metalkunta village

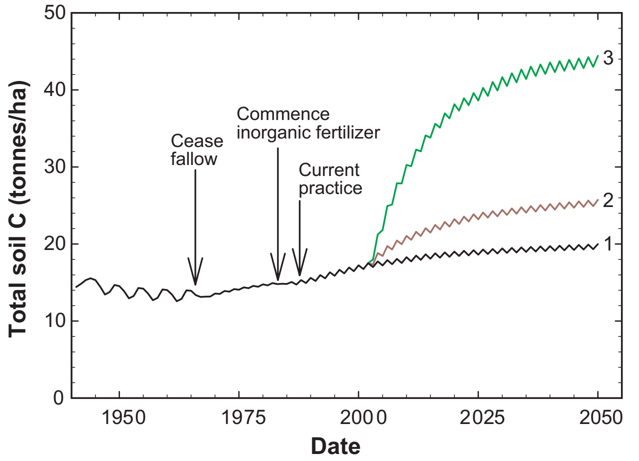
Scenario	Land management
1	Current practice
2	Leave plant residues

FIGURE 24
Average annual change in total soil carbon for a small mixed crop and livestock farm, Metalkunta village (CENTURY)



Scenarios described in Table 26.

FIGURE 25
Total soil carbon for a small farm, Malligere village, Tumkur District (CENTURY)



Scenarios described in Table 28.

TABLE 27
Total soil carbon for a small farm, Malligere village, Tumkur District

Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	17.24	19.97	15.8	19.82	24.32	22.7
2		25.73	49.2		34.2	72.6

* Scenarios described in Table 28.
Source: CENTURY and RothC.

TABLE 28
Scenarios for modelling land management practices, small farm, Malligere village

Scenario	Land management
1	Current practice
2	Replace inorganic fertilizer with FYM
3	Add trees, *Glyricidia*

more fodder to substitute for the plant residues, which again implies mining C.

v. Analysis of land management for a small farm, Malligere village, Tumkur District Karnataka state

This farm covers 2 ha on a red sandy soil. Tractors are hired for transport, livestock are kept and allowed to graze the crop residues, but additional fodder is brought in. The kharif crops modelled are sorghum and millet and the rabi crop is cowpea. On average, 3 tonnes/ha/year FYM is applied. Inorganic fertilizers are also used: 75 kg/ha/year of di-ammonium phosphate and 75 kg/ha/year of urea.

Modelling with CENTURY shows that current practices are increasing soil C and that this will continue to rise by a further 2.7 tonnes/ha in the next 50 years, reaching almost 20 tonnes C/ha in 2050 (Figure 25). RothC also shows that the current practice is increasing soil C but shows an enhanced effect. Soil C in 2000 is predicted to be 19.8 tonnes/ha, rising to 24.3 tonnes/ha in 2050 (Tables 27 and 28).

Effect of organic additions

Inorganic fertilizer has a carbon cost, so replacing the N supplied by the inorganic fertilizer with manure (annual addition 6.3 tonnes/ha) enhances the CS rate to 0.17 tonnes/ha/year. The soil carbon level reaches 25.7 tonnes/ha by 2050 (Figure 26, Scenario 2 in Table 27,). RothC predicts a much bigger effect on SOC of replacing the fertilizer with FYM: soil C is predicted to rise to 34.2 tonnes/ha by 2050.

Effect of trees

Adding trees such as *Glyricidia* to the system (Scenario 3), which are cropped annually for wood after ten years, makes a very large difference, increasing CS to 0.54 tonnes/ha/year (Figure 26).

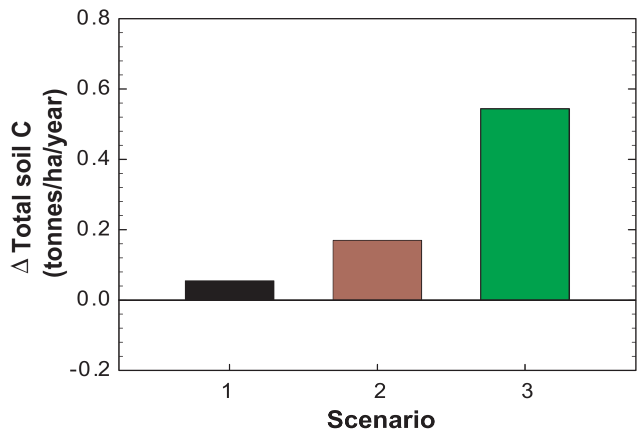
Summary

Both models show similar trends, with a switch from inorganic to organic fertilizer increasing soil C significantly. RothC predicts a larger increase. Cessation of inorganic fertilizer use would remove the negative carbon balance associated with its production, and the addition of trees may be sufficient to offset the inputs of C that arise from fodder grown outside the farm system. However, if tractors are used to transport fodder, the carbon budget for the system will probably be negative.

Conclusions from India cases

The modelling of farm data for the drylands of India shows that soil carbon stocks can be increased with a variety of technologies and practices available to farmers.

FIGURE 26
Average annual change in total soil carbon for a small farm, Malligere village, Tumkur District (CENTURY)



Scenarios described in Table 28.

It also shows that some practices result in substantial declines in carbon stocks, particularly the use of inorganic fertilizer as the sole source of nutrients, and the continuous cultivation of cereals. In the large (5 ha) mixed farm, inorganic fertilizer results in the loss of 0.1 tonnes/ha/year, whereas the use of either FYM, green manures, vermicompost and/or plant residues produces increases of 0.2–0.4 tonnes/ha/year. The use of agroforestry substantially increases belowground CS to 0.9 tonnes/ha/year.

The models show substantial declines in soil C on the small farms that cultivate only sorghum and those that intensively cultivate three irrigated crops per year – a loss of 5 tonnes C/ha in a 25-year period. However, it appears that these falls can be reversed within 5–10 years with the adoption of legumes in rotations, the addition of FYM manure and cultivation of trees.

The small mixed cropping farm, with cereals and cowpea rotations and livestock, increases soil C from a stock of about 13 tonnes C/ha to 24.8 tonnes C/ha in 25 years. It can increase this to more than 40 tonnes C/ha in the next 50 years if plant residues are added to the soil.

For full accounting of the C used or sequestered in these farms, it is important to consider the high energy cost of nitrogen fertilizer manufacture (65.3 MJ/kg for N, 7.2 MJ/kg for phosphorus, 6.4 MJ/kg for potassium) (Pretty *et al.*, 2002), the use of mechanized operations on farms, the cost of irrigation and mechanical transport, and the issue of the transfer of C in feed or livestock themselves from one farm to another or from grazing areas to cropped fields.

There are clear benefits for farmers and soil C if leguminous crops are included in rotations and in agroforestry systems.

Case study 3

Kenya – Makueni District

Arid and semi-arid lands occupy about two-thirds of Kenya (FAO, 1999b). The major factors limiting crop growth and production in these areas of Kenya are erratic rainfall, poor husbandry and declining soil fertility caused by continuous cultivation (Kenya Agricultural Research Institute, 1999). Drylands Research has examined the sustainability of farming systems in semi-arid Kenya, recording physical aspects of the environment together with land-management practices in four villages of Makueni District (Mbuvi, 2000). These span a range of settlement times from the 1950s to the 1970s. A major problem for farming in this region has been the frequency with which it has been affected by drought. Droughts reduce the returns that farmers receive and, consequently, provide little incentive for investment in soil fertility.

PHYSICAL ATTRIBUTES

The climate of this region is characterized by two rainy periods: the short rains, which deliver most precipitation in October–December; and the long rains of March–May. However, superimposed on the average annual rainfall (600–670 mm) is the periodic occurrence of drought (Gichuki, 2000). Annual mean temperature is in the range of 21 –24 °C. Elevation is 800–1 600 m, and the natural vegetation is grassland and dense shrub-land or woodland. Fires have affected the area in the past and the grassland is used for grazing. The soils are mostly Ferralsols (Rhodic and Xanthic) and are naturally low in phosphorus (Mbuvi, 2000).

FARMING SYSTEMS

Annual or multiple cropping is practised with occasional incorporation of one-year fallows, although the latter is becoming less common. Each year covers two cropping seasons. The main crops are maize and pulses, with millet and sorghum recommended as drought crops. Yields vary considerably between years depending on rainfall; on average maize will yield 1 tonne/ha, although some modern varieties yield 4 tonnes/ha of grain (Mbogoh, 2000).

The animal population is not large because it is difficult to supply adequate feed during periods of drought. Consequently, manure is in short supply and highly valued. Scarcity means that its application is often rotated. Little investment is made in the grazing lands, and the animals are usually kept in pens during the wet season. Very little fertilizer is used, especially as drought causes "burning" of the crops. Crop residues are burnt, fed to animals or ploughed into the soil. Tillage is accomplished by using simple ridging ploughs pulled by oxen; hand hoeing and digging are also common. Labour is in short supply and a constraint for farmers. A range of crop-residue management and tillage techniques are used to conserve moisture and to protect against soil erosion (Pretty, Thompson and Kiara, 1995; Gichuki, 2000).

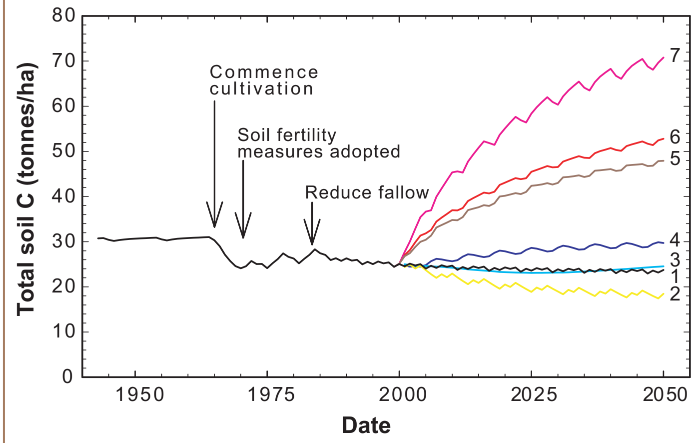
Woodland is being cleared, although selective clearance is often practised to save those species that provide useful products. Most farmers also plant trees, especially fruit trees and others such as mulberry for silk production (Gichuki, 2000). The study villages lie along a gradient of precipitation, decreasing from Kymausoi through Kaiani and Darjani to Athi Kamunyuni. CENTURY was run to equilibrium using a grassland–tree scenario with grass fires every ten years and major fires every 30 years.

i. Darjani

The primary crops for this settlement are millet, sisal, cowpea and sorghum and the natural pasture can support low intensity grazing. Settlement took place in the 1960s. The average soil carbon content of bush soils is 37.6 ± 7.5 tonnes/ha, and for cultivated soils it is 33.7 ± 2.8 tonnes/ha (Mbuvi, 2000).

Once run to equilibrium, CENTURY gave a value for soil C of 31.0 tonnes/ha in 1964. This is just within the range expected for bush soils. The model was then run for a further 35 years, reproducing the current land management. This commenced with a six-year cycle of alternate maize and millet crops for four years followed by fallow for two years. Cultivation was accomplished using a steel ridging plough and hand weeding was included. Crop residues were burnt. In 1971, FYM additions commenced, averaging 1.5 tonnes/ha over the six-year cycle as soil fertility and conservation measures began to be adopted. In 1983, the fallow period was reduced to one year out of six, and by 2000 the modelled soil C was 24 tonnes/ha (Figure 27). This reduction of 7 tonnes/ha from the level modelled for the uncultivated bush soil is greater than the decline of 5 tonnes/ha measured in the field. Continuation of this land-management practice is predicted to lead to a further loss of 1.3 tonnes C/ha by 2050 (Figure 27 and Tables 29 and 30).

FIGURE 27
Total soil carbon for Darjani settlement (CENTURY)



Scenarios described in Table 30.

TABLE 29
Total soil carbon for Darjani settlement

Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	25.04	23.74	-5.2	34.57	34	-1.6
5		47.92	91.4		59.3	71.5
6		52.79	110.8		65.67	90.0

* scenarios described in Table 30.
Source: CENTURY and RothC.

TABLE 30
Scenarios for modelling land management practices, Darjani settlement

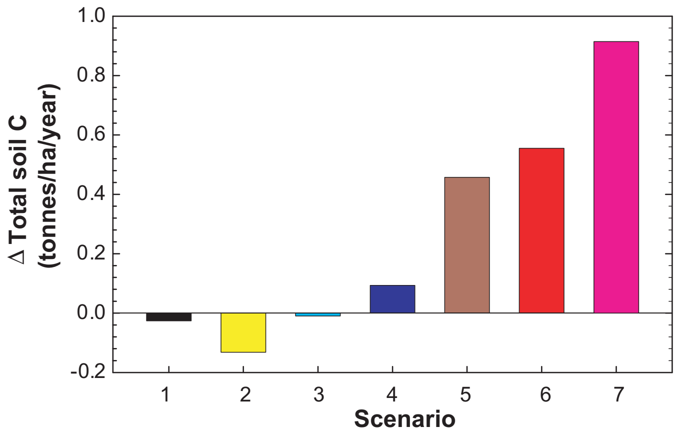
Scenario	Land management
1	Current practice
2	Remove fallow
3	Only inorganic fertilizer, burn residues, no fallow
4	Only inorganic fertilizer, burn residues, fallow
5	FYM 4.5 tonnes/ha/year, burn residues, fallow
6	FYM 4.5 tonnes/ha/year, do not burn residues, fallow
7	FYM 6.75 tonnes/ha/year, do not burn residues, fallow

RothC was run to equilibrium using the current level of bush soil C and then used to predict the effect of land management using plant inputs calculated by CENTURY. RothC predicted soil C to be 34.6 tonnes/ha in 1999, which is within 1 tonne/ha of the measured value. In the next 50 years, RothC predicts a further decline of 0.6 tonnes C/ha (Table 29).

