Carbon Sequestration in Tropical Dryland Agroecosystems

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1. Methodology for Modelling Soil Carbon in Semi-arid Farming Systems

Modeling has been used as an effective methodology for analysing and predicting the effect of land management practices on the levels of soil carbon. A number of process-based models have been developed over the last two decades to fulfill specific research tasks and consequently 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 (SOMNET) also provides a comprehensive description of many models currently available.

1.1 Choice of models for analysis of tropical dryland agricultural systems

RothC (RothC-26 3, Coleman and Jenkinson (1995), Jenkinson and Rayner (1977)) and CENTURY 4.0 (Parton *et al.*, 1987, 1988) are the most extensively used soil organic carbon simulation models. They have been tested against a variety of long-term agricultural field trials and have also been used in a variety of climatic 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 the fewest data inputs and so is simpler to parametise. However, it only deals with soil processes and consequently plant residue carbon is a required input.

The CENTURY agro-ecosystem model has similar soil organic carbon pools but has the advantage of additional sub-models. Although it is able to handle a great many more land management options than RothC, this requires an increased array of input variables that require parmetisation. This is an important point because the ability of any model accurately to predict into the future depends on the accuracy and trustworthiness of the data used to parametise the model.

1.2 Approach adopted for parametising RothC and CENTURY for predicting effects of land management practices on soil carbon in drylands

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

Climatic parameters may be referred to by investigators reporting the effects of land management on soils, but complete data sets are rarely given. Fortunately climatic data is available independently, such as FAOCLIM 2 (2000), which contains a database of over 28,000 weather stations worldwide.

The literature contains the results from many investigations analsying 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. Again, there has been little research on dryland systems.

For the case studies examined here, CENTURY was parametised and run to equilibrium for between 2000 and 5000 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 practiced 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 analyzing the effects of land management on soil carbon, the appropriate plant residue inputs were obtained from the CENTURY plant sub-model and then used to parametise the RothC land management files. Frequently this results in RothC predicting higher levels of soil carbon than CENTURY. This has been noted before and has been attributed to the fact that soil organic carbon tends to turnover faster in CENTURY than RothC, and consequently RothC requires lower carbon inputs to maintain the same organic carbon content (Falloon and Smith, 2002). The CENTURY plant sub-model is quite basic and if 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).

1.3 Choice of systems and sources of data

We use data from four distinctly different dryland systems in Nigeria, India, Kenya and Argentina to model changes in soil carbon with a variety of farm practices and technologies. These systems had different pre-cultivation stocks of soil C, and have lost differing amounts during cultivation (see Table 1). Additions of organic matter to the soil through use of farmyard manure, green manures, legumes in rotations, vermicompost, or use of fallows in rotations, all increased soil carbon as well as increase 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 carbon in all systems, or only small increases if used with zero-tillage. Zero-tillage increases soil carbon, though again the accumulation is greatest where organic matter is added to the soil.

The scenarios show that carbon sequestration 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 carbon sequestration. Crop residues may be required for livestock feed or fuel rather than be returned to the fields, or during difficult times may be sold. Animal manures may be burned 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 carbon can be restored to pre-cultivation 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 at least several centuries or millennia such as in the Nigeria and Kenya cases. 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 carbon sequestration rates are often associated with the introduction of trees to the system. 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 (Falloon and Smith, 2002).

Table 1. Summary of findings on carbon stocks and rates of accumulation and/or loss in four dryland agroecosystems

	Nigeria	**India**	**Kenya**	**Argentina**
Stocks of soil C before cultivation (t ha^{-1})	8-23	15-20	33-41	50-70
Current stocks of soil C after cultivation (t ha^{-1})	6-12	13-22	18-28	37-41
Effect of conventional tillage practices on soil C (t ha^{-1} y^{-1}) [1]	- 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 (t ha^{-1} y^{-1})	+ 0.1 to + 0.3	+ 0.2 to + 0.4	+ 0.4 to + 0.9	-
Effect of trees (t ha^{-1} y^{-1})	+ 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 (t ha^{-1} y^{-1})	- 0.12 to + 0.08	- 0.01	- 0.3	-
Effects of ZT				
ZT alone				+ 0.02
ZT + green manures or fym				+0.1 to +0.25
ZT + 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)

