Article

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Soil Carbon Sequestration in Degraded Semiarid Agro-ecosystems —Perils and Potentials

The Kyoto Protocol opens new possibilities for using the biosphere as a carbon sink. Using agro-ecosystems as carbon sinks may be the most appropriate practice from both environmental and socioeconomic points of view. Degraded agro-ecosystems in Africa might benefit significantly from the improved land management that would be part of a carbon sequestration program. There are vast areas of these agro-ecosystems in Africa and their rehabilitation is an urgent matter. We agree with UNEP that there are potentially important synergies to be made between the Convention on Climate Change, the UN Convention to Combat Desertification and the UN Convention on Biodiversity. In this paper, we have investigated the potential for increasing soil carbon content in semiarid agro-ecosystems in the Sudan and found that increasing fallow periods will result in increased soil carbon content and converting marginal agricultural areas to rangeland will restore the carbon levels to 80% of the natural savannah carbon levels in 100 years. The economic gain from a future carbon sequestration program has the potential of a significant contribution to the household economy in these agro-ecosystems.

INTRODUCTION

Carbon in the form of CO_2 is accumulating in the atmosphere at a rate of about 3.5 gigatonnes (Gt) per year (Gt yr^{-1}) as a result of combustion of fossil fuel, tropical deforestation and other land-use changes. Scientific as well as political consensus now seems to have been reached regarding the risk of dangerous interference with the climate, and is expressed in the UN Framework Convention on Climate Change (UNFCC) (1). At the same time, desertification and land degradation continues to cause poverty and misery to millions of people in the drylands of the developing world. For combating desertification and to alleviate poverty in the affected regions, the UN Convention to Combat Desertification (UNCCD) strives to implement activities aimed at promoting sustainable development. Desertification and land degradation also pose a threat to the biodiversity of many marginal lands, which is one of the foci of the UN Convention on Biodiversity (UNCBD). It is important to acknowledge that in the crosscutting of these 3 major UN conventions we may find the most desirable activities to implement. The aim of this paper is to demonstrate how sound management of semiarid agro-ecosystems might be one way of addressing the 3 environmental conventions. Emphasis, however, will be on the relationship of land management and climate change mitigation.

The convention on which most of the world focuses is the UNFCC, and the related Kyoto Protocol. The Kyoto Protocol, negotiated in December 1997, provides the framework for activities aimed at reducing emissions of greenhouse gases. The Protocol, not yet ratified by enough parties to come into force (as of 14 August 2002), is one of the most ambitious but also one of the most ambiguous international treaties ever adopted (2, 3).

The protocol contains a joint commitment of the industrialized countries to reduce their greenhouse gas (GHG) emissions by at least 5% below the levels of 1990, over the period 2008–2012. This will be achieved by a range of activities, not simply by actual emission reductions. Many controversial issues are subject to intense discussion, 2 of the most debated ones are *i*) accounting for sinks; and *ii*) trade in emission rights.

The so called "flexible mechanisms", by which emissions reductions will be achieved are particularly controversial. The flexibility in these mechanisms is to a large extent geographical. The "joint fulfilment" mechanism (Article 4) means that a group of countries can act as one entity with a joint commitment. The "joint implementation" mechanism (JI, Article 6) means that industrial countries can jointly carry out projects aimed at reducing the GHG emission and the countries can share the emission reduction obtained. Trading of emission rights is another flexible mechanism introduced in the protocol (Article 17). This means that industrial countries (listed in Annex B of the Kyoto Protocol) not capable or willing to fulfil its commitment should be able to trade emission rights from another country. Finally, the most interesting flexible mechanism is the Clean Development Mechanism (CDM, Article 12). The CDM is similar to the JI, but is a mechanism by which industrial countries can invest in developing countries (countries with no commitment under the Kyoto Protocol), in projects promoting sustainable development. Certified emission reductions obtained by the project can be used to assist the investing country to fulfil its emission target.

Carbon sinks in the form of land-use change and forestry is an issue that is still not settled. For the first commitment period (2008–2012), sinks will not be included in the calculation of baselines, but allows the calculation of commitments to include sinks resulting from land-use change and forestry (limited to afforestation, reforestation, and deforestation since 1990). However, according to Article 3.4, other sinks like agricultural soils may be included in the second and subsequent commitment periods. The role of sinks in forestry and agriculture was one of the most discussed topics during the COP-6 conference (COP-6 was the 6^{th} Conference of the Parties of the UNFCCC, held in The Hague, 13–25 November 2000). However, no agreements concerning the inclusion of sinks in CDM were reached.

Even if the Kyoto Protocol never becomes operational, there might very well be other similar mechanisms available in the near future, for example the "Brownback Bill" in the USA, suggesting that companies would be eligble for tax reductions if they invested in carbon sequestration activities outside the USA.

