ARTICLE IN PRESS

Journal of Arid Environments ▌ (▌▌▌▌) ▌▌▌–▌▌▌

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

Sequestration of carbon in soil organic matter in Senegal: an overview

L.L. Tieszen[a,*], G.G. Tappan[b], A. Touré[c]

[a] *USGS/EROS Data Center, 47914 252nd Street, Sioux Falls, SD 57198, USA*
[b] *SAIC, US Geological Survey Earth Resources Observation Systems (EROS) Data Center, 47914 252nd Street, Sioux Falls, SD 57198, USA*
[c] *Centre de Suivi Ecologique, B.P. 15532, Dakar-Fann, Senegal*

Received 2 April 2004; accepted 2 April 2004

Abstract

Sequestration of Carbon in Soil Organic Matter (*SOCSOM*) *in Senegal* is a multi-disciplinary development project planned and refined through two international workshops. The project was implemented by integrating a core of international experts in remote sensing, biogeochemical modeling, community socio-economic assessments, and carbon measurements in a fully collaborative manner with Senegal organizations, national scientists, and local knowledge and expertise. The study addresses the potential role developing countries in semi-arid areas can play in climate mitigation activities. Multiple benefits to smallholders could accrue as a result of management practices to re-establish soil carbon content lost because of land use changes or management practices that are not sustainable. The specific importance for the Sahel is because of the high vulnerability to climate change in already impoverished rural societies.

The project focuses on four objectives in specific locations across the agroecological zones of Senegal. These objectives are: use of soil sampling and biogeochemical modeling to quantify the biophysical potential for carbon sequestration and to determine the sensitivity of the carbon stocks to various management and climate scenarios, to evaluate the socio-economic and cultural requirements necessary for successful project implementation directed toward an aggregation of smallholders to sequester around 100,000 t carbon (C), to support capacity building to develop a Carbon Specialist Team, and to initiate extrapolation from site-specific project areas to the Sahel region and the national level.

*Corresponding author.
E-mail address: tieszen@usgs.gov (L.L. Tieszen).

0140-1963/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2004.04.002

1. Introduction

The collection of papers in this special publication results from an international project: the Sequestration of Carbon in Soil Organic Matter (SOCSOM) in Senegal. The SOCSOM Goal is to:

> …provide quantitative analyses of the environmental, ecological, and economic potential for the sequestration of carbon in soil organic matter in specific study areas and to define the necessary socio-economic enabling conditions and policies to implement successful projects.

The project was proposed to emphasize site-specific studies that would quantify historical changes in both carbon stocks and soil fertility and to evaluate potential local mitigation and adaptation responses in Senegal to the global increase in atmospheric CO_2. Thus, the project attempts to provide quantitative and site-specific information to evaluate the biophysical, social, economic, cultural, and political feasibility of climate change contributions from these lands in developing countries and to guide further project implementation that would also support agricultural sustainability. SOCSOM, as a project, evolved after two major international workshops (Tieszen, 1999; Tieszen and Tschakert, 2000) to identify the importance and potential role of semi-arid and arid regions and soil organic carbon in climate change studies.

Carbon sequestration is defined as the net removal of CO_2 from the atmosphere into long-lived pools of carbon. In SOCSOM, the pools of interest are those that also support agricultural livelihoods. These pools are above-ground biomass, e.g. woody or herbaceous biomass, roots and micro-organisms in soils, and organic and inorganic carbon in soils. Sequestration implies an increase in the sizes of long-lived pools, not simply increasing the fluxes from atmosphere. This project emphasizes the multiple value of re-establishing depleted soil organic matter (SOM) pools by processes that may either increase fluxes to the soil (photosynthesis) or decrease fluxes from the soil (decomposition). All carbon pools are globally important in the livelihood strategies of local communities and individual farmers, but we emphasize soil carbon because of its relationship to soil fertility and agricultural sustainability, especially in semi-arid lands.

1.1. *Carbon pools and the atmosphere*

It is now well established that the various pools of carbon on Earth are changing, and that the fluxes (the rates of these transfers from one pool to another) have recently increased substantially. Although the geological record illustrates the dynamic nature of these carbon pools, it is only in historical times that the atmospheric pool has increased this rapidly. Atmospheric CO_2 has increased about 80 p.p.m.v. since the 1850s, and is presently accumulating in the atmosphere at a rate of about 1.5 p.p.m.v. or 3.3–3.5 gigatons (Gt = Pg) year^{-1}.

The scientific and political consensus now seems to conform with the opinions documented by the UN Framework Convention on Climate Change (UNFCCC) that this degradation represents dangerous interference with the climate. The continuing increase and projections of atmospheric CO_2 concentrations and the potential threats to the climate system and global economy require a thorough understanding of carbon cycling on local and national scales.

The increased net fluxes to the atmosphere are attributed to two principal human activities—the burning of fossil fuels and land use changes including deforestation, grassland conversion, and land management, with estimates of about 5.5 ± 0.5 and 1.6 ± 1.0 Pg C $year^{-1}$, respectively, during the decade of the 80s (Schimel et al., 1995). The differences between fluxes to the atmosphere and net accumulation reflect an increased ''sink'' not yet defined with respect to location or magnitude. Although precise accounting of amounts and sources remains difficult and changes from decade to decade, over the last 100 years activities associated with industrialization account for around 78 percent of this total atmospheric increase. Since the UNFCCC identified differing roles of developed and developing countries with respect to greenhouse gasses emissions, we will examine these roles in more detail.