Effect of fallow removal

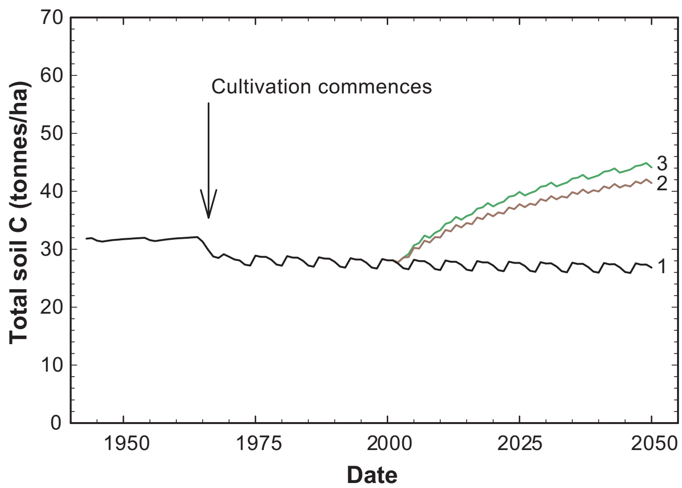
CENTURY predicts that removing the fallow from the current practice will result in a reduction in soil C (6.6 tonnes/ha) by 2050 (Scenario 2, Figure 27).

FIGURE 28
Average annual change in total soil carbon for Darjani settlement (CENTURY)



Scenarios described in Table 30.

FIGURE 29
Total soil carbon for Kaiani settlement (CENTURY)



Scenarios described in Table 31.

Effect of organic inputs

Adding an average 4.5 tonnes/ha/year FYM over the 6-year cropping-fallow cycle leads to a CS rate of 0.5 tonnes/ha/year (Scenario 5, Figure 28). If the crop residues are returned to the soil rather than burnt, a further 4.9 tonnes C/ha can be accumulated by 2050, representing a sequestration rate of 0.6 tonnes/ha/year (Figures 27 and 28). RothC predicts similar increases (Table 29). Increasing the FYM input to 6.75 tonnes/ha/year will increase the sequestration rate to 0.9 tonnes/ha/year (Figure 28).

Effect of inorganic fertilizer

Replacing all organic inputs with inorganic fertilizer (100 kg N/ha/year, Scenario 4) results in only a moderate increase in soil CS (0.09 tonnes/ha/year). However, the quantity of N applied is equivalent to about five times that which is added in FYM for the current practice scenario. If the fallow period is removed and only inorganic fertilizer added (Scenario 3), the system behaves very much like the current practice scenario in spite of the additional N.

Summary

The importance of FYM as an organic input is demonstrated, as is the return of crop residues to the soil rather than burning them. Although addition of inorganic fertilizer can increase CS, the increase in C per unit of N added is much less efficient than if FYM is added. The indirect energy embodied in manufactured N fertilizer is an additional carbon cost.

ii. Kaiani

The settlement of Kaiani has a farming system similar to that at Darajani. CENTURY underestimated the current bush content of soil C, yielding nearly 32 tonnes/ha compared with measured values of 41.5 ± 3.1 tonnes/ha. CENTURY was then run with a scenario to reflect the last 40 years of cultivation using a millet–cowpea system with grazing of plant residues and 4.5 tonnes/ha manure applied once in the six-year cycle. There was one year of fallow. Cultivation is calculated to have reduced soil C to 28.1 tonnes/ha by 2000, which compares with a measured value for cropped soil of 30.5 ± 4.8 tonnes/ha. Soil C is then predicted to decrease by slightly more than 1 tonne/ha in the next 50 years (Figure 29, Tables 31 and 32).

After parametization with the carbon content for bush soils, RothC shows very little effect of cultivation when using plant inputs calculated by CENTURY. Unlike CENTURY, this model predicts a slight rise in soil C by 2050 (Table 31).

Effect of organic inputs

Modest increases in the application rate of FYM (0.75 tonnes/ha/year to 2 tonnes/ha/year) result in quite marked accumulation of soil C (Figures 29 and 30). Adding additional plant residues further increase the sequestration rate to 0.3 tonnes/ha/year. RothC predicts very similar proportional increases in soil C (Table 31).

Summary

The models suggest that the current system is at or near steady state. It is possible to achieve reasonable rates of CS (0.3 tonnes/ha/year) with modest increases in organic manure inputs.

iii. Kymausoi

Kymausoi is situated in a marginal cotton zone where maize, pigeon pea and sisal are also grown. Cattle ranching is practised and the village was settled in the 1950s. The average soil carbon content for bush soils here is 38.4 ± 4.8 tonnes/ha, while for cultivated soils the average is 33.5 tonnes/ha with a range of 17.4–38.9 tonnes/ha. The CENTURY agro-ecosystem model was run to equilibrium and gave a bush soil-carbon level of 28.5 tonnes/ha in 1955, which is below the average concentration for soils in this area.

The model was then run to reflect the farming system since settlement commenced. This includes continuous maize cropping with grazing of the crop residues, and an average manure application rate of 0.75 tonnes/ha/year. Soil conservation and fertility management commenced in the late 1960s, the average annual manure

TABLE 31
Total soil carbon for Kaiani settlement

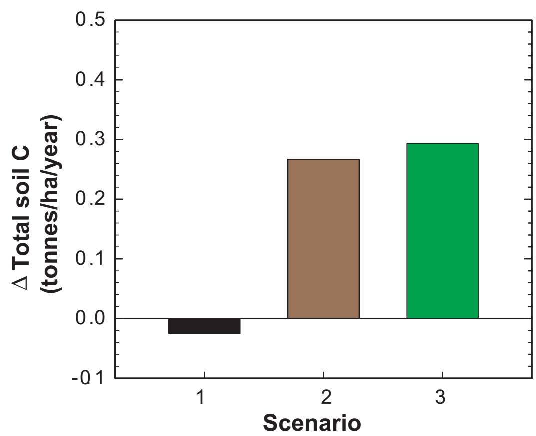
Scenario*	CENTURY 2000 (tonnes/ha)	CENTURY 2050 (tonnes/ha)	CENTURY % change	RothC 2000 (tonnes/ha)	RothC 2050 (tonnes/ha)	RothC % change
1	28.07	26.81	-4.5	42.32	43.89	3.9
2		41.4	47.5		62.82	48.8
3		42.73	52.2		65.16	54.3

*Scenarios described in Table 32.
Source: CENTURY and RothC.

TABLE 32
Scenarios for modelling land management practices, Kaiani settlement

Scenario	Land management
1	Current practice
2	FYM 2 tonnes/ha/year
3	FYM 2 tonnes/ha/year, plant residues 0.3 tonnes/ha/year

FIGURE 30
Average annual change in total soil carbon for Kaiani settlement (CENTURY)



Scenarios described in Table 32.

TABLE 33
Total soil carbon for Kymausoi settlement

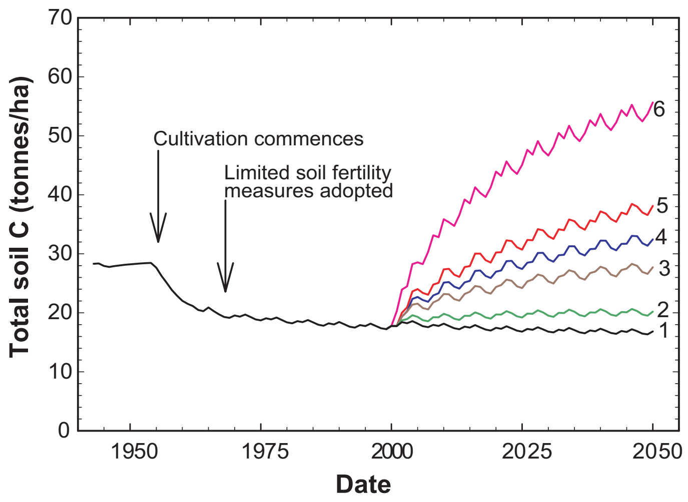
Scenario*	CENTURY 2000 (tonnes/ha)	CENTURY 2050 (tonnes/ha)	CENTURY % change	RothC 2000 (tonnes/ha)	RothC 2050 (tonnes/ha)	RothC % change
1	17.76	16.82	-5.3	35.69	34.79	-2.5
2		20.18	13.6		43.4	21.6
3		27.7	56.0		58.86	64.9

*Scenarios described in Table 34.
Source: CENTURY and RothC.

TABLE 34
Scenarios for modelling land management practices, Kymausoi settlement

Scenario	Land management
1	Current practice
2	Plant residues 0.3 tonnes/ha/year
3	FYM 1.5 tonnes/ha/year, plant residues 0.6 tonnes/ha/year
4	FYM 1.5 tonnes/ha/year, plant residues 0.6 tonnes/ha/year, legume (cowpea)
5	FYM 2 tonnes/ha/year, plant residues 0.6 tonnes/ha/year, legume (cowpea)
6	FYM 4 tonnes/ha/year, plant residues 0.6 tonnes/ha/year, legume (cowpea)

FIGURE 31
Total soil carbon for Kymausoi settlement (CENTURY)



Scenarios described in Table 33.

TABLE 35
Total soil carbon for Athi Kamunyuni settlement

Scenario*	CENTURY			RothC		
	2000 (tonnes/ha)	2050 (tonnes/ha)	% change	2000 (tonnes/ha)	2050 (tonnes/ha)	% change
1	23.75	23.45	-1.3	29.68	28.29	-4.7
2		29.09	22.5		31.40	5.8
3		29.77	25.3		42.76	44.1

*Scenarios described in Table 36
Source: CENTURY and RothC.

application rate being increased to 1 tonne/ha to reflect this. CENTURY estimated soil C to be 17.8 tonnes/ha by 2000, which is at the lower end of measured values. A decline of less than 1 tonne C/ha is predicted to occur in the next 50 years.

After being run to equilibrium for current bush soils and then parametized with plant inputs from CENTURY, RothC calculated a reduction of 3.4 tonnes/ha in soil C resulting from cultivation. Like CENTURY, it suggests a further decline of less than 1 tonnes/ha by 2050 (Tables 33 and 34).

Effect of organic inputs
Adding additional plant residues and increasing the FYM application rate to 1.5 tonnes/ha/year (Scenarios 2 and 3) will increase soil carbon levels by at least 50 percent (Table 33).

Effect of legume crop
Introducing a leguminous crop into the system, such as cowpea, can make a significant improvement in CS (Scenarios 4–6, Figures 31 and 32), increasing the rate from 0.2 to 0.3 tonnes/ha/year at the same rates of FYM application.

Summary
This example illustrates the advantage of including leguminous crops in the rotation. A farm system using 4 tonnes/ha/year of FYM, maintaining plant residues in the field, and with a legume in the rotation, can accumulate 0.7 tonnes/ha/year. The current practice is reducing soil carbon stocks.

iv. Athi Kamunyuni

This village is situated in a lowland agro-ecological zone. Ranching will only support a very low grazing density and the area is at the limit for rainfed production of millet, cowpea and sisal. The village was established in the 1970s. CENTURY was parametized for the commencement of cropping/grazing during the last 30 years. Millet was grown and an average of 0.75 tonnes/ha manure applied during the last six years.

The value for soil C modelled by CENTURY matched the current bush level (33.2 ± 3.2 tonnes C/ha). When settlement commenced, CENTURY calculated a decline in soil C of some 9 tonnes/ha over 25 years. Again, this is close to the actual measurements that show cultivated soils on average contain 24.0 ± 3.0 tonnes C/ha. Continuing this scenario into the twenty-first century suggests that the system has almost reached a new steady state (Figure 33). RothC calculates a smaller effect of cultivation on soil C, predicting a value of 29.7 tonnes C/ha in 2000, and a slight decline over the next 50 years (Tables 35 and 36).

Effect of organic inputs

Increasing the current average application rate of FYM from 0.75 tonnes/ha/year to 1.25 or 2.25 tonnes/ha/year (Scenarios 3 and 4) increases rates of CS by 0.12–0.37 tonnes/ha/year (Figures 33 and 34). Further additions of organic inputs, if available, could yield an increase in CS rates of up to 0.6 tonnes/ha/year.

Effect of fallows

Reducing the fallow period from two years to one year (Scenario 5) has very little effect on soil C providing the organic inputs are maintained. Using this location solely for ranching would result in an increase in soil C as the system returned to similar conditions that existed before cultivation commenced (Scenario 2). The rate of CS is very similar to Scenario 3, where an average of 1.25 tonnes/ha FYM was added annually. RothC predicts a much smaller increase in soil C on return to ranching. This reflects the fact that this model initially calculated a much smaller decline in total soil C following the commencement of cultivation.