CARBON SINKS AND TRADE—CONTROVERSIAL ISSUES

The prospect of using land-use change and forestry activities as accountable carbon sinks under the CDM is very much a controversial issue. The most important reasons for criticizing the use of sinks are:

– Sinks will not solve the problem. The amount of carbon that can be sequestered using biosphere sinks is not enough to reach an acceptable level of atmospheric CO_2.
– The accounting of biosphere sinks might counteract or delay actual emission reductions.

– Carbon sequestered in forests might easily be released again either through deforestation or through climate-change induced emissions.
– Large-scale afforestation projects might not be desirable from a social point of view and might compete for land with agriculture. These projects might also be undesirable from a biodiversity point of view.
– Monitoring and verifying carbon sinks is difficult and might also be expensive and thereby reduce the economic value to land managers.

The critique of sinks listed above must be taken seriously, if carbon sinks are to be used as a tradable commodity it is important to shape the trade in a way that does not counteract the real emissions reductions. One important reason for exploring the utility of using carbon sinks as a tradable commodity is the fact that there is already a trade of carbon emission rights going on. At the time of writing (October 2000) at least 100 contracts have already been signed in North America comprising at least 100 000 tonnes each (pers. comm. L. Tieszen, US Geological Survey, September 2000). It is therefore important to find ways of using this ongoing trade in as benign a way as possible from an environmental, economic, and social point of view.

The Kyoto Protocol, in its original form, focuses on forestry activities as a carbon sink. There might, however, be a number of problems difficult to solve that are related to forestry activities, particularly related to monitoring and verification, permanence, leakage and environmental effects. However, if other types of land-use are included, there are strong reasons for developing sequestration schemes in degraded agro-ecosystems. One reason is that land degradation, particularly in the tropics is an environmental issue as urgent as climate change, and that fighting land degradation might actually be an efficient way of sequestering carbon in the soils. In the context of the 3 major environmental UN conventions, UNFCC, UNCCD, and UNCBD, soil carbon sequestration in degraded agro-ecosystems might be one way to contribute to the fulfilment of all 3 conventions. It will also be a way for developing countries to become active participants in the fight against climate change through something that is as close to a win-win situation as one may get.

AGRO-ECOSYSTEMS AS A POTENTIAL CARBON SINK

When soils under natural vegetation are being transformed to agricultural soils, carbon is usually being lost to the atmosphere (4). However, agricultural soils under appropriate management contain substantial amounts of soil carbon in the form of soil organic matter (SOM). SOM is an important factor contributing to nutrient status, water-holding capacity, resistance to erosion, etc. The restoration of soil fertility through carbon sequestration in agro-ecosystems will, apart from removing CO_2 from the atmosphere, also improve our chances of meeting future food production demands.

Increased carbon sequestration can be achieved by large-scale application of immediately deployable land management practices such as increased use of green fallow periods, conservation tillage (5), increased use of rotational crops, return of crop residues and the application of agro-forestry. The highest potential for increasing soil carbon content can most likely be found in severely degraded ecosystems around the world. There are vast areas of degraded and desertified lands throughout the world, many in developing countries where improvements in rangeland management and rainfed agriculture can increase the sequestration of carbon in the soil. Batjes (6) estimated that between 0.6 and 2 Gt C yr^{-1} could be sequestered by large-scale application of appropriate land management in degraded lands of the world (6). This accounts for between 18–60% of the annual accumulation of CO_2 in the atmosphere.

There are advantages of promoting degraded agro-ecosystems as a potential carbon sink rather than forests. Safeguarding carbon stored in aboveground biomass in forests will be difficult since owners might be tempted to quick economic returns by logging. SOM in cultivated soils, where it contributes to soil fertility, might be less tempting to release through overexploitation due to the slow process compared to forest logging and the fact that the prospects of good crop yields in the future will be jeopardized. Soil carbon can have a very long residence time, hundreds and even thousand of years (7), compared with carbon stored in aboveground vegetation. Another advantage of using agro-ecosystems as a carbon sink are the economic and social benefits, which will be shared by everybody cultivating the land. Compared to carbon passively stored in a forest, the SOM in agricultural soils will actively benefit food production.

CASE STUDY IN SEMIARID SUDAN

In order to estimate the potential of increasing soil carbon storage in degraded semiarid lands in the Sahel, a study, with 2 components, was conducted in western Sudan:

i). The present soil carbon content was measured along a transect of soil samples in 1980 (8). The soil carbon content was then modelled using the CENTURY model (9–11) and the model results were compared with the measurements.