Carbon emissions to the atmosphere from land cover change and management are concentrated in the tropics, and influence environmental services and human needs in various ways (Lambin et al., 2003). Human historical and pre-historical contributions, however, are much different than those operating today. Human activities such as land cover change and management during historical and pre-historical times account for 43 percent of total emissions (185 Pg), one third occurring before 1850. This release was concentrated in temperate zones. Although we are not suggesting we should diminish efforts to decrease emissions from fossil fuel consumption, the dubious legacy just identified creates a potential opportunity.

In principle, many of the losses can be reversed by creating and maintaining ''sinks'' where previous stocks existed, through restoration and appropriate management of carbon pools in soils and forests (see Kessler and Breman, 1991 for West Africa; Lal et al., 1999). Although sinks can help reduce the rate of increased atmospheric CO_2 from both combustion and land use, the relative roles of developed and developing countries will continue to change. Houghton (1999) and Houghton et al. (1998, 1999) document the importance of land use, suggesting that by 2020 developing countries could account for 60 percent of global energy use and associated carbon emissions. Although the imbalance in the carbon system is largely driven by the combustion of fossil fuels, note that 20 times more carbon is exchanged between the atmosphere and the Earth's vegetation and soils than is released from fossil fuels.

1.2. Climate change, mitigation, and adaptation

Most scientists believe that rapid CO_2 accumulation in the atmosphere will result in climate change, particularly global warming. Although it is not yet possible to accurately predict the explicit impacts of global warming, the consequences might be substantial. The review of the Intergovernmental Panel on Climate Change (IPCC) assessment (Watson et al., 2001) indicates that global mean surface temperatures have increased, these increases have affected agricultural and natural systems in detectable ways, the increases in global warming are largely accounted for by human activities, and the projected increases in this century are substantial, especially over land masses.

The impact of global climate change for Africa was recently presented in a valuable special publication by Desanker (2001) and Desanker and Justice (2001). As Hulme et al. (2001) indicate, the uncertainty in probable climate changes, especially for the Sahel, is high and current agreement among modeled projections is low. The possible combination of increased temperature, little increase in precipitation, and enhanced evapo-transpiration suggests, however, that agriculture is likely to be negatively impacted in semi-arid areas, especially those already near thermal optima for crops.

Africa, the continent arguably most vulnerable to the impacts of predicted changes, is likely to face higher inter-annual variability of rainfall, and more extreme climate events such as droughts and floods, especially in arid and semi-arid areas already severely afflicted by land degradation and irreversible desertification (Glantz, 1994). Caution is advised, however, because regional satellite analyses (Tucker et al., 1994) show the advances of the Sahara desert largely paralleling the fluctuations in rainfall (Nicholson et al., 1998; Tucker and Nicholson, 1999) rather than longer-term environmental shifts. In addition, Prince et al. (1998) show no large regional reduction in productivity. Similar complexities are shown in southern rangelands (Dube and Pickup, 2001).

This research suggests that the two fundamental components in the global effort to combat climate change, mitigation and adaptation, may differ substantially along north–south or developed–developing country perspectives. Seemingly, the opportunity or responsibility to reduce driving forces for climate change through mitigation rests largely with developed countries because of their contributions from fossil fuels related to industrialization (e.g. the USA contributes nearly 25 percent of all emissions derived from fossil fuels). Yet, in addition to direct emissions reductions, developing countries can facilitate reductions in net atmospheric accumulations by the strong development of sinks—a direct activity suggested by the Kyoto Protocol.

Thus, developing countries have the potential to become active partners in mitigation efforts, even though their current rates of release from fossil fuels are low. Larger differences exist with respect to adaptive capacity. Developing countries, especially many in Africa, are highly vulnerable to climate change by virtue of geographic location, both from the anticipated adverse impacts of global warming, and because of the reduced technological, institutional, and financial mechanisms available to them.

The attainment of a global future with a secure and sustainable climate system may be facilitated by an approach which justly recognizes that both developed and developing countries have important, although different, responsibilities and roles. Efforts must be undertaken to reduce emissions from fossil fuels and to introduce energy-efficient technologies. The replacement of high carbon-emitting energy sources must be emphasized in both developed countries and in developing countries, as their energy needs increase. We must also recognize that current use of fossil fuels means that carbon sequestration options (both geological and biological) will remain important features of carbon management as shown, e.g. by the recent Carbon Sequestration Leadership Forum (CSLF, 2003).

Both developed and developing countries must initiate activities in agricultural and natural ecosystems that maintain current stocks and enhance potential sinks. Developing countries, poised to bear disproportionate impacts of climate change, also need technologies and resources to facilitate adaptation. The small project discussed here, SOCSOM, was undertaken to help insure that developing countries had opportunities to play active roles in processes of mitigation and adaptation with respect to climate change.

1.3. Special role of SOM and arid lands

SOCSOM emphasizes the importance of carbon in soil for several reasons. Soil carbon, especially organic forms (SOC), is a large pool that globally exceeds that of the biomass and that of the atmosphere. It is, however, dispersed over broad areas and dilute, only uncommonly occurring at concentrations greater than 3 percent. The carbon in this pool is dynamic (Parton et al., 2004) because its turnover time is rapid on both human and geologic time-scales. For example, some compartments of SOC in this pool have a mean residence time of days to dozens of years and are therefore considered "active" or "slow." This SOC can be stabilized by biochemical and physical features of the soil into still more stable or "passive" fractions that may have residence times of hundreds to several thousands of years.