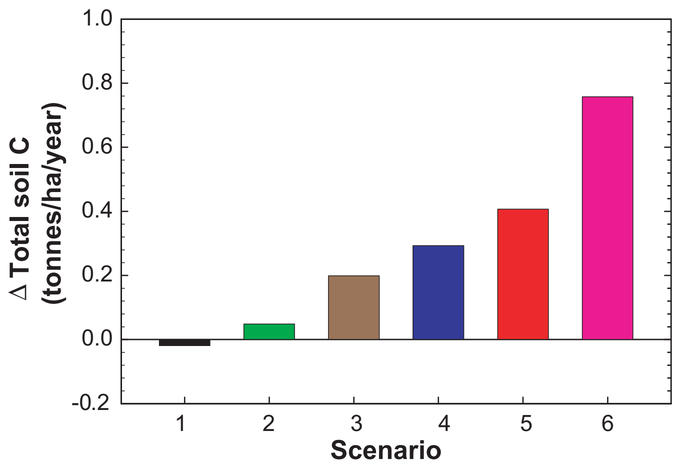
Summary

The level of soil C in this recently settled system could be restored to pre-settlement levels and then raised higher by the addition of FYM. Conditions at this location are not

TABLE 36
Scenarios for modelling land management practices, Athi Kamunyuni settlement

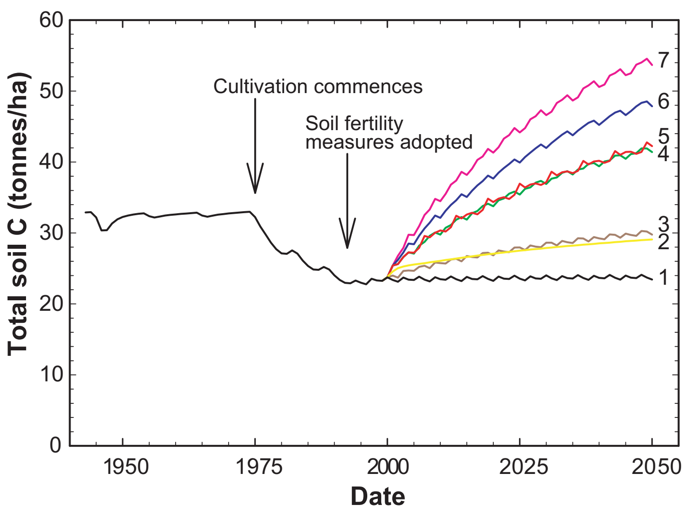
Scenario	Land management
1	Current practice
2	Grazing
3	FYM 1.25 tonnes/ha/year
4	FYM 2.25 tonnes/ha/year
5	FYM 2.27 tonnes/ha/year, fallow reduced to 1 year
6	FYM 3.3 tonnes/ha/year
7	FYM 3.9 tonnes/ha/year, plant residues 0.3 tonnes/ha

FIGURE 32
Average annual change in total soil carbon for Kymausoi settlement (CENTURY)



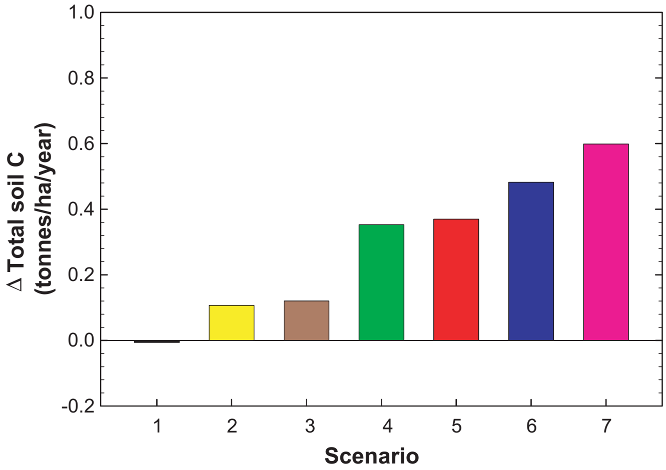
Scenarios described in Table 34.

FIGURE 33
Total soil carbon for Athi Kamunyuni settlement (CENTURY)



Scenarios described in Table 35.

Figure 34
Average annual change in total soil carbon for Athi Kamunyuni settlement (CENTURY)



Scenarios described in Table 36.

ideal for cropping and a return to a grazing-only system should also restore soil C to its pre-settlement level.

Conclusions from Kenya cases

The modelling of farm data from four communities in the semi-arid Makueni District again shows that carbon stocks can increase when a variety of technologies and practices already available to farmers are used.

Modest inputs of organic material in the form of FYM and plant residues can lead to CS, particularly where systems are currently at or near steady state for soil carbon stocks.

Removal of fallow periods from existing systems results in losses of 0.1 tonnes C/ha/year. Inorganic fertilizers are again an inefficient choice for plant nutrients when soil C is a concern. Burning plant residues is not desirable.

The combination of legumes in rotations, 2–4 tonnes/ha/year of FYM in addition to 0.6 tonnes/ha/year of plant residues, results in the highest rate of CS in all the dryland cases – 0.7 tonnes C/ha/year. At lower levels of FYM but with maintenance of fallows, combined with legumes in rotation, increases in soil C of 0.3–to 0.4 tonnes/ha/year can be achieved.

Case study 4

Argentina – Tucuman, Catamarca and Cordoba Provinces

In recent years, Argentina has experienced a rapid growth in the adoption of reduced and no-tillage systems, especially in dryland regions. This change has been brought about by a deterioration in soil quality and associated crop yields. Many local soils are not suited to the heavy tillage and cropping practices introduced by European settlers.

The Argentine Pampa now has very little natural vegetation. Xerophitic vegetation such as *Prosopis algarrobilla* and *Larrea divaricata* can still be found in the most arid areas. Agricultural practices commenced with the arrival of colonists in the sixteenth century. Ungulates were introduced to graze the grasslands, which have now been mostly re-sown. Very few trees remain except around farmsteads. Wheat was initially cultivated and row-crop production has increased with time. In many parts, grazed pasture was dominant until the 1990s but since then there has been a marked increase in the cultivation of summer annuals, such as maize, sunflower and soybean (Diaz-Zorita, Duarte and Grove, 2002). The Argentine Pampa has been recognized as a region with potential for increased production, if soils can be improved (Alvarez, 2001).

Crop yields have declined in many areas. These declines have been correlated closely with a reduction in SOM content (Diaz-Zorita, Duarte and Grove, 2002). This has prompted the need for change in existing land-management practices. The negative effects of heavy tillage on SOM led to the commencement of no-tillage experiments in the 1960s, in an attempt to produce a more sustainable agricultural system. Now some 13 million ha, or about half of the agricultural area in Argentina, is under some form of reduced-tillage system. Fertilization of crops is primarily achieved through the use of inorganic fertilizers, with organic material tending to be conserved for use in horticultural farming systems.

NO-TILLAGE MODELLING STUDIES

Three case studies are reviewed to model soil C under a variety of conventional and no-tillage systems in Tucuman, Catamarca and Cordoba Provinces.

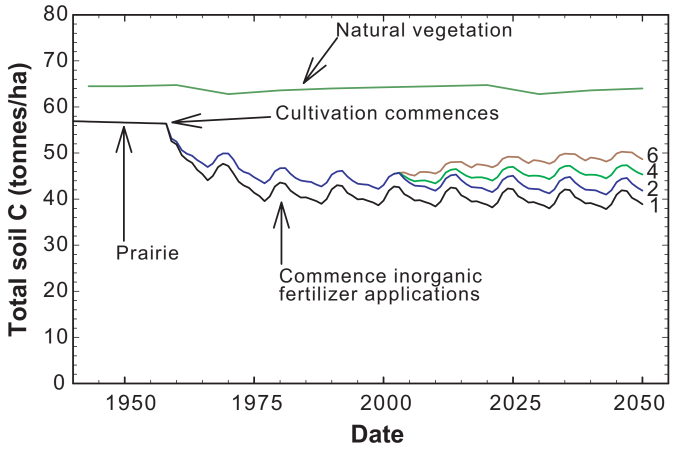
i. Monte Redondo, Tucuman Province

This is a semi-arid area that naturally supports xerophitic vegetation. The agricultural practices include grazed prairie lands and row cropping, the two systems often being rotated. The studied site consists of cropping for seven years followed by four years of prairie grassland. The crop sequence is wheat/soybean, maize, soybean, wheat/soybean, maize, soybean, wheat, and four years of prairie. Both conventional tillage and no-tillage cultivation are practised. In the tillage system, disc and chisel plough are used for soil preparation, while the no-tillage system uses the same cropping sequence without tillage.

After an equilibrium phase of grassland and trees, with fire every 60 years, CENTURY was parametized to run with improved prairie grassland from the mid-nineteenth century. The model predicts that the prairie system is losing C at the rate of 0.06 tonnes/ha/year under the current regime, but at stocks of 55.4 tonnes C/ha, it is overestimating the current measured level of 48.8 tonnes C/ha.

Cultivation is scheduled to commence in the 1950s (Figure 35). Fertilizer applications of 110 kg/ha urea begin in 1980. Two scenarios compare the effect of conventional

FIGURE 35
Total soil carbon for Monte Redondo (CENTURY)



Scenarios described in Table 37.

TABLE 37
Total soil carbon for Monte Redondo

Scenario*	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
	(tonnes/ha)			(tonnes/ha)		
Prairie	55.40	54.50	-1.6	43.95	43.21	-1.7
Tillage	40.43	39.27	-2.9	32.57	27.58	-15.3
No-tillage	43.64	42.23	-3.2	35.33	33.58	-5.0
5		48.23	4.4		41.89	18.6

*Scenarios described in Table 38.
Source: CENTURY and RothC.

TABLE 38
Scenarios for modelling land management practices, Monte Redondo

Scenario	Land management
1	Conventional tillage, inorganic fertilizer
2	No-till, inorganic fertilizer
3	No-till, FYM 1.5 tonnes/ha/year, inorganic fertilizer
4	No-till, green manure 10 tonnes/ha/crop, inorganic fertilizer
5	No-till, FYM 1.5 tonnes/ha/year, green manure 10 tonnes/ha/crop, no inorganic fertilizer
6	No-till, FYM 3.3 tonnes/ha/crop, no inorganic fertilizer

tillage with that of no-tillage. The model predicts a consistent difference between the two systems of less than 3 tonnes C/ha. This is less than the difference of 6 tonnes C/ha currently measured in the field. CENTURY predicts that this difference between the two systems will be maintained into the future, although both systems continue to lose soil C. The pattern of fall and rise in the soil C curve occurs because the crop part of the rotation results in soil C loss, while the return to prairie increases soil C.

RothC calculates lower levels of soil C but predicts a greater differential of 6 tonnes/ha by 2050, mainly through a higher loss of C from the tilled system (Tables 37 and 38).

Effect of no-tillage and organic additions

Additions of green manure (10 tonnes/ha/crop) or FYM (1.5 tonnes/ha each cropping year) to the no-tillage system both lead to increases in CS (Scenarios 3 and 4; 0.029–0.034 tonnes/ha/year) (Figure 36). A combination of these inputs without inorganic fertilizer yields a similar result (Scenario 5).

Cessation of inorganic fertilizer usage and using FYM as a replacement source of N results in the highest rate of CS (Scenario 6), 0.1 tonnes/ha/year (Figure 36).

Summary

Both models register the improvement that no-tillage has on soil carbon content. However, if the decline in soil carbon content is to be reversed, additional inputs of organic matter are required – either from FYM or use of green manures in the rotation. An increase in prairie in the rotation will also increase soil carbon stocks.

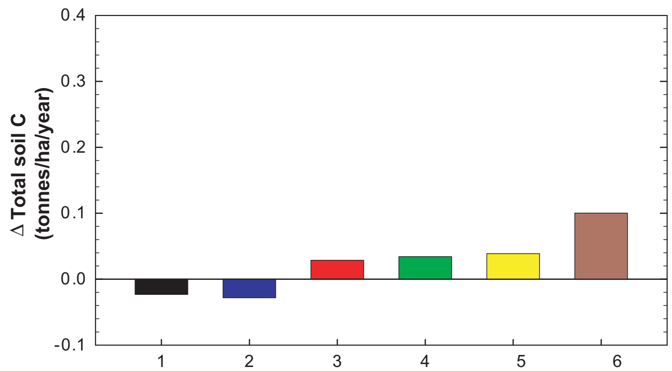
ii. Santa María River Valley, Catamarca Province

This is an arid region, with mean annual rainfall of 400 mm and temperatures in the ranging of 7–32 °C. The native vegetation is xerophitic consisting of creosote bush scrub (*Larrea divaricata*) and trees such as *Prosopis algarrobilla*. In cultivated areas, vines are grown and crops include alternate plantings of red pepper and barley. Measured soil carbon stocks are high in this district at 3.9 percent.

After reaching equilibrium with natural vegetation, CENTURY was run with a prairie scenario from the mid-nineteenth century and cultivation commenced in the late 1950s using conventional tillage (disc plough). A cotton–barley rotation commenced in 1980. CENTURY calculates that soil C had decreased to two-thirds of its initial value by 2000 (Figure 37). Measurements in the region confirm declines in soil C in cultivated areas of 33–66 percent. Therefore, the model estimate is at the top of this range. However, the system is predicted to reach a new steady state and the decline in soil C is estimated to be 3 tonnes/ha over the next 50 years.

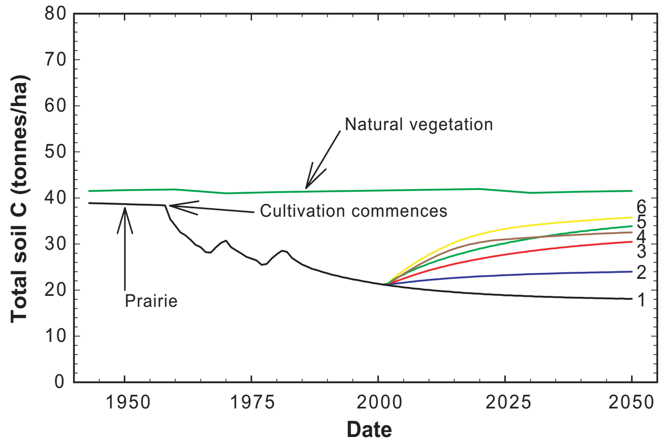
RothC, parametized with the higher, measured level of soil C and using quantities of plant inputs calculated from CENTURY shows a proportionately smaller effect of the current cultivation practice on soil C (Tables 39 and 40).

FIGURE 36
Average annual change in total soil carbon for Monte Redondo (CENTURY)



Scenarios described in Table 38.

FIGURE 37
Total soil carbon for Santa Maria (CENTURY)



Scenarios described in Table 40.

Effect of no-tillage

Adopting a no-tillage system not only halts the loss of soil C predicted by CENTURY. It also leads to a low sequestration rate of 0.05 tonnes/ha/year in the next 50 years (Figures 37 and 38). The RothC model is less sensitive to this scenario (Table 39).