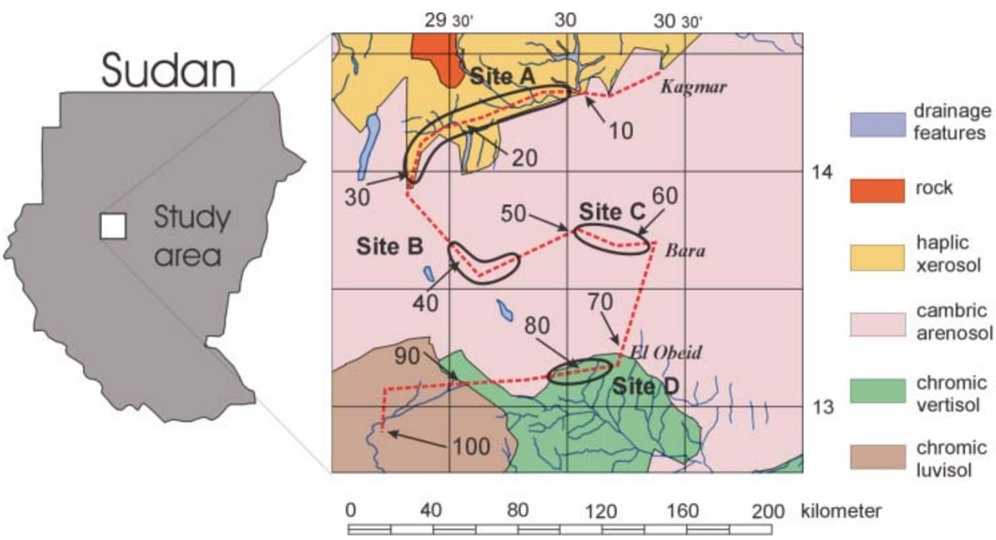


Figure 1. The study area with the sampling transect indicated as a red dotted line (numbers refer to sampling sites in Figure 4). Wadis and wadi areas are shown in blue colors. The red dots show major settlements. The four study sites along the transect are indicated. Source of map: FAO/UNESCO Soil Map of the World (13, 34).

ii). Scenarios for future land management and effects on soil carbon storage were simulated using CENTURY in order to estimate the future options for carbon sequestration.

STUDY AREA

The study was undertaken in the northern Kordofan Province of the Sudan (Fig. 1). The dominating soil types of the study area are Xerosols, Arenosols and Vertisols (12, 13). Xerosols in the northern part of the area are generally fine textured with a clayey topsoil, comparatively rich in organic matter in spite of the low rainfall. Arenosols comprising the largest part of the area are coarse textured soils with aeolian origin, locally named Qoz soils (14). The texture is characterized by 60–70% coarse sand, 20–30% fine sand and 5–10% clay (15). A small part of the area in the south is covered by Vertisols locally named Gardud soil, which is a non-cracking clay soil, mixed with aeolian sand. 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.

The climate is semiarid 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 due to the lack of permanent water sources. Cultivation of mainly millet (*Pennisetum typhoideum*) and to a lesser extent sesame (*Sesamum indicum*), karkade (*Hibiscus sabdariffa*) and groundnuts (*Arachis hypogaea*), dominates when rainfall and water resources increase towards the south. Grazing by cattle and goats is also an important factor in the cultivated parts of the area. Camel grazing occurs in the northern part.

From interviews it is evident that the land-use practices have changed markedly from a rotation system with long fallow periods (15–20 yrs) interspersed with short periods of cultivation (4–5 yrs) (16) to more or less continuous cultivation over the last three to four decades. During the same period, crop yields have decreased (8). Crop yields have decreased mainly due to a marked decline of rainfall, but to some extent also due to the abandonment of fallow periods (17). Increased demand for food due to population increase combined with decreasing yields have forced farmers to extend their cultivated area primarily by reducing fallow periods. It is interesting to note that the decline of crop yield is of the same magnitude as the reduction of fallow periods, which has resulted in a net increase of cultivated area (17).