The SOC is an important determinant of soil fertility because of its impact on ion exchange capacities and its near-stoichiometric relationship to nitrogen (C:N ratios often between 8 and 20). The SOC is susceptible to mineralization as organic forms are converted to CO_2 and returned to the atmosphere with a proportional release of soil N. The magnitude of the SOC pool and its rate of replenishment are determined in part by the rate that CO_2 is incorporated into plant tissues by photosynthesis or net primary production (NPP), followed by the addition of plant and animal residue into the soil, or direct carbon input to soil from plant roots. This biological replenishment is a function of both the NPP and the land cover type or species.

These relationships, driving variables, and algorithms governing exchanges are incorporated in various carbon biogeochemistry models, of which CENTURY (Parton et al., 2004) is perhaps best known and most commonly used to simulate carbon fluxes and pool changes. The researchers explored the applications of this model in different ways across our sites in Senegal, as the SOCSOM project evaluates management opportunities and climate constraints on pool sizes, turnover rates, and the magnitudes of fluxes or exchanges. Because SOM contributes to soil structure and fertility, it is closely associated with those features that make soils valuable for the production of food and fiber. Thus, SOM is intimately integrated with human land use.

The changes in land use and land cover from grasslands, shrublands, woodlands, or forests to agricultural lands have clear and dramatic impacts on the services those ecosystems provide. The loss of biomass carbon and its release to the atmosphere is obvious and dramatic in both its suddenness and its magnitude. Sanchez (2000) summarizes magnitudes of woody biomass losses from the "Alternatives to Slash and Burn" projects as high as 200 t ha^{-1} along the margin of the humid tropics to lower values, likely from 75 t ha^{-1} to only a few t ha^{-1} in semi-arid systems. What is not so obvious is the continuing loss of SOC as these new agricultural uses now exploit the carbon and associated nutrient capital in these soils.

Under most agricultural practices, soils have been depleted of SOC by nearly 50 percent in 20–50 years (Scholes and Hall, 1996) as documented in various experimental (Jenkinson and Rayner, 1977) and natural systems. Woomer's work in East Africa illustrated some of the complexity and mitigating factors when he documented losses of around 0.69 t C ha^{-1} year^{-1}. These losses were reduced when fertilizer, especially animal manure, was applied (Woomer et al., 1997), even in recently cultivated land. This loss of soil C is associated with losses of N and thus usually results in decreased fertility unless NPP can be sustained with exogenous fertilizer and accompanied by residue returns. If not, the normal spiral leads to decreasing fertility, decreasing yield, and reductions in SOC. The consequences of this are "unintentional" land degradation (Levia, 1999), and desertification which may affect 2.6 billion people worldwide and as much as 20–50 percent of the land in sub-Saharan Africa, containing 200 million people (Nachtergaele, 2002).

2. Sahel and Senegal

2.1. Sahel and Senegal land degradation

Although the relationships among poverty and land degradation or depletion of soil carbon are complex, a recent Food and Agricultural Organization (FAO) study (FAO, 2002) concludes that when the natural soil resources are depleted, poverty results. Senegal land has been cultivated and farmed without appropriate management of organic and mineral fertilizer applications (Tiessen et al., 1998), resulting in enhanced mineralization and loss of SOM (Feller, 1977; Kushwaha et al., 2001). Sanchez (2000) also concludes that the depletion of soil fertility is the "biophysical root cause of declining food security" in this part of Africa.

This degradation and depletion likely results from loss of effective natural resources due to over-cultivation, overgrazing, extensive fuelwood gathering, and other ill-suited land management practices as well as unfavorable economic and agricultural policies. According to Gaston et al. (1998), Neill et al. (1998), and Reenberg (2001), these changes in developing countries occur where significant population growth is associated with a lack of knowledge and poor control of resources.

This land deterioration and lack of nutrient replenishment may be especially relevant in the Sahelian countries (Pieri, 1995) where cereal production fell by 12.7 percent in 2000. Despite the declining soil fertility, inorganic fertilizer consumption is currently very low (8 kg ha^{-1} relative to 107 kg ha^{-1} in all developing countries) and it is expected to remain low until 2030. Over the last decades, the Sahelian and

Sudanian zones have experienced increased difficulties in producing sufficient and adequate food for their growing populations. Despite the fact that sub-Saharan Africa is relatively well-endowed with natural resources, the incidence of hunger and poverty is greater than in other developing regions, while the population growth rate is higher and the number of poor is increasing at an alarming rate. Rural poverty still accounts for 90 percent of total poverty and roughly 80 percent of the poor still depend on agriculture or farm labor for their main source of livelihood. The Sahel is notable in sub-Saharan Africa, however, for the absence of large-scale episodic famines.

2.2. Sahel and Senegal climate change

The social consequences of land degradation have been exacerbated by a long-term reduction in rainfall in parts of the Sahel, amounting to 20–40 percent in certain areas (Nicholson, 2001). Senegal, in the western Sahel, confirms this increasing trend to aridity as suggested by Richard (1990). A linear regression of rainfall data for the St. Louis station from 1855 to 2003 shows a negative slope, from about 450 mm $year^{-1}$ in 1855 to roughly 280 mm $year^{-1}$ in 2003. This trend is consistent with the findings of Nicholson and Palao (1993), who calculated a negative slope in a linear regression of rainfall data since 1901 from all Sahelian stations. The trends appear even more acute in recent decades. The strong rainfall decrease in the Sahel, exemplified by the St. Louis data, characterizes all zones of Senegal. Rainfall levels for all of Senegal have dropped about 26 percent since the 1960s.

In the 20th century, Senegal was also hard hit by four droughts during 1910–1914 (Aubréville, 1949), 1942–1949, 1968–1973, and 1982–1984. Droughts, however, have been a long-term feature of West African climate, and by themselves do not necessarily indicate a trend toward aridity. A more prominent change is the long-term impact on vegetation and the southward shift of Sahelian characteristics.