TABLE 39
Total soil carbon for Santa Maria

Scenario*	CENTURY 2000 (tonnes/ha)	CENTURY 2050 (tonnes/ha)	CENTURY % change	RothC 2000 (tonnes/ha)	RothC 2050 (tonnes/ha)	RothC % change
Prairie	37.11	35.75	-3.7	70.68	74.71	5.7
Tillage	21.39	18.11	-15.3	51.46	47.36	-8.0
No-tillage		24.00	12.2		53.53	4.0
3		30.49	42.5		58.71	14.1

* Scenarios described in Table 40.
Source: CENTURY and RothC.

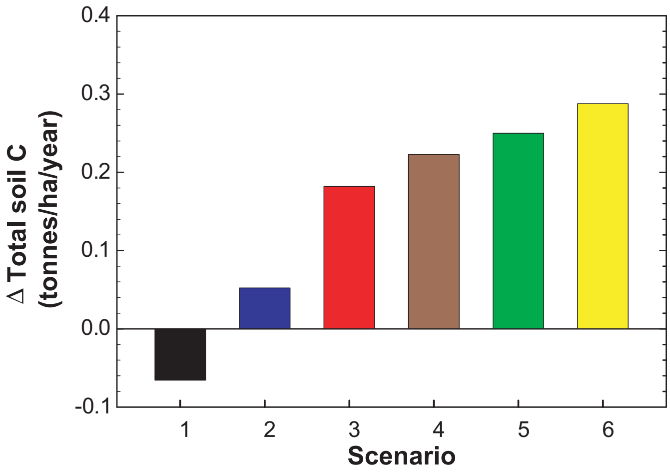
Effect of organic additions

Additions of FYM and green manure (Scenarios 3 and 5) both lead to marked increases in CS rates of 0.18–0.25 tonnes/ha/year (Figures 37 and 38). RothC again shows a smaller effect (Table 39).

Effect of inorganic fertilizer

Replacing inorganic fertilizer with FYM (Scenario 4) promotes CS (0.22 tonnes/ha/year). Combining the green manure and FYM applications gives the best carbon accrual rate, 0.29 tonnes/ha/year (Scenario 6, Figures 37 and 38). Inorganic N fertilizer is inefficient owing to the high energy cost of manufacture

FIGURE 38
Average annual change in total soil carbon for Santa Maria (CENTURY)

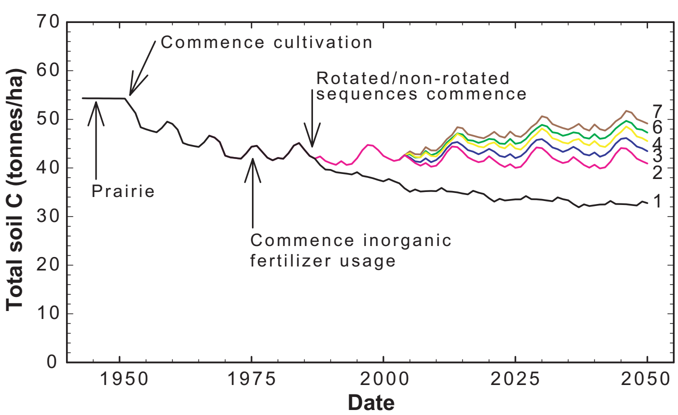


Scenarios described in Table 40.

TABLE 40
Scenarios for modelling land management practices, Santa Maria

Scenario	Land management
1	Conventional tillage, inorganic fertilizer
2	No-till, inorganic fertilizer
3	No-till, FYM 1.5 tonnes/ha/year, inorganic fertilizer
4	No-till, FYM 3.3 tonnes/ha/crop, no inorganic fertilizer
5	No-till, green manure 10 tonnes/ha/crop, inorganic fertilizer
6	No-till, FYM 1.5 tonnes/ha/year, green manure 10 tonnes/ ha/crop, no inorganic fertilizer

FIGURE 39
Total soil carbon for rotated and non-rotated plots (CENTURY)



Scenarios described in Table 42.

Summary

Both models suggest that adopting no-tillage will halt the decline in soil C. However, to increase CS, higher organic additions are necessary (green manures and FYM), which can be used to replace the inorganic fertilizer applications.

iii. Cordoba Province, Buenos Aires Province, and La Pampa Province

Following an equilibrium period with natural vegetation and subsequent prairie conditions from the mid-1800s, CENTURY was parametized with a cultivation regime commencing in the 1950s. This included a four-year cropping (wheat–soybean–maize–soybean) and a four-year prairie cycle with inorganic fertilizer applications (100 kg/ha urea) starting in 1985. In 1987, a rotated and a non-rotated cropping system was applied that is similar to cultivation practices occurring in the field. The rotated crop sequence was winter forage–soybean–maize–soybean–wheat–soybean–maize–four years of prairie and winter forage–wheat–soybean–maize–soybean–maize–prairie. The non-rotated crop sequence was similar but without the prairie interludes.

Modelled results for the non-rotated crop system show an initial steep fall in soil C to 37 tonnes/ha in 2000 and further losses over subsequent years (Figure 39). RothC estimates a proportionately larger fall from a higher base (Tables 41 and 42). The rotated crop–prairie system does not show the same sharp decline in soil C as the non-rotated system did and oscillates around a level of slightly more than 40 tonnes/ha (Figure 39). However, RothC estimates a slightly larger proportionate decline in C for the rotated crop system. Both models calculate smaller differences between the rotated and non-rotated cropping systems in 2000 compared with the difference of 8.5 tonnes/ha measured in the field.

Effect of no-tillage

The adoption of a no-tillage regime for the rotated-plots system increases soil C by 2.5 tonnes/ha in the next 50 years, representing a CS rate of 0.02 tonnes/ha/year (Figure 40). The rate increases to about 0.1 tonnes C/ha/year if green manures and FYM are used instead of fertilizers.

Effect of organic inputs

Additions of green manure and FYM with or without inorganic fertilizer can lead to CS rates of 0.06–0.13 tonnes/ha (Figures 39 and 40). Organic material can replace inorganic fertilizer successfully.

Summary

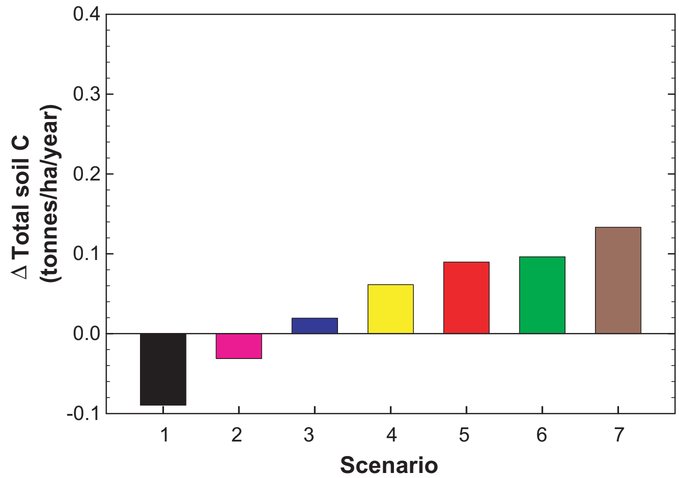
The inclusion of prairie interludes in the cropping system is an important factor for reducing the decline in soil C. However, the models show that no-tillage and organic inputs are required if C is to be sequestered in this system.

Conclusions from Argentina cases

The modelling of farm data from three dryland provinces of Argentina shows that carbon stocks have fallen substantially since the prairies were opened up for cultivation. At all three locations, there have been sharp falls in soil carbon stocks, with losses of about 15 tonnes/ha. However, the adoption of no-tillage systems in recent years has halted these declines and, on their own, resulted in small annual increases in soil C of the order of 0.02 tonnes/ha/year. Rotations with significant periods for return to prairie grassland (e.g. 4 years in 11) result in further increases in soil C.

The highest rates of sequestration (0.1–0.25 tonnes/ha/year) occur when no-tillage systems also include cultivation of green manures and additions of FYM.

FIGURE 40
Average annual change in total soil carbon for rotated and non-rotated plots (CENTURY)



Scenarios described in Table 42.

TABLE 41
Total soil carbon for rotated and non-rotated plots, modeled with CENTURY and RothC

Scenario*	CENTURY 2000 (tonnes/ha)	CENTURY 2050 (tonnes/ha)	% change	RothC 2000 (tonnes/ha)	RothC 2050 (tonnes/ha)	% change
Non-rotated plots	37.22	32.74	-12.0	50.61	41.17	-18.7
Rotated plots	42.47	40.91	-3.7	54.62	49.53	-9.3
4		45.54	7.2		62.86	15.1

*Scenarios described in Table 42.

TABLE 42
Scenarios for modelling land management practices, Santa Maria

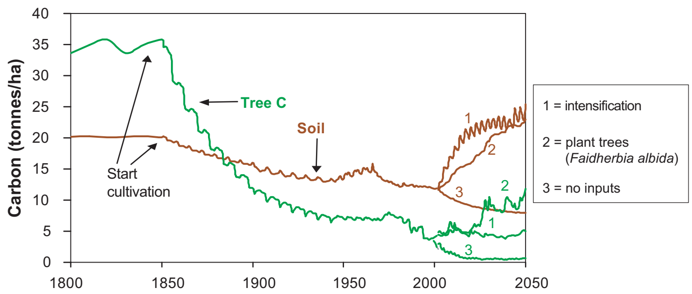
Scenario	Land management
1	Non-rotated plots, inorganic fertilizer
2	Rotated plots, inorganic fertilizer
3	Rotated plots, no-till, inorganic fertilizer
4	Rotated plots, no-till, FYM 1.5 tonnes/ha/year, green manure 10 tonnes/ha/crop, no inorganic fertilizer
5	No-till, FYM 1.5 tonnes/ha/year, inorganic fertilizer
6	No-till, green manure 10 tonnes/ha/crop, inorganic fertilizer
7	No-till, FYM 3.3 tonnes/ha/crop, no inorganic fertilizer

Case study 5

Senegal – Old Peanut Basin

FIGURE 41

CENTURY model simulation with a historic scenario based on undisturbed savannah grasslands to the current condition and the impact of selected management practices on soil and tree C, 2002–2050



Source: Tschakert (2004b).

The Senegal study area, the "Old Peanut Basin", is located in the west-central part of the country. The climate is semi-arid with annual precipitation ranging of 350–700 mm. Almost all arable land is used for rainfed agriculture, with millet, groundnuts, sorghum and cowpea as major crops. The rainy season usually lasts from July to September/October. However, both spatial and temporal variation in rainfall are high and episodic crop failures are not uncommon. The natural vegetation, including *Faidherbia albida* and various other tree species, has become heavily degraded, primarily because of a long agricultural history and increasing population pressure.

As described in Tschakert (2004b), CENTURY model simulations suggest that soil C in the study area decreased from 20.1 tonnes C/ha under a native savannah environment in 1851 to 11.9 tonnes C/ha in 2001. This indicates an annual loss of soil C of 0.055 tonnes C/ha/year. Tree C declined from 33.6 tonnes/ha to 4.2 tonnes/ha, corresponding to an annual decrease of 0.2 tonnes C/ha/year.

Under improved management conditions (assuming a 50–year period), soil C could increase by 0.3–13.5 tonnes/ha, or 0.006–0.27 tonnes/ha/year. C gains in trees could be tripled (from 4.2 to 11.8 tonnes/ha), assuming a conversion of croplands to grassland–tree plantations. Given the fact that most of the C gains are achieved in the first 25 years, annual increases for this time period range from 0.02 to 0.43 tonnes C/ha/year, which is higher than the estimates provided by Lal, Hassan and Dumanski (1999). Under poor management, in this case an annual millet–sorghum rotation with no inputs and permanent browsing and pruning of tree resources, both soil and tree C continue to drop, reaching an absolute minimum level of 7.9 tonnes/ha and 0.6 tonnes/ha, respectively (Figure 41).

Table 43 lists the various improved management practices with the anticipated changes in soil C over two time periods (2002–2026 and 2027–2050) as discussed by Tschakert (2004b). As illustrated, considerably higher gains in soil C can be achieved in the first 25 years, except for the tree-plantation scenario. However, in some cases, these gains cannot be sustained in the second twenty 25-year period, and losses would have to be expected if no additional inputs occurred. This is particularly true for the fallow scenarios.

TABLE 43
Effects of land management practices or land use on carbon sequestration potential in the Old Peanut Basin, Senegal

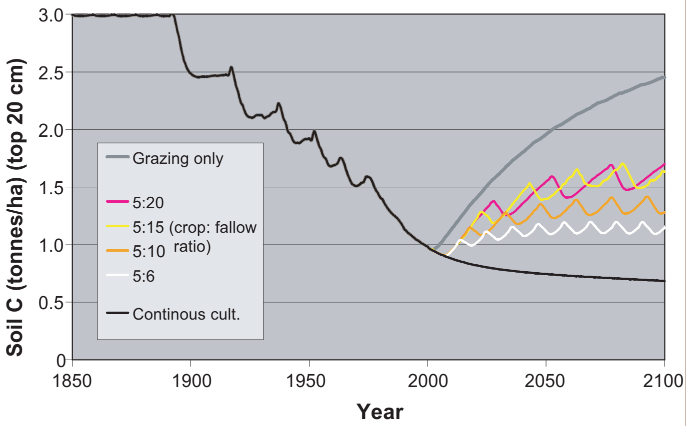
Technological options*	Change in soil C (tonnes/ha/year) 2001–2026 (first 25 years)	Change in soil C (tonnes/ha/year) 2027–2050 (second 25 years)
Compost (2t)	0.02	-0.01
Conversion of croplands to grasslands + grazing	0.06	0.02
3-year fallow + 2 tonnes manure in rotation with 4 years cropping	0.14	-0.05
Cattle manure (4 tonnes)	0.10	0.01
Conversion of croplands to grasslands	0.17	0.04
Cattle manure (4 tonnes) + min. fertilizer (250kg on millet; 150kg on groundnuts)	0.12	0.01
Sheep manure (5 tonnes)	0.13	0.01
3-year fallow + Leucaena prunings (2 tonnes) in rotation with 4 years cropping	0.18	-0.05
Conversion of croplands to grasslands with tree protection	0.10	0.04
Sheep manure (10 tonnes)	0.17	0.01
10-year fallow + 2 tonnes manure in rotation with 6 years cropping	0.25	-0.04
10-year fallow + Leucaena prunings (2 tonnes) in rotation with 6 years cropping	0.25	-0.04
Conversion of croplands to grasslands + tree plantation *(Faidherbia albida)*	0.23	0.21
Agricultural intensification (improved millet, manure, Leucaena prunings, min. fertilizer, animal traction, 1-year fallow)	0.43	0.11

* All technological options calculated for 1 ha. Annual rotation between millet and groundnuts for cropping scenarios.
Source: Tschakert (2004b).