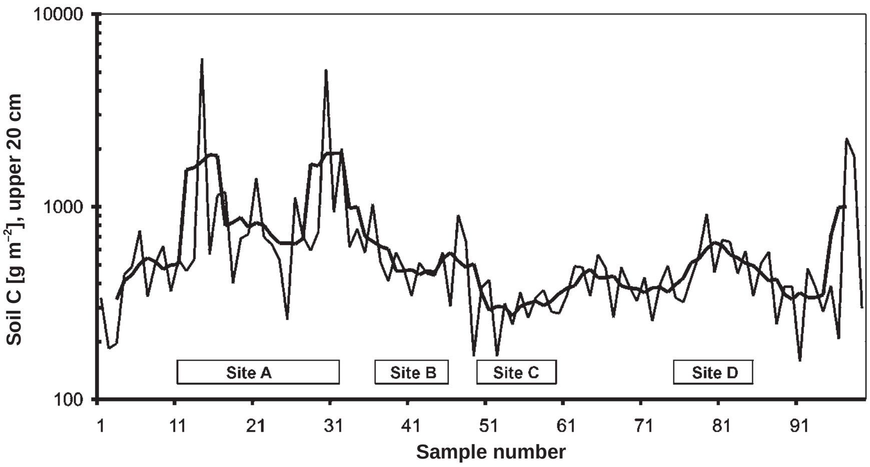
In order to estimate the effect of land management and climate on soil carbon content, a biogeo-chemical model, CENTURY was used. CENTURY is an ecosystem model simulating biogeochemical fluxes of carbon (C), nitrogen (N), phosphorous (P) and sulfur (S) (9–11). The primary purpose of the model is to supply a tool for ecosystem analysis enabling evaluation of changes in climate and management of ecosystems. The model uses a monthly time step and estimates, among other output variables, total soil C (g m^{-2}) for the upper 20 cm.

The soil organic carbon (SOC) in 1980 estimated with CENTURY was compared to the median SOC of a number of sample points (Table 1, Figs 1 and 2) for which the soil carbon content was measured in 1980. Below are descriptions of the simulations carried out at each site.

ESTIMATING CURRENT SOIL CARBON

For the 4 sites used (A-D, Table 1 and Fig. 1), we tried to mimic the actual environment, land-use (current and historical) and management as close as possible using available data. For all sites we ran the model to equilibrium (for 4900 yrs) before introducing any specific scenario. Generally, climate data were obtained from the Department of Meteorology, Khartoum, soil tex-

Figure 2. Soil organic carbon content (0–20 cm, g m^{-2}) measured in 1980 along the transect shown in Figure 1. Numbers on the x-axis refer to sampling numbers in Figure 1. Note the logarithmic scale. The solid line is a 5 sample running mean.



Typical vegetation and land use from site A (Gabra). A camel is browsing an Acacia (*Acacia* sp.). The ground is usually covered by a dense grass cover. Photo: J. Ardö.

Typical land-use scene from the site C (Bara 2). Large portions of the land are used for cultivation, in this case millet (*Panicium miliaceum*) and karkade (*Hibiscus sabdariffa*) are intercropped. Photo: L. Olsson.

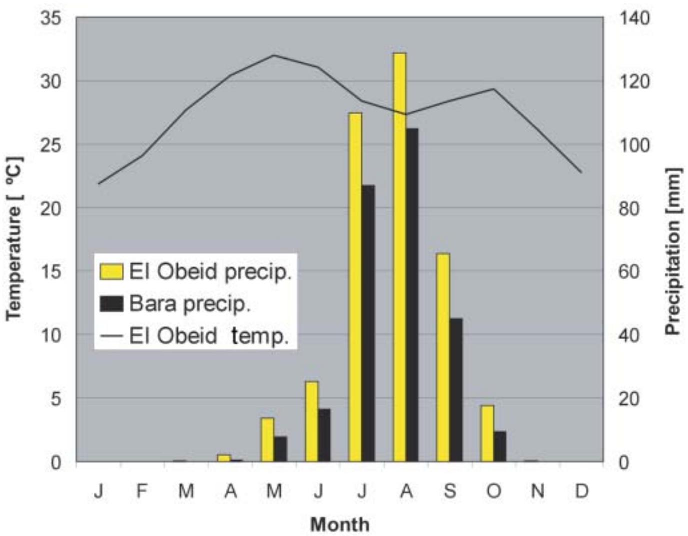
ture from FAO soil map of the world (12), field observations and literature (14, 15). Tree species, crops, management, length of fallow periods, etc. were determined by field observations, interviews and from the literature (8, 16, 18–24).

Climate data were available for 3 meteorological stations, Bara, (13° 42'N, 30° 30'E) with precipitation data for 1908–1988 and El Obeid Aero (13° 6'N, 30° 12'E) with precipitation data for 1902–1994. Almost all precipitation in the area occurs from May to October (Fig. 3). Temperature data (monthly min. and max.) were obtained from El Obeid Town (13° 6'N, 30° 18'E) for the period 1943–1985. For all sites temperature data from the El Obeid Town station were used. Missing data (< 10 observations per station) within the observation periods were replaced with mean values of all observations available for the month with missing data. For model simulations outside the time-span with actual observations, mean values of all observations for each month were used.