In a study of north-western Senegal, Gonzalez (1997, 2001) found that drought-hardy Sahelian plant species expanded from the north, while mesic Sudanian and Guinean species retracted to the south. Species richness decreased about 30 percent. Vegetation zones shifted at a rate of 500–600 mm $year^{-1}$ from about 1945 to 1993.

In a countrywide study of vegetation trends, Tappan et al. (2000) compared woody vegetation conditions at 300 field sites between 1982–1984 and 1994–1997. They found that a combination of drought and longer-term decreases in rainfall significantly affected woody vegetation over the northern two-thirds of Senegal. They recorded moderate to high mortality rates among less-hardy tree species, and extremely high mortality rates in the Ferruginous Pastoral Region (in the north-east). The biological evidence from woody vegetation clearly supports the evidence in the recent climatic record of a shift towards a more arid environment.

The projected climate changes associated with global warming in this region (Hulme et al., 2001) will only exacerbate this land degradation. These changes are expected to result in increased regional temperatures where crops are already near thermal maxima, greater water requirements due to increased evapo-transpiration where water is already often limited, and a greater incidence of extreme events.

Hulme's interpretation of the ensemble of climate models suggests that the climate of Africa is already warmer than it was 100 years ago and that increased warming for the continent ranging between 2°C and 6°C is possible.

Although we can document the recent change in rainfall, we can predict less certainty about impacts of climate change. Furthermore, the inadequate incorporation of land cover changes, vegetative cover, dust, and aerosols makes regional climate predictions using general circulation models even more difficult in the Sahel than in many other parts of the world. Nevertheless, global warming in Africa and the Sahel is expected to continue and will most adversely affect farmers in arid, semi-arid and sub-humid areas due to drought-caused crop failure, falling livestock prices, and reduced availability of capital. This may lead to greater impoverishment, hunger, and eventually famine. This situation could result in greater agricultural extensification and further land use and tenure conflicts as resources become more scarce and biodiversity is sacrificed for new land resources.

3. Role of the SOCSOM project

3.1. Workshops to define the SOCSOM approach

SOCSOM in Senegal was undertaken as a feasibility project to advance understanding on how developing countries could participate in climate mitigation and improve smallholder livelihoods through sustainable management. The project was supported because co-operative development activities at the US Geological Survey/Earth Resources Observation Systems Data Center (EDC) clearly defined the important roles that soil carbon restoration could play in improving agricultural productivity and sustainability. It was apparent that land management interventions could result in enhanced carbon uptake, that this restoration would be associated with increased productivity, and that international programs might develop to provide incentive funding. The project aimed to insure that countries in Africa understood the potential interest in climate mitigation activities for land restoration, realized the potential economic and environmental significance, and became active partners to mitigate climate change and develop enhanced adaptive capacities.

An international workshop, "Carbon Sequestration in Soils and Carbon Credits: Review and Development of Options for Semi-Arid and Sub-Humid Africa," was held at EDC in 1999 (Tieszen, 1999). The international workshop brought together diverse African, European, and North American stakeholders, experts, and donors with expert soil scientists from Africa and other countries. In addition, recent meetings and workshops at the World Federation of Scientists (Permanent Monitoring Panel on Desertification) and the World Meteorological Organization in Geneva have reinforced the recommendations for implementation activities in African countries.

These efforts led to the first SOCSOM workshop in Dakar, Senegal "Carbon Sequestration In Soils," funded by the US Agency for International Development (USAID), the Rockefeller Foundation, the National Science Foundation, and the

United Nations Environment Programme, which formulated the scientific approach for SOCSOM in Senegal (Tieszen and Tschakert, 2000). This approach emphasized collaborative work and the estimation of real and definable opportunities in two scientific areas, the biophysical and the socio-economic. The approach also defined the needs for realistic and specific feasibility studies and capacity building, as well as the generalization from nationally based projects to those specific to the Sahel region.

3.2. Objectives of SOCSOM in Senegal

The participants in the workshops defined the need for specific feasibility studies, in the absence of full prototype project implementation, in selected regions of the country to allow an evaluation and full assessment of proposed management opportunities. The overall goal in this work was to use a combination of ground observations, local expertise, community resources, simulation modeling, and long-term records of remotely sensed data to identify areas of potential intervention and opportunities for carbon sequestration in natural resource management projects. Specific objectives in SOCSOM were defined as:

1. Quantify the carbon status and sequestration potential across agroecological zones in Senegal to define the biophysical potential, evaluate possible management impacts, and approach a full assessment in three areas for subsequent extrapolation

These areas were identified as the Podor, Bambey, and Velingara Departments. These areas span the agroecological zones of the country and encompass sylvo-pastoral systems in the most arid north, agricultural systems in the central area, and woodland–agricultural transitions in the south. They also represent regions where substantial other research was underway or had been completed. The challenge of the feasibility project was to define how much carbon can be sequestered, what is needed to achieve this goal, and what value (economic, social, environmental, sustainable) this carbon will have.

2. Understand and quantify the socio-economic incentives and requirements as well as policy issues necessary to implement a project level (100,000 t C) activity

The Bambey Department was selected because it was located near the laboratory of Institut Sénégalais de Recherches Agricoles (ISRA), was in the old peanut basin, and had several cultural groups representing different entities. Because of the limited funding and less certain understanding of the human components, we decided that only one area, Bambey, could be studied intensively. The emphasis was on a project level, defined as 100,000 t C, to approximate a sale of $1 million US, considered the minimal size of interest to potential buyers. Assuming that the biophysical potentials are significant and can be achieved, it is essential to have broad-based community support to run projects that will not only be successful in sequestering carbon, but will also lead to enhanced smallholder livelihoods and be attractive to potential carbon traders.