Case study 6

Sudan – Northern Kordofan Province

FIGURE 42
Land-use change scenarios for the Sudan case study



Source: Olsson and Ardö (2002).

The study was undertaken in Northern Kordofan Province in the Sudan, an area dominated by coarse-textured soils of Aeolian origin, locally named *Qoz*. The study site is representative in terms of soils, climate and vegetation type for a large region stretching from the Atlantic coast to the Ethiopian highlands (Olsson and Ardö, 2002; Olsson and Tschakert, 2002).

The climate is semi-arid with annual rainfall ranging from less than 200 mm in the north to about 350 mm in the south. Land use can be characterized as a gradual increase in intensity with rainfall. In the northern part, only very extensive grazing by camels is possible owing to the lack of permanent water sources. Cultivation of mainly millet and to a lesser extent sesame and groundnuts predominates where rainfall and water resources increase towards the south. Grazing by cattle, sheep and goats is also an important factor in the cultivated parts of the area.

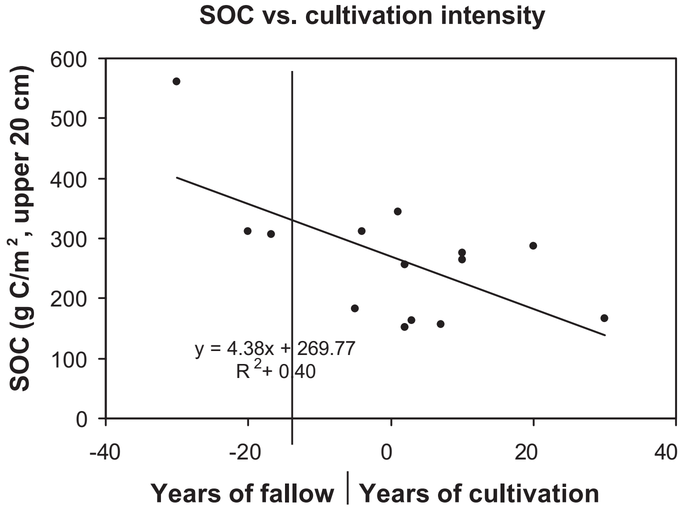
Interviews and literature indicate that land-use practices have changed markedly from a rotation system with long fallow periods (15–20 years), interspersed with short periods of cultivation (4–5 years), to more continuous cultivation in the last three to four decades. In the same period, crop yields have decreased, mainly because of a marked decline of rainfall but to some extent also due to the abandonment of fallow periods. Increased demand for food (as a result of population increase) combined with decreasing yields has forced farmers to extend their cultivated area primarily by reducing fallow periods.

In order to investigate the potential for increasing the soil carbon content through land-management changes, a number of future scenarios were simulated. First, the equilibrium level was established by running the model for 2 000 years with no land use, and then six different land-management scenarios were simulated for the period 2000–2100. The land-management scenarios were: continuous cultivation, crop-to-fallow ratios of 5:6, 5:10, 5:15, 5:20, and no cultivation but only grazing. Figure 42 presents the results of the simulations.

While the results in Figure 41 come from model simulations, the results in Figure 42 show the result of empirical research, using soil sampling, linking fallow periods to increased levels of SOC. In order to investigate the role of the length of fallow periods, fields in different stages of the crop rotation were sampled and their corresponding SOC levels were determined (Olsson and Ardö, 2002). The graph verifies to a large extent the model results and shows that there is significant potential for increasing SOC even in these dry sandy soils.

Figure 43 shows that increasing the length of the fallow periods, i.e. decreasing the crop–fallow ratio, causes an increase in the soil carbon content proportional to the ratio (i.e. longer fallow more soil C). A land-use change from millet cultivation to grazing is estimated to increase the soil carbon content from about 1.5 tonnes/ha to 2.5 tonnes/ha in 100 years. This is 82 percent of the equilibrium phase prior to millet cultivation. If millet cultivation is continued into the future, a further decrease in the soil carbon content is expected to 0.68 tonnes/ha in 2100. Changing the continuous cultivation to crop–fallow ratios of 5:6, 5:10, 5:15 and 5:20 will increase the soil carbon content according to Figure 42 to 1.15, 1.28, 1.63 and 1.70 tonnes/ha, respectively, by 2100.

FIGURE 43
SOC in relation to fallow and cultivation history in fields in Northern Kordofan Province in the Sudan

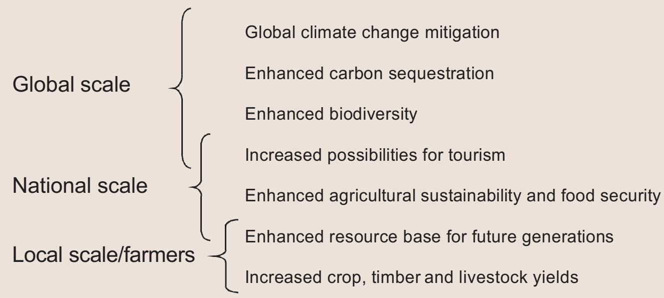


Source: Olsson and Ardö (2002).

Chapter 6
Carbon sequestration projects

The results obtained in the Senegal and Sudan case studies presented in Chapter 5 were analysed in order to illustrate some economic aspects of CS. Increasing soil C can yield local, national and global benefits. Figure 44 depicts these three levels. It also shows that these benefits can occur on an individual farm as increased crop, timber and livestock yields resulting from increased soil fertility, or in the form of off-farm social benefits on all three levels. On the local level, this second type of benefit constitutes an enhanced land and soil-resource base for future generations. Benefits on the national scale refer primarily to improved food security and agricultural sustainability. On the global level, anticipated benefits from improved soil carbon management are: enhanced biodiversity, increased carbon offsets, and climate change mitigation. Thus, CS in dryland soils could be a win–win situation.

FIGURE 44
Main benefits of improved soil carbon management at various spatial scales



Source: Izac (1997).

However, as stressed by Izac (1997), caution is required as the costs will be primarily local while the benefits will be local, national and global. From a cost/benefit perspective, it would be rational for farmers to manage their carbon resources with respect to on-farm benefits while ignoring the broad social off-farm benefits. In other words, in the absence of policy interventions and external financial support, local smallholders would use improved management practices at individually optimal levels but at socially suboptimal levels. The following sections provide an overview of the anticipated benefits and costs both from carbon trading (policy intervention) and from direct investment at local level.

BENEFITS FROM CARBON TRADING

One of the anticipated benefits for smallholders benefiting in CS schemes is the financial gain that could be achieved from carbon trading. Currently, carbon credit values as set by carbon exchange and trading systems range between US$1 and US$38 per tonne of C (FAO, 2001b).

In order to put the estimated gain from CS into the farmer's perspective, prices of agricultural products and assumed prices of C as a tradable good were compared for the Senegal and Sudan case studies. In both cases, farmers were assumed to use an improved management practice or an alternative type of land use on all their current croplands (Tables 44 and 45). Total amounts of croplands vary depending on the wealth status of the farming populations studied. Annual increases in C, as estimated by CENTURY, were assumed to generate US$15/ha, resulting in financial gains per group of households. These financial gains were then compared with the average value of food and cash crops that farmers would grow on these lands if no other alternative existed.

TABLE 44
Anticipated economic benefits from carbon trading (1 tonne C = US$15).

Management practice	C sequestration (tonnes/ha)	Annual gains poor HH (US$15)	Annual gains average HH (US$15)	Annual gains rich HH (US$15)	% of annual crop value
Compost (2 tonnes) .	0.02	0.73	1.93	2.28	0.2
Conversion of croplands to grasslands + tree protection	0.10	3.65	9.63	11.39	0.9
Cattle manure (4 tonnes) + chem.fertilizer	0.12	4.38	11.55	13.66	1.1
Sheep manure (10 tonnes)	0.17	6.20	16.36	19.36	1.6
Rotation 10-year fallow – Leucaena (2 tonnes) and 6 years crops	0.25	9.12	24.07	28.46	2.3
Agricultural intensification.	0.43	15.68	41.39	48.96	4.0

HH = households.
Source: Tschakert (fieldwork).

In the Senegal case, average farm sizes in the study villages vary between 3.2 and 15.5 ha, of which 2.8–8.9 ha are cultivated (Tschakert, 2004a). If C were sequestered on these lands following the management practices in Table 43, the potential financial gains from carbon trading would range from US$1.4 to US$31 per year. Such gains are expected to be significantly lower for poor households compared with average and rich households. This is because the poor households have less land that could be used for alternative management practices and/or land uses. As Table 44 shows, the maximum annual gains would amount to about US$16 for poor households, US$41 for average households, and US$49 for rich households. A comparison of the expected benefits from carbon trading with the actual value of millet and groundnuts (the main crops in the study area) indicates that the anticipated benefits would range from less than 1 percent to 4 percent of the annual crop values. These values are extremely low and, hence, highly unlikely to represent a sufficient financial incentive for smallholders to participate in a CS programme.

In the Sudan example, similar calculations on the potential economic importance of CS are rather different. Because of the larger farm size and lower economic inputs, CS could play a larger role.

Based on a census of two villages concerning landholdings and agricultural practices (Warren and Khatir, 2003), two categories of households were assumed for the calculation of the economics of CS: a rich household having 5 ha of millet and 2 ha of sesame; and a poor household having 5 ha of millet. If C were sequestered on these lands according to the CENTURY estimations above, the potential economic gain would be as shown in Table 45. At a price of US$15/tonne, the economic gain from converting cultivation to grazing land would be about 17 percent and 4 percent of the crop yield normally obtained by the poor and rich households, respectively. However, when costs and labour required to produce the crop are taken into account, the economic

TABLE 45
Annual economic gain from adopting land management changes for millet for different price levels of carbon

Management options (crop to fallow ratio)	C sequestration (kg/ha)	Annual gains poor HH (US$15)	Annual gains rich HH (US$15)	% of annual crop value (poor)	% of annual crop value (rich)
Grazing	15.00	1.15	1.56	16.6%	3.8%
05 : 20	7.20	0.55	0.75	8.0%	1.8%
05 : 15	6.50	0.50	0.68	7.2%	1.7%
05 : 10	3.00	0.23	0.31	3.3%	0.8%

HH= households
Source: Olsson and Ardö (2002).

gain from CS is much more significant. A study carried out in a neighbouring region (International Fund for Agricultural Development, 1988) showed that the economic gains from several crops were negative. On average, the study showed that only the income from watermelons and karkade gave a surplus while millet, sorghum, sesame and groundnuts all cost more to produce than the income from selling the produce. This economic comparison indicates that the level at which CS becomes economically important is very low for farmers in the Sudan case study.

The results from the two case studies suggest that the benefits from carbon trading per participating farmer are relatively low. An alternative to small individual cash income that should be considered during project negotiations with local smallholders and designated institutions might be new or improved communal infrastructure, such as schools, wells and health services.

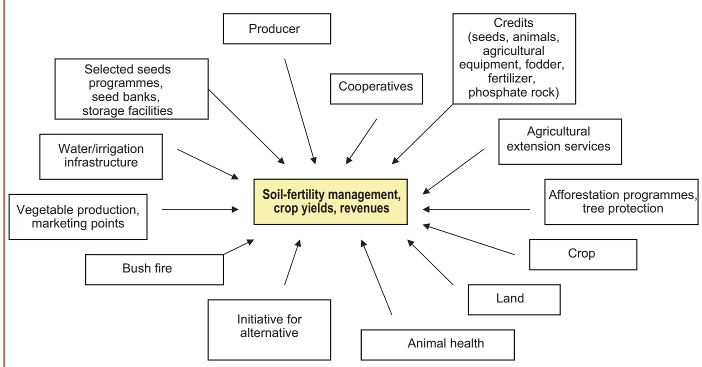
DIRECT LOCAL COSTS AND BENEFITS

Direct benefits for local smallholders are expected to occur at the field level primarily through increased soil fertility and crop yields that, in turn, will contribute to improved livelihood and food security at the national scale (Figure 45). Practices that involve animals for the production of manure can be combined with income generating activities, such as animal fattening and sale, also creating additional incomes. Switching from cropping to alternative types of land uses, such as grasslands and grazing lands, would free up agricultural labour, primarily during the main cropping season. Such gains in time and energy could be used for alternative, income-generating activities in rural and urban areas. Well-managed agroforestry systems are expected to generate incomes from controlled wood harvesting, seeds and the sale of fruit. However, such gains are unlikely to occur in the short term. In the case of N-fixing species, such as *Faidherbia albida*, positive impacts can also be expected on yields if they can be introduced into the fields.