Description of the 4 sites and the modelling parameterization

Site A (Gabra), semidesert, grazed by camels.
Site A is located in the dry northern part of the study area (Fig. 1) on fine textured soil. As no precipitation data were available for Gabra, the precipitation record for Bara (see above), the closest station available, was scaled to an annual precipitation of 200 mm using $Gabra_{precipitation} = 0.74 \cdot Bara_{precipitation}$. This downscaling is based on linear interpolation between the station at Bara and the station at Hamrat el Wuz, some 100 km north. *Calibration scenario:* Until 1941 there was low intensity grazing during July– November each year and a fire in February every 9th year. From 1942–2000, the area was overgrazed (July–November) while the rest of the parameters were unchanged.

Figure 3. Mean monthly temperature for El Obeid and mean precipitation for El Obeid and Bara.



Site B (Bara1), grazing only.
This site is a savannah woodland/grassland with Acacia senegal and C4 grasses on a cambric arenosol in the central part of the area (Fig. 1). The soil is coarse textured and partly of aeolian origin. Precipitation data comes from the Bara station with a mean annual precipitation of 269 mm. The land-use in this site is characterized by light grazing only and low population pressure due to the lack of adequate groundwater supply. *Calibration scenario:* Low intensity grazing during July–October each year and fire every 9th year in February.

Site C (Bara2), millet cultivation.
Rotational millet cultivation with a decreasing crop:fallow ratio from 1891 to year 2000. This decrease is introduced to mimic the increased demand for food due to a higher population density and decreasing yields (17). Groundwater in this area is plentiful, and therefore the population density is high. Soil and climate data are the same as for Bara1. *Calibration scenario:* Before 1890 the area was grazed each year with low intensity from July to October with a fire occurring in February every 9th year. During all cropping periods there was a fire every year in May (before planting). During the fallow period, a fire occurred every 9th year. Crop: fallow ratios used were 5:20 (1891–1915), 5:15 (1916–1935), 5:10 (1936–1950), 5:6 (1951–1974) and from 1974 to 2000 continuous cultivation (i.e. no fallow) (20). From 1890 to 1950 there were trees (*Acacia senegal*) during the fallow periods. These were removed after each fallow period when cropping started again. There were no trees during the fallow periods after 1950. Each year after the harvest in October the area was grazed during November and December. During the fallow periods the area was grazed all year with low intensity. After 1974, the grazing intensified, simulating an intensified land utilization.

Site D (El Obeid), woodland savannah.
This site is a woodland savannah with *Acacia senegal* and C4 grasses on a fine textured Vertisol. The mean annual precipitation is 358 mm (Fig. 4). Calibration scenario: Prior to year 1942 the area was grazed annually with low intensity from July to October. From 1943 to 2000 the area was overgrazed all year round. Fire occurs every 5th year in February.

The results from the estimation of soil carbon content at the 4 sites using CENTURY is presented in Figure 4 and summarized below.

Table 1. Site and management variables used for estimation of soil carbon for 4 sites in central Sudan using CENTURY.

	A. Gabra	B. Bara 1	C. Bara 2	D. El Obeid
Site variables				
Mean annual precipitation (mm)	200	269	269	358
Texture (% sand, silt, clay)	(40,40,20)	(95,3,2)	(95,3,2)	(85,5,10)
Fire frequency (years) (in month)	9 (February)	9 (February)	See text	
Type of vegetation	Grassland (C4 grass)	Savanna with Acacia senegal, C4 grass	Millet cultivation/fallow with pasture	Savanna with Acacia senegal, C4 grass
Management	Grazing/ overgrazing	Low intensity grazing	Increasing Crop:fallow ratio	Grazing/ overgrazing
Points used for evaluation*	11–18, 28–33	36–45	50–60	75–85

*See Figs 1 and 4.

Site A (Gabra).
After an initial equilibrium phase, the SOC content slowly decreases when the overgrazing starts in 1942. In 1980, the estimated soil C was 672 g m^{-2} compared to the measured 746 g m^{-2}, a deviation of 74 g or 10% (Fig. 4).

Site B (Bara1).
This site is stable at a SOC content level around 300 g m^{-2} with minor oscillations due to climate. In 1980, the estimated soil C was 299 g m^{-2} compared to the measured 490 g m^{-2}, a deviation of 191 g or 37% (Fig. 4).

Site C (Bara2).
The SOC content started to decrease when millet cultivation was introduced in the

1890s. The increased crop: fallow ratio from 5:20 to continuous cultivation from 1975 and onwards caused a decrease in the soil C content. In 1980, the estimated soil C was 146 g m^{-2}, compared to the measured 338 g m^{-2}, a deviation of 192 g or 57% (Fig. 4).