3. Develop national capacity for measuring, monitoring, and implementation

This goal was a high priority for the workshop participants, the country, and USAID which resulted in the initiation of a National Carbon Team immediately convened following the first Dakar workshop, chaired by the environmental advisor to the president of Senegal. This objective also implied that capacity building was necessary for all project participants and was achieved by joint collaboration in the fieldwork, analyses, and interpretation. In addition to national capacity, the collaboration was intended to develop a "Carbon Specialist Team" as a resource for the Sahel or other parts of Africa. This capacity building also resulted in the workshop suggested by the participants now published as "Landscape Carbon Sampling and Biogeochemical Modeling" (Woomer et al., 2001).

4. Generalize the results to national and regional scales

The intent of the project was to define an understanding adequate to provide guidance for national carbon sequestration. Furthermore, it was hoped that approaches and techniques might be applicable across broader areas of the Sahel and other semi-arid areas of sub-Sahara Africa.

3.3. Approaches to project assessment in Senegal

Approaches to project-level activities to support climate change mitigation in semi-arid areas have been described by past workshop participants (Izzauralde et al., 2001). Basically, we define two approaches to measure carbon sequestration across large and diverse spatial areas, as might be required to achieve a 100,000 t C project. First and most traditionally, one can measure carbon stocks in permanent and control plots (including dynamic baselines). This approach usually requires some level of prior landscape stratification to understand and quantify the variability across the terrain that may entail detailed land cover, land use, and management information as well as detailed soil and biomass carbon sampling and analyses. A Geographic Information System (GIS) is also necessary for spatial accounting. This approach generally characterizes projects in Africa and at our SOCSOM sites.

Second, it is possible to directly monitor the performance, or ecosystem service, of the land cover and then extrapolate these measurements spatially. Although the normalized difference vegetation index (NDVI) is closely correlated with both green biomass and NPP in non-forested systems, it is not yet possible to quantify with continuous accuracy carbon flux at high spatial resolution (smaller than 0.25 km). Although not employed in any African ecological or agricultural system, continuous point measurements of carbon flux from small (less than 1 km) fetch areas can be used to define daily patterns of net ecosystem exchange (NEE) for specific measurement sites.

Recently, Wylie et al. (2004) have calibrated NDVI data for flux tower sites in semi-arid systems of Central Asia and North America, developed statistical modeling approaches to predict carbon fluxes from satellite data, and extrapolated flux estimates across broad regions of similar land use and land cover types. This direct measure of carbon sequestration (not accounting for losses or gains to erosion) promises to provide both quantitative estimates and predictions over large areas. The approach is not yet fully operational and is not used in SOCSOM in Senegal. Satellite data have been used to develop models of gross primary production in the western Sahel (Seaquist et al., 2003), and these data show promise for directly quantifying carbon flux over large and data-poor areas.

Each approach requires remotely sensed data for either land cover analyses or NDVI, GIS for spatial quantification, and simulation modeling to place measured annual (or shorter) changes into a long-term biogeochemical perspective, essential because of the lags and hysteresis shown by various SOC pools. Our effort must be to estimate long-term changes in carbon stocks, not simply short-term increases or decreases which may require years before a new steady state is achieved. The incorporation of simulation modeling also allows researchers to incorporate various sensitivity analyses.

3.4. SOCSOM research presented in this special publication

Although the project emphasized detailed research in three Departments, the status of land change and carbon status was assessed across the entire country. This effort was made possible by the detailed time-series of remote sensing information provided by Tappan and colleagues at CSE, documenting both land cover changes and trends on woody density within land cover classes. The availability of Corona, MSS and TM data provided detailed high-resolution analyses across the country. This land cover analysis was supplemented by the development of new approaches in the papers by Li and Budde.

These approaches exploited the long-term archives of 8 km Advanced Very High-Resolution Radiometer (AVHRR) data and 1 km AVHRR and *Systeme pour l'Observation de la Terre* (France) imagery to assess the site-specific and temporal changes in the land surface performance as evaluated by its greenness component during the growing season. This approach let researchers relate NPP (the source for input of carbon into SOM) to climate (e.g. precipitation), and to evaluate trends during the archival period.

The detailed analyses of land cover performance across the entire country with consistent archives of NDVI allowed us to extract spatially explicit areas of land degradation or land improvement and to identify anthropogenic or climate causes.

The prototype work just started in Senegal suggests it may be possible to convert these different signals into estimates of NPP. In combination with spatial implementation of CENTURY, it may be possible to estimate long-term impacts on NEE and new steady states of carbon stocks. The nature of these impacts was verified with local knowledge and the high-resolution imagery.

In SOCSOM in Senegal, somewhat different approaches were used in each selected study area. The Podor study was least intensive, but typifies the sylvo-pastoral zone and reports changes documented because of long-term monitoring by *Centre de Suivi Ecologique* (CSE). This work resulted in estimates of carbon losses with degradation and preliminary assessments of management needs to re-establish prior carbon stocks.

The Bambey study emphasized socio-economic analyses with fully georeferenced specific and detailed farm-level soil carbon measurements. CENTURY simulations assessed the impacts of various land use or management scenarios for those specific points, and large-area carbon estimates required stratification and aggregation from those points. Detailed socio-economic analyses in the Bambey area identified various management options that resulted in sequestration or the continued loss of carbon and the economic costs and benefits.