On the cost side, the use of improved management practices or the shift from one management practice to another might include significant transaction costs. Today, the vast majority of smallholders in drylands are unlikely to have the necessary inputs to implement improved management practices as assumed with CENTURY. Costs at the local level would include the purchase of animals, fodder, agricultural equipment, and labour, depending on the actual resource endowment of smallholders interested in such a CS scheme. Farmers are also likely to demand compensation for foregone production on croplands converted to alternative land uses (grassland and grazing lands) and long-term fallow periods. As, in most cases, at least half of all croplands are used for subsistence crops, such compensation could occur in kind. A detailed cost–benefit analysis carried out for the Old Peanut Basin revealed significant differences in anticipated net benefits for 15 management options in crop-fallow systems, ranging from -US$1 400 to US$9 600/tonne C (Tschakert, 2004a). These differences are primarily the result of: differential resource endowments of farmers; highly unequal first-year investment costs; and maintenance costs over an assumed period of 25 years.

In addition to local transaction costs, CS schemes would also involve costs related to project design,

FIGURE 45
Policies affecting household economics and soil-fertility management



implementation, monitoring and verification. Costs for monitoring and verification might be substantial because direct soil sampling at the field level would be required in order to obtain reliable and effective results. As shown by Poussart and Ardö (2002), relatively high numbers of soil samples would be needed to detect differences in soil C with satisfactory confidence. In the case of semi-arid Sudan, at least 100 samples would be needed in order to detect a difference of 50 g C/m^2 90 percent of the time, testing at a significance level of 0.05. The value 50g C/m^2 corresponds to the average amount that could be sequestered in this area in 100 years. If monitoring and verification were to occur every ten years, the number of samples required would be at least ten times higher. Techniques to use remotely sensed imagery to assess carbon changes from the air exist, but they lack the precision to detect small-scale variation within farms and farming systems.

Given the results from the case studies, it can be concluded that substantial funds from development organizations or carbon investors will be necessary in order to make soil CS projects in dryland small-scale farming systems a reality. The expected benefits are probably insufficient to compensate farmers for costs occurring at the local level. In addition to these purely economic calculations, there is an ethical concern. Expecting local smallholders to adopt management practices at socially and globally optimal levels implies that they would subsidize the rest of society in their respective countries and as well as the global society, especially the large polluters in the North (Izac, 1997). Thus, institutional arrangements and policy interventions are perceived as crucial to rectifying this situation.

INSTITUTIONAL AND POLICY FACTORS

Policy factors

There seems to be increasing recognition among stakeholders, researchers and policy-makers that policies in blueprint format, including broad plans of action and universal solutions to a highly dynamic and diverse rural environment, are insufficient and might be counterproductive. As noted by Scoones and Chibudu (1996), efforts to collect more data and build more impressive models in order to construct a more precise picture of reality will not necessarily yield better policies. Only if the uncertainties and complexities of living in risk-prone dryland environments are taken seriously and are consciously integrated into policy formulation, will superior policies be possible.

If one of the main goals of CS in drylands is to contribute simultaneously to sustainable agriculture, environmental restoration, and poverty alleviation on a large scale and over a longer period of time, a more flexible and adaptive management and policy approach is needed (Tschakert, 2004a). Such a policy approach needs to be based on a more detailed understanding of farming systems. It should generate possibilities to strengthen farmers' own strategies for dealing with uncertainty while providing the necessary incentives to encourage successful pathways. Mortimore and Adams (1999) offer nine principles for inclusion into a new policy framework, all of which are of relevance for the success of anticipated CS programmes. These principles are:

- countering variability;
- promoting diversity in adaptive technologies;
- facilitating the flexible use of labour;
- enabling agricultural intensification (through closer integration of crops and livestock);
- multisectoral scope;
- promoting open-market conditions;
- alleviating poverty among vulnerable groups: poor households;
- alleviating poverty among vulnerable groups: women;
- reducing the impact of sickness.

As a starting point, it is necessary to understand current and historical links between policies and decision-making processes among smallholders. Of most relevance are policies with respect to agriculture, environment, and land-tenure arrangements. Especially in Sahelian countries, the deterioration of basic rural services that has occurred as a result of structural adjustment policies and State disengagement since the 1980s has had major impacts on farming systems. Figure 45 shows the range of policies that are likely to affect crop production, revenues, and soil management decisions at local level.

In addition to agriculture and environment policies, farmers' decision-making about possible pathways in farming-system strategies is, to a large extent, determined by access to and control over land, usually regulated by both formal and informal land tenure arrangements. It is critical to understand the extent to which official land tenure laws are enforced and, where not, how strong the influence of informal/customary arrangements might be.

One of the main concerns of potential investors in CS in drylands is insecure title to land. There is considerable debate as to what land tenure security means to local smallholders and whether or not supposedly insecure titles prevent them from making long-term commitments to and investments in improved land and soil management (Zeeuw, 1997; Kirk, 1999). Results from the Senegal study show that farmers perceive usufruct rights as sufficient to invest in "their" lands, although these lands are officially State-owned (Tschakert and Tappan, 2004). What is considered more important than an official title to the land is the possibility to engage freely and flexibly in long-term land transactions, including free loans, rental agreements and mortgages. Currently, the Senegalese law on land tenure (Loi sur le Domaine National) prohibits any type of transaction as well as non-productive uses of land (fallowing) exceeding the duration of one year. Thus, farmers are less inclined to use management practices with longer-term effects on land they will cultivate for no longer than one year. Where they have the means, they will probably buy fertilizers to extract as much as possible from this land in the short period of time allowed.

Thus, current farming systems have also to be seen as a result of land tenure arrangements. The notion of setting aside land for alternative land-use types (conversion of croplands into grassland or grazing lands, tree plantations, or improved and long-term fallow lands) needs to be understood in this context. The extent to which changes in land-use patterns for large-scale CS activities are feasible will depend on: the degree to which formal tenure arrangements are enforced; the perseverance of customary tenure arrangements; and the flexibility of social networks to circumvent one or the other.

Institutional arrangements

The "principle of subsidiarity" (Scoones and Chibudu, 1996) also needs to be included in a more flexible and adaptive management and policy approach. According to this principle, tasks related to CS programmes will have to be divided between various levels of decision-making. These levels range from institutions at the local level (farmers and farmers' organizations) to community and district-level institutions and service providers (rural and regional councils, extension services, and research organizations) and up to the national government, State institutions, and international agencies.

A long-term and large-scale CS programme that might include several thousand individual smallholders is unlikely to succeed if all programme decisions are taken following an interventionist, top-down approach. This kind of "macro control" is likely to disillusion local farmers and increase the risk that will opt out of agreements.

A first important step towards institutional integration is to identify already existing local and/or regional institutions that might be best suited to function as a vehicle for an anticipated CS programme. In addition to being trusted by the majority of smallholders, such an institution should be able and willing to: participate in the design of a local/regional programme; ensure the necessary participation of an aggregate of smallholders; guarantee a fair distribution of costs; coordinate monitoring and verification; and channel expected benefits in a most desirable and equitable way (Tschakert, 2004b).

Farmers in the Senegal case study defined the following requirements as key for an institution chosen to organize, mobilize and monitor local farmers participating in a carbon programme:

- capable of making a detailed assessment of all villages within their scope of influence, including all households, their food needs, farming systems, environmental conditions, land availability, and major constraints for agricultural development;
- capable of identifying the most promising as well as feasible land-management options and land-use changes for their land units with and without modifications in agricultural and environmental policies (subsidies and credits) and land-tenure arrangements;
- have sufficient influence to request changes in regional and national policies if considered essential;
- capable of identifying villages and households with a history of innovativeness and commitment (especially in terms of credit reimbursements);
- capable of ensuring a fair distribution of costs and benefits;
- capable of deciding for which purpose benefits and additional funds might be used best (rural infrastructure, environmental monitoring, etc);
- capable of ensuring the fulfilment of commitments by participating smallholders

CARBON ACCOUNTING AND VERIFICATION

Accounting and verification of the sequestered C is an integral component of a CS project. Accounting implies that all removals by sinks and emissions by sources of CO_2 must be recorded and accounted for. Verification implies that any net removals of CO_2 by sequestration in the soil or in the biomass must be verified through actual measurements.

Verification will usually be carried out by an independent organization. However, continuous monitoring of carbon losses and gains in the farming system must be an integral part of a project for which a designated local institution could be responsible. The overall procedure for verification is that a baseline survey is carried out before any project activities start and after a certain period of time, governed by a project contract. Another survey is carried out to verify any changes in the carbon stock.

Both baseline and follow-up surveys will make use of modelling and stratification as tools for improving the reliability and reducing the costs of surveys, but direct soil sampling will also be required. The number of samples necessary to verify changes in soil carbon stock over time is related to:

a. the spatial variability of the soil carbon stocks in the project area;
b. the minimum change of carbon stock that must be detected;
c. the statistical level of significance that must be obtained.

Table 46 and Figure 46 illustrate an example of the soil sampling required for verification (Poussart and Ardö, 2002). The study included three different but adjacent agricultural fields in the Sudan case study. The fields all had similar natural conditions in terms of soil, relief and climate, but different land-uses. The land use of the three fields were: cultivation of millet since 1996; fallow with trees for more than 20 years; and grazing only for 18 years. Table 46 shows the descriptive statistics for the three fields. Figure 46 illustrates the number of samples required to verify a change in carbon stocks for different levels of detectable difference and different levels of statistical significance.

RISKS AND UNCERTAINTIES FOR INVESTORS AND FARMERS

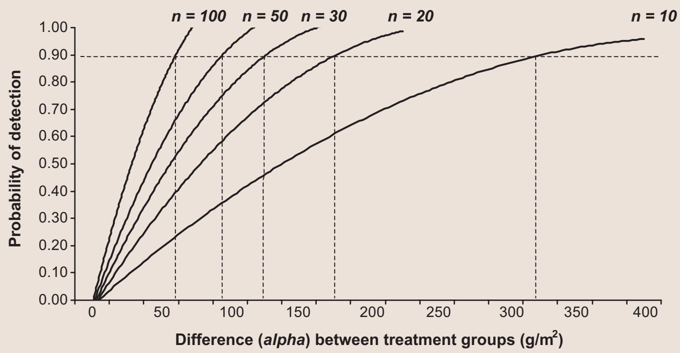
There are a number of predictable and unpredictable risks associated with CS activities (Bass and Dubois, 2000; FAO, 2002b; Tschakert and Tappan, 2004). These risks seem inevitable in a programme that has a long life span (25 years) and requires a large number of smallholders to participate in order to reach a total amount of C sequestered that is attractive to potential investors. Risks will have to be spread at various levels of decision-making. The efficiency of spreading risks will depend on the institutional strength of each organizational structure, ranging from farmers' associations to the top level of national governments and international organizations.

TABLE 46
Measured soil data for the experimental sites in the Sudan case study

	Cultivated	Fallow	Grazing
SOC, 0-20 cm, [g/m²] (n = 100)			
Mean ± standard deviation	519.2 ± 461.5	532.3 ± 455	411 ± 226.8
Median	374.7	426	367.9
Minimum, maximum	242.9, 3 716.3	239.5, 4 277.5	181.4, 2 303
Variance	212 952	207 043	51 425
Texture [%] sand, silt, clay	93.7, 3.6, 2.7	95.1, 3.0, 1.9	93.6, 3.2, 3.2

Source: Poussart and Ardö 2002.

FIGURE 46
Probabilities of detecting differences for different sample sizes



Note: The dotted lines indicate the differences detectable 90 percent of the time with a Kruskal-Wallis test (testing at significance level • = 0.05) for five sample sizes (n = 10, 20, 30, 50 and 100).

Risk of reversal

Gains from certain management practices or changes in land use can be reversed as soon as they are interrupted or abandoned. This might occur either as a consequence of natural hazards or shocks (droughts, wild fires, climate change, etc.) or of farmers' conscious decision to opt out of an agreed-upon scheme. Factors that discourage or hinder farmers from fulfilling their agreements could include:

- more promising economic alternatives for a piece of land;
- lack of means to continue practices (labour, land and capital);
- more lucrative economic activities outside agriculture;
- lacking confidence in the institutional arrangements set in place;
- insecurity of land-tenure arrangements;
- changes in market prices for agricultural products;
- changes in national and regional policies (e.g. removal of subsidies, changes in land-tenure arrangements, new regulations required by external agencies such as the World Bank);
- changes related to international interventions and carbon-trading schemes.

Inaccuracy of baseline data, monitoring and verification procedures and tools

Imprecise data at the beginning, during, and at the end of a project could underestimate or overestimate the actual benefits that local smallholders and the society as a whole will obtain from sequestration activities. Additional previsions need to be made in order to take account of uncertainties in the carbon storage potential.

Confusion of priorities and goals

Conflicting interests between carbon buyers, sellers and sequesters might undermine a successful project design and implementation. Donors and investors are more likely to focus on carbon-maximizing management practices while local smallholders are more likely to perceive CS as an additional tool in their risk management portfolio with the ultimate goal of improving their adaptive mechanisms in a risk-prone environment rather than carbon balances. This might imply that a specific piece of land receives a combination of carbon-increasing, carbon-stabilizing, and even carbon-decreasing practices alternating during the entire duration of a project, depending on the overall dynamics of the farming and livelihood system in question.

Unsuccessful implementation of an institutional structure

It is unlikely that a project involving a large number of smallholders over a long period of time could operate successfully without a strong, respected and trusted local or regional institution. Such an institution will organize, mobilize and monitor farmers' participation, and ensure compliance with the project agreement and fair remuneration among all participants. Thus, sufficient time and care will need to be devoted to the selection or creation of such an institution.

Increased inequality among local stakeholders

Projects have a tendency to focus on the most interested, motivated and innovative farmers as potential participants simply because project success rates in the short run are likely to be higher. These farmers are often the ones that have the largest resource endowment and face the smallest risks and, thus, are more likely to adopt new practices. Those who most need the benefits of CS because they are the most disadvantaged and face the highest risks are often left out because they are more reluctant to participate. In order to minimize the risk of increasing inequality among rural populations, this "innovativeness–needs paradox" (Rogers, 1995) will need to be taken into account. If one of the ultimate goals of CS is to improve rural livelihoods, distinct incentives will have to be made available to include the economically weaker groups of farmers (Tschakert, 2004a).