Site D (El Obeid).
After an initial stable SOC content around 320 g m^{-2} a small increase occured from 1960 and onward. In 1980, the estimated soil C was 372 g m^{-2}, compared to the measured (median of the evaluation points) 513 g m^{-2}, a deviation of 141 g or 27% (Fig. 4).

ESTIMATING FUTURE SOIL CARBON SEQUESTRATION POTENTIAL

In order to investigate the potential for increasing the soil carbon content through land-management changes a number of future scenarios were simulated for Site B. Six different land management scenarios were simulated for the period 2000–2100. The land-management scenarios were: continuous cultivation, crop:fallow ratios of 5:6, 5:10, 5:15, 5:20, and no cultivation only grazing. All 6 scenarios were continuations of the scenario for Site B presented above. The results of the simulations are shown in Figure 5.

The current millet cultivation in the vicinity of Bara is often continuous without fallow periods. 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 carbon). This is illustrated in Figure 5.

A land-use change from millet cultivation to grazing is estimated to increase the soil carbon content with approximately 147 g m^{-2} to 245 g m^{-2} in 100 yrs. This is 82% of the equilibrium phase prior to millet cultivation. If continuous millet cultivation occurs into the future, further decreases in the soil carbon content is expected to 68 g m^{-2} in the year 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 5, to 115, 128, 163, and 170 g m^{-2}, respectively, by 2100.

ECONOMIC SIGNIFICANCE OF SEQUESTRATION

In order to put the estimated gain from carbon sequestration into the farmer's perspective, prices of agricultural products and assumed prices of carbon were compared. Agricultural yields of the staple crops in Sudan are shown in Figure 6. These figures are however significantly higher than the yields reported by farmers in the study area, mainly due to the fact that the study area is a drier than average farming area. The millet yield used for comparison in Table 2 has been set to 150 kg ha^{-1}, which is an average from interviews carried out in 2000. According to interviews in a comparable region the average farm size is 22 ha of which 7.3 ha is cultivated. If carbon is sequestered on these lands according to the estimations above, the potential economic gain would be as shown in Table 2. At a price of USD 20 per $tonne^{-1}$ the economic gain from converting cultivation to grazing land would be about 30% of the crop yield normally obtained (based on the current local market price of millet). However, if costs and labor required to produce the crop are taken into account the economic gain from carbon sequestration is much more

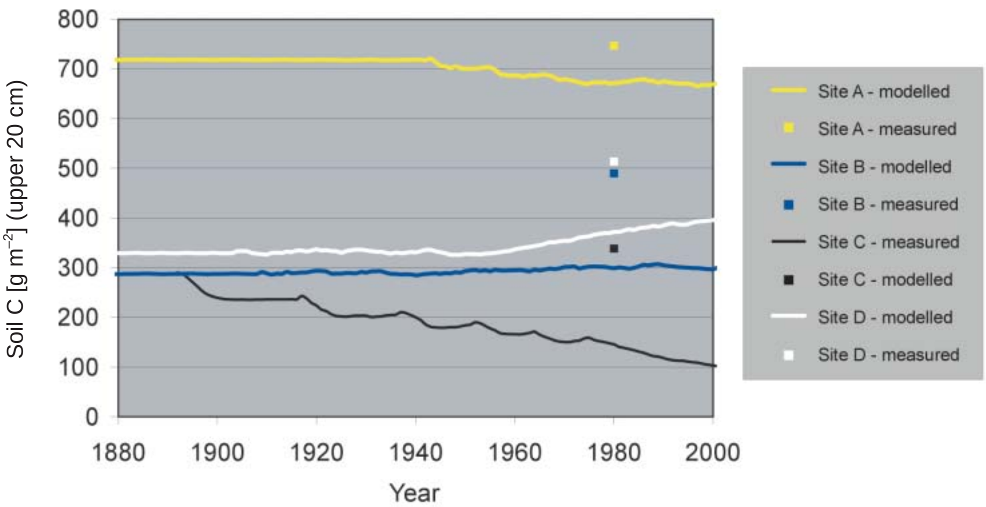


Figure 4. Result of the modelling of soil organic carbon content (lines) and the measured values (symbols).