In contrast, the system in Velingara assessed the change in land use as forest systems were converted to agriculture with varying lengths of fallow. In this area, SOCSOM employed new applications of CENTURY in a spatially explicit, but large-area modeling approach. This assessment allowed large spatial areas, e.g. the Velingara Department, to be simulated as a unit with the retention of high-resolution landscape detail. This powerful ensemble approach to biogeochemical modeling may facilitate large-area analyses which will be required for the applications across the Sahel.

In addition to the regional studies, which provided varying levels of detail, Parton provided a national synthesis simulated from a coarser perspective to identify potential national impacts of carbon sequestration in Senegal. This information provided a somewhat more independent estimate of national trends than the detailed land use and woody cover changes documented by Woomer and others. These analyses indicated a loss of 292 Mt C over 35 years.

The combined economic assessment and biogeochemical modeling of Tschakert suggest management options and implementation strategies that represent ‘‘win-win’’ situations—both increasing carbon and sustainable agriculture and enhancing wealth. Implementation across the Sahel, however, must be site-specific and must provide up-front capitalization support.

Finally, the sensitivity analyses suggest that the climate impacts suggested by $2 \times CO_2$ will result in continued loss of C stocks and severe reductions in crop yields. Further attention to mitigation and adaptation in the Sahel are urgently needed.

3.5. Overall results and suggestions from SOCSOM

The review presented above and papers in this workshop identify several important results and suggestions for further action.

(1) The conversion of woodland and savanna systems of the Sahel, exemplified by Senegal, resulted in loss of biomass and SOM carbon to the atmosphere upon conversion to agriculture.
(2) Agricultural extensification and decreased fallow periods resulting from population pressure and the lack of nutrient inputs have resulted in reduced fertility and agricultural productivity with the loss of natural vegetation, including woody biodiversity (Gonzalez, 2001).
(3) Many soils are now infertile with very low SOM values and farmers remain impoverished. This situation is associated with undernourished people in sub-Saharan Africa where one-third of the populations were undernourished in 1997–1999 (FAO, 2002), accounting for nearly one-fourth of all undernourished people in the world.

(4) Major international workshops have identified multiple benefits associated with the re-establishment of SOM in these degraded and non-sustainable systems.
(5) Senegal's woodlands, agricultural lands, and grazing lands have significant potential for sequestering large amounts of carbon through improved land management practices and increasing productivity, and the economic and social requirements are being defined.
(6) We have an adequate understanding of the factors controlling the biophysical drivers of carbon sequestration and have made substantial steps allowing us to measure, monitor, and model the quantitative responses to potential management strategies.
(7) The researchers now understand the contribution of carbon sequestration to climate mitigation in semi-arid and degraded lands.
(8) A carbon market is now in operation but without substantial inclusion or participation of Sahelian projects or countries.
(9) Economic analyses of various farm management strategies need to be quantified in the context of the social systems for each potential project area.
(10) Policy support for smallholder participation and an understanding of appropriate socio-economic incentives for participation need to be developed.
(11) Fully operational projects need to be implemented to provide experience for developing countries, international donors, brokers, and carbon credit buyers.
(12) Full and effective implementation of carbon sequestration with enough magnitude to provide substantial global impact will require robust institutional mechanisms.
(13) Developed and developing countries need to jointly generate the scientific basis for societal decisions about the management of CO_2 and the carbon cycle.
(14) The value of "ecosystem services" should be considered to develop strategies and official assistance programs.

3.6. SOCSOM and future opportunities

It should be clear that the processes leading to the loss of SOC and fertility are generally reversible. This research and collaboration suggests that sequestration of carbon in soils is a viable strategy with multiple benefits. If SOC can be restored to levels approaching those before land conversion, the flux from the atmosphere to the soil pool will have to increase. This reversal cannot happen without adequate nutrients, especially nitrogen and water, as well as good farm management that includes appropriate residue management or manuring. The adoption of these practices and the multiple benefits including climate mitigation, enhanced soil fertility and agricultural sustainability, increased economic returns, etc. led to support for the SOCSOM project. Our research implies a managed approach to land rehabilitation that results in greater agricultural intensification and therefore less extensification. Although SOC exists as a dispersed and dilute resource, the sheer magnitude of the land area in sub-Saharan Africa provides an opportunity for large climate mitigation impacts (Ringius, 2002), providing massive projects over large areas with potentially small returns to individuals can be implemented.

The single most significant activity that can be implemented soon to mitigate the increase in atmospheric carbon is to sequester carbon in forms and pools that are relatively inert. Although geological sequestration may be important, it is biological sequestration of carbon in biomass and in SOM that may have the greatest impact during the next few decades. We suggest that SOCSOM is of special value because these practices can have large impacts in reducing the rate of increase in the atmosphere. This value accrues because the accumulation of SOM has manifold benefits, including enhanced fertility and sustainability. Furthermore, the potential exists to reduce pressure on land conversion from forests to more agricultural land. In contrast, afforestation, although in some cases more productive as a sequestration mechanism, will increase the use of already marginalized agriculture. Thus, carbon sequestration in soil does, in actuality, provide a greater ecological service.