Non-approval of "additional activities" for developing countries

CS in soils is not eligible during the first commitment period (2008-2012) of the KP. Although political pressure to include it at least under the second commitment period is increasing, there is no guarantee that financial support for soil carbon projects will be available through the United Nations Framework Convention on Climate Change (FCCC) in the future.

PLANNING, DESIGNING AND MANAGING CARBON SEQUESTRATION PROJECTS

In order to plan, design, implement, monitor and manage a CS project, a number of stages of work must be carried out. Figure 47 presents a conceptual model of these stages.

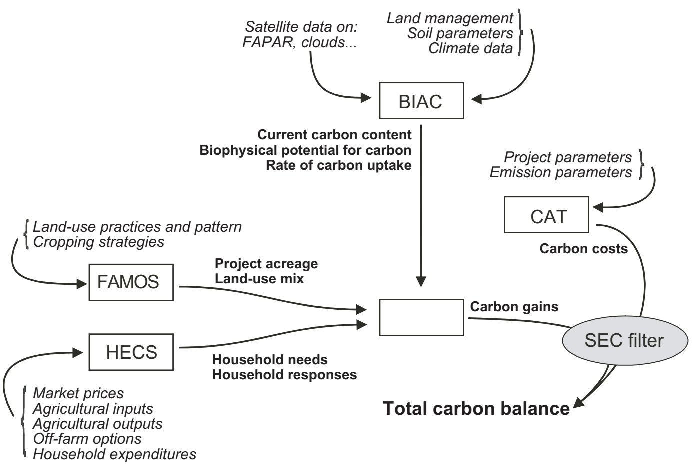
The components in Figure 47 would need to be developed as system models by which different planning scenarios could be tested before implementing projects. In detail, the different components are:

- Biogeochemical analysis of carbon balance (BIAC). The BIAC model, driven by various biophysical variables and remote-sensing data, will yield information on the biophysical potential to increase the storage of soil C, given information on GPP, climate, soils and management.
- Farmers management options for sequestration (FAMOS). This component will be a model of how land and management practices are used in a village framework. The model outlines the likelihood of different groups of farmers to intensify

certain portions of their land while putting others into fallow or pasture, depending on a multitude of factors (e.g. labour availability, alternative sources of income, access to credit to cover transaction and opportunity costs, agronomic practices, and land tenure rights). The outputs are the amount of land dedicated to different use, and the rate of conversion.

- Household economics of carbon sequestration (HECS). This component models the economic performance of a household both with and without CS. The model yields information about how financial inputs and outputs from new land uses might be distributed in households and between households. A first prototype has been developed and tested in Senegal and the Sudan (Olsson and Tschakert, 2002).

FIGURE 47
Conceptual model of the stages involved in planning a carbon sequestration programme



BIAC = *biogeochemical analysis of carbon balance*, FAMOS = *farmers management options for sequestration*, HECS = *household economics of carbon sequestration*, PROMIS = *project management for increasing soil carbon*, CAT = *carbon accounting tool*, SEC filter = *sustainability and equity criteria*.

- Project management for increasing soil carbon (PROMIS). This model will use data from the models above to simulate the rate at which farmers and villages can be induced to participate in a carbon-sequestering project. It will need additional data on how quickly farmers and villages can be contacted by the project (primarily through existing institutional networks), how many staff and what infrastructure are needed in this process, etc.
- Carbon accounting tool (CAT). Project accounting in terms of sources and sinks of CO_2 is vital. This component will compute the total carbon balance of a project. The data are necessary for defining any contract with investors.
- Sustainability and equity criteria (SEC) filter. As the main objective of the project is to improve the lives of poor farmers, any solutions suggested by other means must be tested against criteria for their contribution or otherwise towards more sustainable and equitable agricultural systems.

PHASE I
PROJECT SELECTION

Phase I includes the collection of data necessary for selecting a target area and for modelling various CS scenarios. This process is an iterative dialogue between biophysical and socio-economic inquiries. The iterations might be:

i. Socio-political criteria to select a broad zone of interest: For example, selection of communities in need of development, using criteria such as productivity and income. A major political unit might be selected.

ii. Collection of biophysical data for this zone: Data on soil, rainfall, biomass, etc from database, map and remote-sensing sources. These data should be sufficient to run models of biophysical potential:

- Initiation of models with these data: The biophysical potential to increase soil carbon content is a first prerequisite for a project. This is mainly addressed in the BIAC component of Figure 47.

- Data on land-use categories and distribution (or relative importance): The data for these surveys can come from published sources, remote-sensing surveys, and some ground traverses. These data can then be used with the initial models to produce carbon projections for different land-use scenarios. These scenario models need to be verified with sample data from the ground.
- Preparation of a portfolio of possibilities for land-use change: These possibilities should be ranked according to carbon-sequestration potential. When summed in various combinations and compared with target quantities, such a portfolio provides target figures for proposed types of land-use change.
- Sampling questionnaire surveys to determine the total area of a possible project: The area will depend on the probable number of participants, the rate at which they might join the project, and the mix of land-use changes that may occur: longer fallow periods; total withdrawal of land from cultivation; increase/decrease in irrigated area; and increase/decrease in use of fertilizers.

PHASE II
SELECTION OF PROJECT AREA AND PERSONNEL

The first process in Phase II is the selection of a particular project area, using the criteria developed in Phase I. Selection will be both political/administrative process and a technical process.

Having selected an area, the next step is to set up a local management committee and a technical team. This close-coupled system must then design the details of a project

PHASE III
PROJECT DESIGN

Recalling that dryland farming systems are diverse, complex and risk averse, the design of a CS project should fit into the farming system and add components that farmers perceive as valuable. It is important for any CS project to provide a range of income opportunities both in farming and non-farming activities (e.g. processing local produce, manufacturing and services). Local value-added processing may be an important component for achieving a range of benefits, e.g. improved terms of trade, income opportunities, reduced transport costs, and provision of useful by-products.

The kind of components which a CS project may offer can be structured as credit facilities and re-compensation facilities for farmers who have signed up for the project and general services to the entire community:

- Credits: Credit facilities should provide fair and equitable credits to farmers for investments that benefit CS, such as tree planting, animals, improved stoves, equipment and buildings.
- Re-compensation: Re-compensation should provide compensation to farmers for production foregone until the incomes from the CS investments are realized.
- Services: Services should allow farmers to adopt CS activities and to reduce risks associated with these activities, such as veterinary services, training and extension, health services, water supply, energy supply, range management, marketing, and liaison with authorities.

A CS programme should ideally be combined with other GHG management activities in order to reduce current and prevent future GHG emissions. Such activities would contribute to the sustainable development of the entire community. Some examples are:

- Provision of electricity to vital social institutions, such as schools, clinics and water supply, possibly provided by solar and wind power. Such devices are economically viable in a longer term, but their implementation must be supported by credit and insurance facilities. Carbon emissions could be reduced if diesel-powered devices were replaced.

- Where quantities of biomass fuel for cooking used in a community exceed the annual re-growth of vegetation, there is a net emission of C. Furthermore the use of crop residues may impoverish the soils. Replacing open fires with improved stoves or by biogas from fermentation of organic waste (such as household waste or animal dung), will reduce CO_2 emissions. Reductions in fuelwood burning can also reduce the hazard of smoke, ranked by the World Health Organization as one of the major hazards to health worldwide.
- In a GEF-funded pilot project in Sudan, it was found that up to 50 percent of the quantity of fuelwood could be saved by using improved clay stoves (UNDP, 1999). The stoves were manufactured locally from local material (mud-dung paste). They used less fuel for the same result, and shifted sources from trees and branches to plant litter. The stoves were adopted by 90 percent of the households. Table 47 indicates the effect on fuelwood consumption in these households.

TABLE 47
Average fuelwood consumption from households in the Sudan pilot project before and after adopting the improved stoves

Fuelwood consumption	Before adoption	After adoption
> 4.5 kg/day	60%	0%
4.5 kg/day	26%	0%
3 kg/day	10%	0%
1.5 kg/day	3%	41%
< 1.5 kg/day	0%	59%

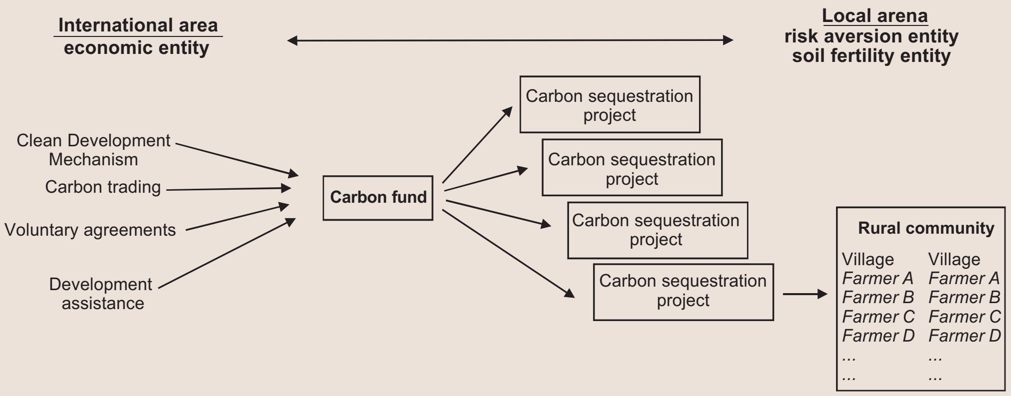
Source: UNDP (1999).

The total annual consumption of fuelwood in the project area dropped from 1 836 tonnes to 432 tonnes between 1995 and 2000. Labour formerly used in fuel collection became available for productive use in agriculture and off-farm activities.

PHASE IV
PROJECT IMPLEMENTATION

In this phase, the necessary infrastructure for a functioning project needs to be established. A crucial part of this will be to create the necessary linkages between the international arena, where policies are formulated and where decisions are taken, and the national/local arena where the project is being implemented. In the international arena, C is generally seen as a tradable commodity, valued in monetary terms, while at the local level it is seen as a biophysical entity that has many different functions and is valued in many ways (Figure 48). A carbon fund, such as the BioCarbon Fund or the Community Development Carbon Fund (see below) might function as the required link between the local and international arenas.

FIGURE 48
Conceptual frame for linkages between the international and local arenas



PHASE V
MONITORING AND MANAGEMENT

Monitoring and adjustments must be an integral part of any CS project. A local management committee or an entrusted local/regional institution will have to play a critical role in this phase of a carbon project. Through adjustments and continuous negotiations, it will have to ensure that all elements of a carbon contract are fulfilled, including number of participating farmers, selected management options, fair distribution of credits and compensation, equal access to services, etc. Efficient monitoring will also require a control case ("business-as-usual scenario") to which the effects of adopted management options or altered land-use patterns can be compared. Such a control case could be based on empirical and controlled experiments (control plots) that should be fairly simple, yet representative for the project area and carefully described. The purpose is to have controlled reference areas where it is possible to document what actually happens to soil C/soil fertility while implementing certain strategies. These experiments could be a type of "management truth", also maintained by a selected project/local management committee.

POLICY AND FUNDING FRAMEWORK FOR CARBON SEQUESTRATION AND POVERTY ALLEVIATION IN DRYLANDS

The idea of CS for poverty alleviation is based upon the fact that carbon management can be seen as the centre of several international regimes. The FCCC stated as its main objective: "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*". The subsequent CCD is concerned that extensive land degradation in drylands in specified areas, which might otherwise be productive, has been rendered unsuitable to meet the needs of the population. This process of land degradation also means that C otherwise stored in these ecosystems has been lost and added to the atmosphere in the form of GHGs (mainly CO_2 and CH_4). Thus, the CCD and FCCC with the KP share a common goal: the proper management of C. Moreover, land-use change, agriculture and forestry activities recognized by the KP are also closely linked to the CCD and CBD, although the KP does not explicitly address its relation with these.

The FCCC was itself constructed with issues of desertification in the minds of the Parties' negotiators. The Preamble recalls:

> "*the pertinent provisions of General Assembly resolution 44/172 of 19 December 1989 on the implementation of the Plan of Action to Combat Desertification*,"
> a forerunner to the CCD. The Parties further recognized that:
> "*countries with . . . arid and semi-arid areas or areas liable to floods, drought and desertification, and developing countries with fragile mountain ecosystems are particularly vulnerable to the adverse effects of climate change*".

More significantly, under Articles 4.8 (c) and 4.8 (e), the Parties to the FCCC are to:

> "*give full consideration to what actions are necessary ..., including actions related to funding, insurance and the transfer of technology, to meet" the developing countries' specific needs arising "from the adverse effects of climate change, ... especially on: ... (c) countries with arid and semi-arid areas .. : [and] .. (e)countries with areas liable to drought and desertification*[.]"

A more broadly worded FCCC requirement, which could be interpreted to be effective in bringing together the more diverse activities contemplated under the CCD, is Article 4.1 (d) and (e): all Parties shall:

- *(d) Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems;*
- *(e) Cooperate in preparing for adaptation to the impacts of climate change; develop*

> *and elaborate appropriate plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods[.].*

Thus, the CCD and the FCCC are linked and this connection provides a conceptual basis for fulfilling compatible goals.

THE CLEAN DEVELOPMENT MECHANISM OF THE KYOTO PROTOCOL

The KP provides one mechanism that can potentially provide an avenue for agricultural CS programmes involving developing countries of the kinds discussed in this report: Article 12, often referred to as the Clean Development Mechanism (CDM).

The CDM is the only one of the three flexible mechanisms that explicitly addresses developing countries. The purpose of the CDM is to assist developing countries in achieving sustainable development and at the same time to assist developed countries in fulfilling their commitments under the KP. However, in the first commitment period of the KP, there is an important restriction for inclusion of CS in the CDM. This is that the eligibility of land use, land-use change and forestry project activities is limited to afforestation and reforestation (Article 12, Paragraph 3b and Article 3). Their treatment in future commitment periods will be decided as part of the negotiations on the second commitment period. It also necessary to decide on how to treat the storage of belowground C.