Information for the Nigerian and Kenyan case studies was kindly supplied by Drylands Research, Crewkerne, UK. The Indian case study utilised data collected by the Natural

Resources Institute, Chatham, UK in association with the Deccan Development Society, Hyderabad and Pastapur and the BAIF Institute of Rural Development, at Tiptur and Lakihalli, India. Details of the tillage systems in Argentina were provided by E. Rienzi. We are very grateful for the assistance provided by Michael Mortimore and Mary Tiffen at Drylands Research, B. Adolph & J. Butterworth at NRI, V. Srinivas at BAIF and Roberto Peiretti of AAPRESID and CAAPAS in Argentina.

Case Study 1
Nigeria - Kano Region

Introduction

Nigeria comprises some of the most densely inhabited areas of semi-arid West Africa (Harris, 2000). This is not a recent phenomenon as indication 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, recently this trend has intensified because over the last 40 years the cultivated area of northern Nigeria has increased from 11% to 34% of the total land area (Harris, 2000). In particular the Kano Close-Settled Zone exhibits a level of agricultural intensity not found elsewhere in semi-arid west Africa.

Investigations into the farming systems of this region and their effect on soil fertility have been conducted by Drylands Research. Overall their studies have found a close correlation between the intensity of farming and the adoption of soil fertility management techniques. Generally, in the Sahel, plant production is limited either by rainfall or nutrients (Breman and De Wit, 1983). However, the economy and infrastructure of northern Nigeria is not suited to high external inputs such as fertilizers. Consequently the smallholder farming units operate as low input systems, with the most common form of organic input into agriculture being cattle manure.

Physical Aspects

This semi-arid region has a rainy season from May-July until September. However rainfall is erratic (Mortimore, 2000) and this makes crop cultivation particularly difficult. The soils are principally ferruginous tropical soils that are sandy with poor water-holding capacity and contain 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 > 60 %. The low intensity systems operate a shrub/short bush fallow regime and the cropping intensity is between 30% and 60%. Finally, the extensive system is one of long bush-fallow and uncultivated areas, where the cropping intensity is typically < 30 %.

The major crops grown are millet, sorghum, groundnut, sesame and cowpea. Since the systems are low input, yields of grain are only about 1 t ha^{-1}. 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 of the order of 1 – 7 t ha^{-1}. Crop residues are either collected for fodder or else left to be grazed in the fields.

Fallowing is practiced in the less intensive systems although the land is still ‘harvested’ through grazing and collection 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, for providing nitrogen input. Inorganic fertilizers are scarce and seldom available at the optimum 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 parametised 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 2 seasons of millet cultivation incorporated, repeated every 60 years. In the 19th century, the frequency of cultivation events was increased to a thirty-year cycle, and then once every 15 years by the commencement of the 20th century.

i) Futchimiram, Borno State

This is a low intensity, or extensive, agro-pastoral system practising shifting cultivation. Some land has now become degraded. CENTURY was run for the last 60 years with alternate 5-year cycles of grazing and millet cropping. Crop residues are grazed and there are no other inputs. This current practice produces a gradual decline in soil carbon that persists into the future (Figure N1a). The estimated level is slightly above the measured value of soil carbon for cultivated soils that range between 3.5 and 4.4 t ha^{-1}. RothC also predicts that the current practice will slightly decrease soil carbon over the next 50 years (Table N1a). The scenarios in Figure N1a, detailed in Table N1b compare current practices with additions of inorganic fertilizer, farmyard manure, plant residues, fallow removal, retained plant residues and grazing. Figure N1b illustrates predicted average annual change of soil carbon over a 50 year period.