Carbon trading is already an active process. A significant number (about 300) of contracts for carbon credits have been signed, although Africa has very little activity. Details concerning these transactions and opportunities with the World Bank were summarized at the SOCSOM final workshop in Senegal in 2003 (http://edcintl.cr.usgs.gov/carbonseq/cd/index.html or on CD). Although many projects are associated with energy efficiency and reforestation, a number of these deal with sequestration of carbon in soil. In this sense, a market for soil carbon exists; the value for the carbon sequestered ranges from US\$1 to \$10 t^{-1} of carbon. Furthermore, the contracts already specify liability, which is often designated to the seller, and stipulate measurement, management, and verification procedures. The exact nature of these contracts is likely to change following decisions at future UNFCC conference of the parties meetings. Contracts vary in size but are generally easier to manage when they are at least 100,000 metric tons C, and when they are made with one legal organization or owner. Projects will have to aggregate smallholders into an appropriate legal grouping with clear liability.

It is, of course, helpful that efforts to restore carbon in these degraded lands support the UN Convention to Combat Desertification, a convention recently ratified by the US Such efforts fully implement the UNFCCC and can also reduce the threats to biodiversity, which is the focus of the UN Convention on Biological Diversity. These multiple reasons show that carbon in the form of restored SOC should be considered substantially more valuable than carbon in the form of biomass. International efforts need to be directed toward the feasibility of projects that can demonstrate the ability of smallholders to undertake profitable land management scenarios that yield these sustained benefits. This important and strategic need demands selection of soil management options that decrease the efflux of CO_2 from soil to atmosphere and increase the total soil organic carbon pool at the expense of the atmospheric carbon pool.

For Senegal, this triple benefit—combating desertification, increasing agricultural productivity, and mitigating global warming—is of particular interest because it reflects the major goals of its national environmental and agricultural policies and action plans. SOCSOM initiated activities to determine Senegal's biophysical and socio-economic potential for carbon sequestration in soils with the ultimate objective to promote sustainable agriculture, restore degraded environments, and enhance food security and livelihoods among Senegal's people.

Acknowledgements

This special publication and the research and development activities have received core funding from the USAID. We especially thank Paul Bartel who managed this project activity. Initial planning and project development were facilitated by the major international workshops with significant support from the Sand County Foundation and from numerous organizations including the World Bank, various Consultative Group on International Agricultural Research Centers, the United Nations Environment Programme, FAO, International Fund for Agricultural Development, Winrock International, the Rockefeller Foundation, and others.

We extend sincere appreciation to each coauthor in this collection for his extensive collaboration and integration over 2 years with minimal financial support. The CSE played an indispensable role in this project by providing direct scientific assistance, extensive scientific and local understanding, and effective logistic support. Mr. Moctar Niang and Mr. Assize Touré helped guide this research. Mamadou Khouma, Modou Séne and the *Institut Sénégalais de Recherches Agricoles* also contributed extensive specific scientific understanding and excellent co-operation for our field activities. Mr. Mbareck Diop, who headed the Senegal Carbon Team, provided very effective leadership for all co-operating scientists. Jane Smith was invaluable in facilitating this special publication. Gray Tappan's familiarity with and understanding of the Sahel made much of the project possible.

References

Aubréville, A., 1949. Climats, forêts, et désertification de l'Afrique tropical. Société d'Editions Géographiques, Maritimes, et Coloniales, Paris, France.

Charter for the Carbon Sequestration Leadership Forum (CSLF), 2003. A carbon capture and storage technology initiative, http://www.energy.gov/engine/doe/files/dynamic/16200392037_CSLF_Charter.pdf.

Desanker, P. (Ed.), 2001. Africa and global climate change. Climate Research Special 8. Inter-Research, Oldendorf/Luhe, Germany.

Desanker, P., Justice, C.O., 2001. Africa and global climate change: critical issues and suggestions for further research and integrated assessment modeling. Climate Research 17, 93–103.

Dube, O.P., Pickup, G., 2001. Effects of rainfall variability and communal and semi-commercial grazing on land cover in southern African rangelands. Climate Research 17, 195–208.

FAO, 2002. The State of Food and Agriculture 2002. FAO Agriculture Series No. 34, Rome.

Feller, C., 1977. Evolution des sols de défriche dans la région des Terres Neuves (Sénégal Oriental). 2éme Partie: aspects biologiques et charactéristiques de la matière organique. Cahiers de l'ORSTOM, Série Pédologie 17 (4), 302–339.

Gaston, G., Brown, S., Lorenzini, M., Singh, K.D., 1998. State and change in carbon pools in the forests of tropical Africa. Global Change Biology 4 (1), 97–114 (Blackwell Publishing).

Glantz, M.H., 1994. Drought, desertification and food production. In: Glantz, M.H. (Ed.), Drought Follows the Plow. Cambridge University Press, Cambridge, MA, pp. 6–32.

Gonzalez, P., 1997. Dynamics of biodiversity and human carrying capacity in the Senegal Sahel. Ph.D. Dissertation, University of California, Berkeley.

Gonzalez, P., 2001. Desertification and a shift of forest species in the West African Sahel. Climate Research 17, 217–228.

Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1950–1990. Tellus, Series B: Chemical and Physical Meteorology 1999 51, 298–313.

Houghton, R.A., Davidson, E.A., Woodwell, G.M., 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochemical Cycles 12, 25–34.

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The US carbon budget: contributions from land-use change. Science 285, 574–578.

Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1900–2100. Climate Research 17, 145–168.

Izzauralde, R.J., Rosenberg, N.J., Lal, R., 2001. Mitigation of climate change by soil carbon sequestration: issues of science, monitoring, and degraded lands. Advances in Agronomy 70, 1–75.

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

Kessler, J.J., Breman, H., 1991. The potential of agroforestry to increase primary production in the Sahelian and Sudanian zones of West Africa. Agroforestry Systems 13, 41–62.