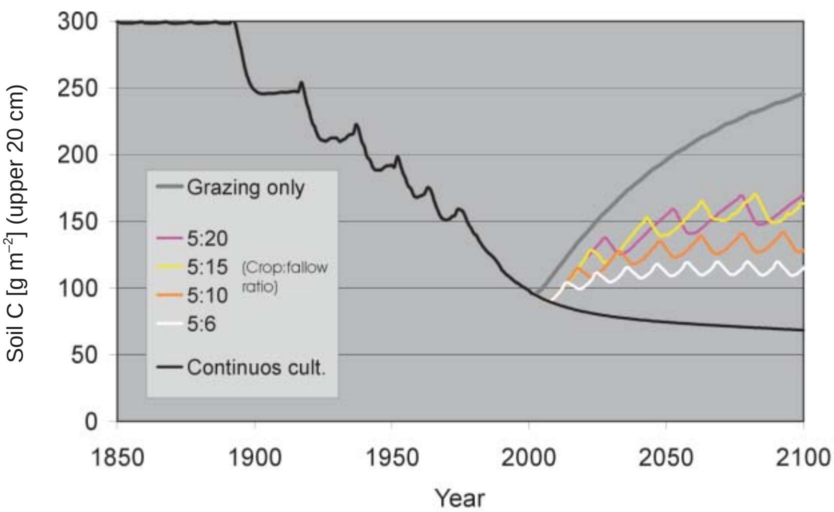


Figure 5. Recovery scenarios for site B, based on modelling of soil organic carbon content according to the scenarios described in the text.

Figure 6. Yield of groundnuts, millet, sesame and sorghum from The Sudan, 1961–2000. Source of data: FAO.

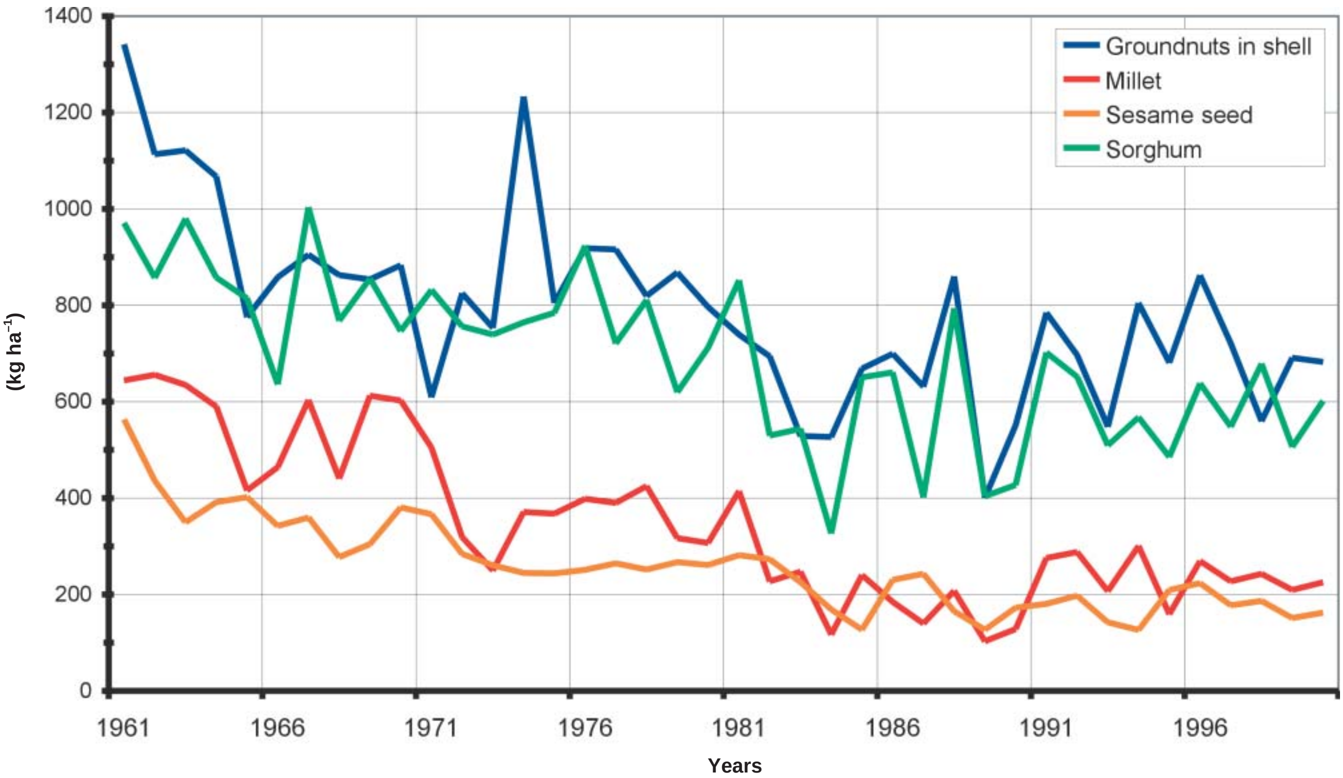


Table 2. Annual economic gain from adopting land management changes according to scenarios in Figure 5 for 3 different price levels of carbon. The units are USD and percentage of the average yield of millet.