Another characteristic of the CDM, restricting its application to many drylands of developing countries, is the complicated procedures for CDM projects and the required scale of projects. Most CDM projects have been very large, too large in fact for the often poor institutional capabilities of some African countries. However, there was an important modification to the CDM statutes in January 2003. This now allows small-scale and bundles of small-scale CDM projects. It also includes simplified requirements for baseline surveys and the monitoring of project achievements.

Simplified baseline and monitoring methods have been defined for 14 small-scale CDM activities grouped into three types of projects as shown below:

- Type (i) projects: renewable energy projects with a maximum output capacity equivalent of up to 15 megaWatts (or an appropriate equivalent). Eligible activities are:
  A. Electricity generation by the user/household;
  B. Mechanical energy for the user/enterprise;
  C. Thermal energy for the user;
  D. Electricity generation for a system.
- Type (ii) projects: energy-efficiency improvement projects that reduce energy consumption, on the supply and/or demand side, by up to the equivalent of 15 gigaWatt hours per year. Eligible activities are:
  E. Supply-side energy-efficiency improvements – transmission and distribution activities;
  F. Supply-side energy-efficiency improvements – generation;
  G. Demand-side energy-efficiency programmes for specific technologies;
  H. Energy-efficiency and fuel-switching measures for industrial facilities;
  I. Energy-efficiency and fuel-switching measures for buildings.
- Type (iii) projects: other projects that both reduce anthropogenic emissions by sources and directly emit less than 15 kilotonnes of CO_2 equivalent annually. Eligible activities are:
  J. Agriculture;
  K. Switching fossil fuels;
  L. Emission reductions in the transport sector;
  M. CH_4 recovery.

Although none of these project types today include land use, land-use change and forestry operations (LULUCF) and the use of soils as a sink, there is strong international pressure from many actors to include these as eligible activities under the CDM.

Even with the present restrictions on the inclusion of LULUCF activities, the small-scale activities might be integrated successfully with sequestration projects.

Based upon several United Nations environment conventions, there are a number of important funding opportunities that could potentially assist in implementing CS programmes for poverty alleviation. The most important conventions that are addressed are the FCCC, CBD and CCD.

CARBON FUNDS

In 2002, worldwide trading of credits in GHG emissions tripled to about 67 million tonnes of CO_2. However, only 13 percent of these credits involved developing countries. In order to increase the potential for developing countries to participate in this trade, the World Bank has recently created two carbon funds specifically aimed for projects in developing countries. However, these funds are based on the rules of the CDM and are ultimately dependent on the CDM as the international body for recognition and certification. The target of both funds is small-scale projects in the least-developed countries. Both funds comprise a mix of public and private funding and each have a target of US$100 million.

BIOCARBON FUND

The BioCarbon Fund was launched in November 2002 and scheduled to become operational in autumn 2003 and run for 18 years (Newcombe, 2003). The fund is intended to provide funds for carbon-sink projects through various landscape-management activities, such as the activities described in this report. The BioCarbon Fund should be seen as a learning opportunity for post-pilot projects on how to implement, monitor and verify CS schemes and also to test the permanence of the stored C. It is estimated that the BioCarbon Fund will comprise less than 4 million tonnes of CO_2, which is much less than the 1 percent stipulated by the CDM. In spite of its relatively small amount of C, it has the potential to result in substantial investments in drylands.

The BioCarbon Fund will implement projects in two different “windows”. The first will be fully compliant with the present CDM requirements, i.e. restricted to afforestation and reforestation. The second window will implement activities that are currently not eligible for KP-compliant carbon credits. This includes LULUCF and soil-sink activities.

Another contentious issue in the CDM is the possibilities of obtaining credits for avoided deforestation. There are currently no credits available for this type of activity. However, the second window of the BioCarbon Fund might well provide opportunities for exploring them.

THE COMMUNITY DEVELOPMENT CARBON FUND

The Community Development Carbon Fund (CDCF) was announced by the World Bank in April 2003, and is similar in many respects to the BioCarbon Fund. The main difference is that the CDCF will not invest in carbon sinks but in emission reductions. The main underlying principle is that each project must lead to improvements in the material welfare of the community or communities involved in it.

Projects under the CDCF need to comply with the CDM principles mentioned above. However, projects that do not comply with these principles might be proposed and can be considered for funding by the Executive Board. Examples of the types of goods and services that may be provided in a project by the CDCF are: electricity for schools, health clinics, workshops, potable water, teaching and medical services. In most cases, the project sponsor will provide the benefits directly or through contracting a third-party provider.

THE GLOBAL ENVIRONMENT FACILITY

The GEF is a joint funding programme established by developed countries to meet their obligations under various international environment treaties. The GEF has allocated US$4 000 000 000 in grants and leveraged an additional US$12 000 000 000 in cofinancing from other sources to support more than 1 000 projects in more than 140 developing nations and countries with economies in transition. There are six focal areas of the GEF: biodiversity, climate change, international waters, ozone, land degradation, and persistent organic pollutants. The projects that are funded and implemented through the GEF are governed by the operational programmes (OPs). As of March 2003, there are 14 operational programmes through which the GEF provides grants. Eleven of these reflect the original focal areas of the GEF: four in the biodiversity focal area, four in climate change, and three in international waters. The most relevant OP in relation to CS as described in this report is the OP12 Integrated Ecosystem Management. It encompasses cross-sectoral projects that address ecosystem management in a way that optimizes ecosystem goods and services in at least two focal areas within the context of sustainable development.

The OP12 is aimed specifically at initiating projects where synergies between three of the GEF focal areas (biodiversity, climate change and international waters) and land degradation can be obtained. This may include two or more of the following benefits:

a. conservation and sustainable use of biological diversity, as well as equitable sharing of benefits arising from biodiversity use;
b. reduction of net emissions and increased storage of GHGs in terrestrial and aquatic ecosystems;
c. conservation and sustainable use of waterbodies, including watersheds, river basins, and coastal zones;
d. prevention of the pollution of globally important terrestrial and aquatic ecosystems.

The expected outcomes of GEF-supported projects should also include:

a. creation of an enabling environment: appropriate policies, regulations, and incentive structures are developed to support integrated ecosystem management;
b. institutional strengthening: the capacity of institutions to implement integrated ecosystem management approaches is strengthened through training and logistical support;
c. investments: investments are made, based on integrated ecosystem approaches and stakeholder partnerships, to simultaneously address local/national and global environmental issues within the context of sustainable development.

In order to reach the above-mentioned benefits of both categories, the GEF defines a number of activities that are eligible for funding within GEF-funded activities, these come under three categories:

a. Technical assistance, including: surveys of different kinds; development and modification of policies; human resource development; development of mechanisms for conflict resolution; and development of public/community/private sector partnerships.
b. Investments, for purposes such as: rehabilitation of rangelands to restore indigenous vegetation and improve water management; rehabilitation of forested watersheds or floodplains; integrated management of coastal ecosystems; and

development of measures to control pollution to prevent degradation of habitats and minimize public health risks.

c. Targeted research, such as: development of integrated natural-resource management systems; and development of innovative and cost-effective integrated ecosystem management approaches.

Activities supported by the GEF are always collaborative arrangements with public and private partners, including NGOs. The activities should also support a broader development plan of the country or region where they are implemented.

ADAPTATION FUND

The establishment of the Adaptation Fund was decided at the sixth session of the Conference of the Parties to the FCCC (COP6). According to this decision, the Adaptation Fund will:

- be established under the GEF as a trust fund;
- finance the implementation of concrete adaptation projects in non-Annex I Parties, including the following adaptation activities: avoidance of deforestation, combating land degradation and desertification. Projects will be implemented by the implementing agencies of the United Nations.
- receive finance generated by the share of proceeds on the CDM in the order of 2 percent of certified emissions reductions – and by other sources of funding. COP6 invited Annex I Parties to provide this additional funding.
- be managed by the CDM Executive Board, under the guidance of the COP/MOP. Such guidance will be given by the COP/MOP on programmes, priorities and eligibility criteria for funding of adaptation activities.

PROTOTYPE CARBON FUND

The Prototype Carbon Fund (PCF) has three primary strategic objectives:

- High-quality emission reductions: to show how project-based GHG emission reduction transactions can promote and contribute to sustainable development and lower the cost of compliance with the KP;
- Knowledge dissemination: to provide the Parties to the FCCC, the private sector, and other interested parties with an opportunity to "learn-by-doing" in the development of policies, rules and business processes for the achievement of emission reductions under the CDM and Joint Implementation (JI);
- Public–private partnerships: to demonstrate how the World Bank can work in partnership with the public and private sectors to mobilize new resources for its borrowing member countries while addressing global environmental problems through market-based mechanisms.

The PCF will pilot production of emission reductions within the framework of JI and the CDM. The PCF will invest contributions

TABLE 48

Possible sources of funding for carbon sequestration multifocal programmes in drylands

Carbon funds under UN conventions	Web site
CONVENTION TO COMBAT DESERTIFICATION (CCD)	www.unccd.int
❑ Global Mechanism (GM)	www.gm-unccd.org
❑ GEF land degradation focal area	www.gefweb.org
CLIMATE CHANGE CONVENTION (CCC)	http://unfccc.int/
❑ GEF climate change	http://gefweb.org
❑ CEF multifocal area: integrated ecosystem management	
❑ GEF special climate change	
❑ GEF least-developed countries	
KYOTO PROTOCOL (KP)	unfccc.int
❑ GEF Adaptation Fund	http://www.gm-unccd.org
❑ BioCarbon Fund	www.carbofinance.org
❑ Prototype Carbon Fund	http://prototypecarbonfund.org

made by companies and governments in projects designed to produce emission reductions fully consistent with the KP and the emerging framework for JI and the CDM. Contributors, or “Participants” in the PCF, will receive a pro-rata share of the emission reductions, verified and certified in accordance with agreements reached with the respective countries “hosting” the projects.

A purely carbon-market approach is unlikely to be successful for drylands. A multifocal approach is required where other aspects such as sustainable development, desertification, biodiversity and food security are also considered. Funds under other conventions could also be used to fund CS programmes in drylands (Table 48).

Chapter 7
Conclusions

The concentration of CO_2 and other GHGs in the atmosphere is increasing as a result of fossil-fuel combustion, cement production and land-use change. The increase in GHGs in the atmosphere is leading to climate change and global warming. Concern about climate change has led to the KP, under which most countries are committed to reducing their GHG emissions and to increasing carbon sinks. Currently, the biosphere is considered to be a carbon sink absorbing about 2.8 gigatonnes of C a year, which represents 30 percent of fossil-fuel emissions.

The process of soil CS or flux of C into the soil forms part of the global carbon balance. Many of the factors affecting the flow of C into and out of the soil are affected by land-management practices. Although the real potential for terrestrial soil C sequestration is unknown, any action to sequester C in biomass and soils will generally increase the organic matter content of soils. In turn, this will have a positive impact on environmental, agricultural and biodiversity aspects of ecosystems. The long-term CS potential is determined by the input of C into the soils and the residence time of the pool in which C is stored.

The soils of drylands have lost a significant amount of C and, therefore, offer a great potential for rehabilitating these areas, estimated at 12–16 Pg C. There are vast areas of dryland ecosystems in developing countries where improvements in farming systems could add C to soils. The results from the case studies presented in this report show that several practices are available to increase carbon stocks in soils.

Whereas CS itself is not a priority in poor countries, land-management options that increase CS and concurrently enhance plant productivity and prevent erosion and desertification are of major interest in these regions. However, it is unlikely that current mechanisms, such as the CDM, can provide the necessary funds for these regions. Although soils are the major terrestrial carbon reservoir, and agriculture is recognized as one of the major causes of GHG emissions, neither soils nor land-use practices are eligible under the first commitment period of the KP.

However, investments in CS in drylands, as less favoured areas, are needed because they are home to large numbers of poor people and because they are the custodians of globally important environmental resources that are at risk of degradation or depletion. Investments in improved land management leading to increased soil fertility and CS can also be justified in many cases because they can be win–win situations with higher agronomic productivity and contribute to national economic growth, food security and biodiversity conservation.

Enhancing CS in degraded drylands could have direct environmental, economic and social benefits for local people. It could increase benefits for farmers as well as mitigate global warming, at least in the coming decades until alternative energy sources are developed. Therefore, CS initiatives linked to the improvement of degraded soils and plant productivity, and consequently food safety and poverty alleviation in dryland regions, are welcome and are among the main priorities of FAO.

As a purely carbon-market approach is unlikely to be applicable to small-scale farming systems in developing countries, a multilateral approach for the mobilization of resources under existing mechanisms is required. The Global Mechanism (GM) of the CCD promotes such a multilateral path in implementing its mandate to increase the effectiveness and efficiency of existing financial resources and to explore new and additional funding mechanisms for the implementation of the convention. It places specific emphasis on small-scale farming systems in dryland areas of the developing countries. Multilateral approaches include sources to combat climate change with desertification funds, links with sustainable livelihoods and provision of visible benefits to local people, and the mobilization of resources from the private sector.

The CCD, FCCC, CBD and KP all share a common goal: the proper management of soils, including the increase in soil C. Therefore, an important goal of the FAO-GM programme on CS is to promote synergies with the conventions and the private sector for the establishment of an environment fund specifically targeted to CS projects in drylands. Opportunities exist for bilateral partnerships with institutions in industrial countries to initiate soil CS projects involving local communities, also linked to global networks on CS. FAO believes that more effort should go into exploring and exploiting those opportunities.

FAO will take part in the design and implementation of CS programmes in tropical dryland countries based on the regional policies. It will bring the attention of governments to the benefits that CS measures could bring to the dryland farming communities and society. FAO could also play an important role in providing a secure institutional support for the implementation of CS programmes that encourage collaboration between local farmers and investors.

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