Kushwaha, C.P., Tripathi, S.K., Singh, K.P., 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Applied Soil Ecology 16, 229–241 (Elsevier).

Lal, R., Kimble, J.M., Follet, R.F., Cole, C.V., 1999. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, CRC Press, Boca Raton, FL.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in the tropics. Annual Review of Environment Resources 28, 205–241.

Levia Jr., D.F., 1999. Land degradation: why is it continuing? Ambio 28, 200–201.

Nachtergaele, F., 2002. Land degradation assessment in drylands (LADA project). LUCC Newsletter 8, 15.

Neill, C., Cerri, C., Melillo, J., Feigl, B., Steudler, P., Moraes, J., Picollo, M., 1998. Stocks and dynamics of soil carbon following deforestation for pasture in Rondônia. In: Lal, R., Kimble, J.K., Follet, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. Advances in Soil Science. CRC Press, Boca Raton, FL (Chapter 2).

Nicholson, S.E., 2001. Climatic and environmental change in Africa during the last two centuries. Climate Research 17, 123–144.

Nicholson, S.E., Palao, I.M., 1993. A re-evaluation of rainfall variability in the Sahel. Part I. Characteristics of rainfall fluctuations. International Journal of Climatology 13, 371–389.

Nicholson, S.E., Tucker, C.J., Ba, M.B., 1998. Desertification, drought, and surface vegetation: an example from the West African Sahel. Bulletin of the American Meteorological Society, pp. 815–829.

Parton, W., Tappan, G., Ojima, D., Tschakert, P., 2004. Ecological impact of historical and future land use patterns in Senegal. Journal of Arid Environments, this issue.

Pieri, C., 1995. Long-Term Soil Management Experiments in Semiarid Francophone Africa. CRC Press, Boca Raton, FL, pp. 225–266.

Prince, S.D., Brown de Colstoun, E., Kravitz, L.L., 1998. Desertification of the Sahel? Evidence from remotely sensed rain-use efficiencies. Global Change Biology 4, 359–374.

Reenberg, A., 2001. Agricultural Land Use Pattern Dynamics in the Sudan-Sahel-Towards an Event-Driven Framework. Land Use Policy 0:1-11. Elsevier Science Ltd., Pergamon.

Richard, J.F., 1990. La dégradation des paysages en Afrique de l'Ouest. ORSTOM/AUPELF/CCF/UICN/ENDA.

Ringius, L., 2002. Soil carbon sequestration and the CDM: opportunities and challenges for Africa. Climate Change 54, 471–495.

Sanchez, P.A., 2000. Linking climate change research with food security and poverty reduction in the tropics. Agriculture, Ecosystems, and Environment 82, 371–383.

Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, E., Raynaud, D., Wigley, T., 1995. CO_2 and the carbon cycle. In: Houghton, J.T., Filho, G.M., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995. Cambridge University Press, Cambridge, MA, pp. 76–86.

Scholes, R.J., Hall, D.O., 1996. The carbon budget of tropical savannas, woodlands, and grasslands. In: Breymeyer, A.I., Hall, D.O., Melillo, J.M., Agren, G.I. (Eds.), Global Change: Effects on Coniferous Forests and Grasslands. Wiley, Chichester, pp. 69–100.

Seaquist, J.W., Olsson, L., Ardö, J., 2003. A remote sensing-based primary production model for grassland biomes. Ecological Modelling 169, 131–155.

Tappan, G., Wood, E., Hadj, A., Sall, M., 2000. Monitoring climate and human impacts on the vegetation resources of Senegal. Report to USAID/Senegal, US Geological Survey, EROS Data Center, Sioux Falls, SD.

Tiessen, H., Feller, C., Sampaio, E.V.S.B., Garin, P., 1998. Carbon sequestration and turnover in semi-arid and dry forest. Climate Change 40, 105–117.

Tieszen, L.L., 1999. Carbon sequestration in soils and carbon credits: review and development of options for semi-arid and sub-humid Africa. International Workshop in Sioux Falls, SD, USA, May 19–21, 1999, http://edcintl.cr.usgs.gov/carbonseq/workshop.html.

Tieszen, L.L., Tschakert, P., 2000. Carbon sequestration in soils. International Workshop in Dakar, Senegal, September 25–27, 2000, http://edcintl.cr.usgs.gov/carbonwkshp2000.html.

Tucker, C.J., Nicholson, S.E., 1999. Variations in the size of the Sahara desert from 1980 to 1997. Ambio 28 (2), 587–591.

Tucker, C.J., Newcomb, W.W., Dregne, H.E., 1994. AVHRR data sets for determination of desert spatial extent. International Journal of Remote Sensing 15, 3547–3566.

Watson, R.T., Core Writing Team (Eds.) (IPCC), 2001. Climate change 2001: synthesis report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 2001.

Woomer, P.L., Palm, C.A., Qureshi, J.N., Kotto-Same, J., 1997. Carbon sequestration and organic resources management in African smallholder agriculture. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 153–173.

Woomer, P.L., Tieszen, L.L., Tschakert, P., Parton, W.J., Touré, A., 2001. Landscape carbon sampling and biogeochemical modeling. Report of a Workshop at Centre de Suivi Ecologique, Dakar, Senegal, 2001.

Wylie, B.K., Gilmanov, T.G., Johnson, D.A., Saliendra, N.Z., Akahalov, K., Tieszen, L.L., Reed, B.C., Laca, E., 2004. Intra-seasonal mapping of CO_2 flux in rangelands of northern Kazakhstan at one-kilometer resolution. Environmental Management, accepted for publication (on line March 4 2004; www.springerlink.com).