Management practice	Sequestration over 100 years ($g\ m^{-2}$)	Carbon Price: 10 USD	Carbon Price: 20 USD	Carbon Price: 30 USD	Normal yield at 10 USD	Normal yield at 20 USD	Normal yield at 30 USD
5 : 6	17	0.12	0.25	0.37	2%	4%	5%
5 : 10	30	0.22	0.44	0.66	3%	6%	9%
5 : 15	65	0.47	0.95	1.42	7%	13%	20%
5 : 20	72	0.53	1.05	1.58	7%	15%	22%
grazing	150	1.10	2.19	3.29	16%	31%	47%

significant. A study carried out in a neighboring region (25) showed that the economic gains from several crops were negative, i.e. the investments were higher than the economic value of the harvest on the local market. The study showed that only the income from water melons 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 carbon sequestration becomes economically important for farmers is very low.

DISCUSSION

The efforts to estimate the current soil carbon content are reasonable with a deviation ranging from 10 to 57% (74–192 g C m^{-2}). Site A illustrates a slowly decreasing (49 g C from 1942–2000) soil carbon content as a result of grazing. The grazing pressure in the area varies substantially from year to year depending on precipitation. Site B, with summer grazing only, differs from Site A and have a soil carbon content that is almost stable around 300 g C m^{-2}. The difference between 1880 and 1980 is only 10 g m^{-2}.

For all 4 sites, CENTURY underestimates the soil carbon content compared with the field data. This can be the result of the "reverse texture effect", in which the greater infiltration rate and hence lower bare-soil evaporation rate in coarser textured soils results in higher production in arid environments (11). Estimated primary production may also be lower than actual production since no N-fixation for Acacia senegal was included in the simulations, potentially yielding lower simulated soil N than the actual soil N content.

Generally, available data do not indicate any consistent response of SOC and nitrogen to grazing (26). Both decreased (27–29) and increased (26, 30) SOC have been reported as a result of grazing.

Earlier results generated with the CENTURY model are within ± 25% of the observed soil C content (31). This, however, is valid for sites with much more detailed information than we have had access to here. More detailed input data may produce results closer to the measured soil carbon content.

How the length of the fallow periods influence the soil carbon content are currently being investigated using soil sampling and interviews carried out in western Sudan (32). The preliminary results support the modelled results presented here.

The studies clearly indicate that carbon sequestration might be a significant contribution to the household economy (Table 2). The main reason for this is of course that livelihoods are to a large extent based on subsistence, which means that even a small financial contribution from outside will have a significant effect. It is our hope that it might be possible to develop this into a mechanism that could trigger a chain reaction of development in the drylands.

RECOMMENDATIONS FOR FURTHER STUDIES

It is likely that carbon sequestration can be increased significantly in degraded agro-ecosystems in drylands of the world and that this will be beneficial for their productivity. However, land-management improvements have been tested and applied before, and are known to be difficult to implement for a variety of reasons. One reason might be the question of social acceptance, but it might also be negative unforeseen economic and/or environmental side effects. It is therefore essential to pay attention to the implementation and sustainability of these land-management strategies. One important constraint for a successful implementation of improved land management is that people often are too poor to forego the present for a future improved productivity. A successful implementation of a benign carbon trading scheme might be the kind of economic incentive needed to implement improved land management on a larger scale than hitherto seen. We recommend that intensified research should be carried out to:

- elucidate the carbon balance over the last three decades in selected degraded agro-ecosystems in Third World countries in order to establish the potential for increased carbon sequestration in these ecosystems in a quantitative form;
- further investigate the effect of grazing on soil carbon and other nutrients and to better incorporate this knowledge into models for prediction of soil carbon content;
- achieve an operational method for monitoring of carbon sequestration in these agro-ecosystems, based on combined measuring and modelling at different scales;
- determine quantitatively the carbon sequestration gains of different land-use practices in these agro-ecosystems;
- carefully assess the conditions for implementing land management strategies for increased soil carbon sequestration and improved land productivity;
- determine the economic and social gains for the different parties from an international trade of carbon emission rights.

So far the Kyoto Protocol does not include crediting for carbon sequestration in agricultural soils, even though this might be the most efficient and environmentally sound activity. There is, however, growing pressure to include soil conservation and agricultural land management in the range of activities recognized and regulated under the Kyoto Protocol.

It is important to recognize that many technologically advanced agricultural practices, like irrigation, fertilizers and pesticides, aimed at enhancing biological production have hidden costs in terms of carbon released to the atmosphere in their manufacture, delivery and application (33). The most cost effective and environmentally friendly technique to increase sequestration of atmospheric carbon is through the large-scale adoption of ecologically sound land-use, for example: crop rotation, increased fallow periods, agro-forestry, soil conservation, conversion of marginal agricultural land to rangeland.

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