Table N1a Total soil carbon (t ha^{-1}) for Futchimiram settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
1	5.54	4.94	-10.8	5.38	5.18	-3.7
2		3.93	-29.1		3.72	-30.9
5		9.4	69.7		9.7	80.3
6		10.57	90.8		12.45	131.4

[1] scenarios described in Table N1b

Table N1b Scenarios for modeling 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 fertilser only (100 kg ha^{-1} urea), no grazing
5	plant residues average 0.5 t ha^{-1} y^{-1}, no grazing of residues

6	5 y fallow, 5 y cultivation, 2 applications fym 3 t ha^{-1}, graze residues
7	continuous cultivation, fym 1.5 t ha^{-1} y^{-1}, graze residues
8	continous cultivation, fym 1.5 t ha^{-1} y^{-1}, plant residues 0.5 t ha^{-1} y^{-1}, no grazing

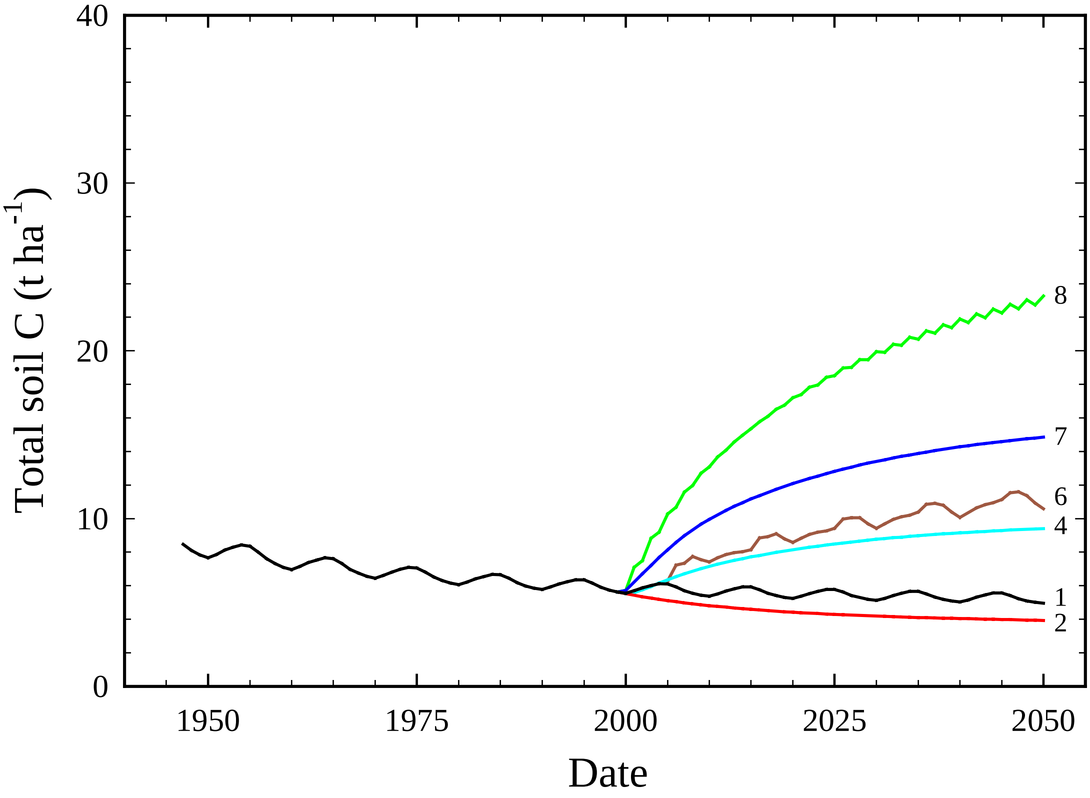

Figure N1a Total soil carbon for Futchimiram settlement (CENTURY)
scenarios described in Table N1b

Effect of loss of fallow

Removing the fallow period only (scenario 2) results in a greater decline in soil carbon over subsequent years, with both models predicting similar reductions (Figure N1a, Table N1a). Preventing grazing of the crop residues under these conditions (scenario 3) has very little effect on soil carbon (Figure N1b).

Effect of organic inputs

Addition of farmyard manure (2 applications of 3 t ha^{-1} in each 5 year cropping cycle, average 0.6 t ha^{-1} y^{-1}) has a positive effect on soil carbon, the two models indicating an increase of 5 to 7 t C ha^{-1} over the next 50 years (0.08 t C ha^{-1} y^{-1}). Figures N1a,b show the outcome of further scenarios using different combinations of fallow and organic inputs. The gradual increase in soil C occurs with farmyard manure (fym), retaining plant residues and no grazing after harvest, with soil stocks rising from 6 to 24 C ha^{-1} 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 carbon sequestration (0.08 t C ha^{-1} y^{-1}).

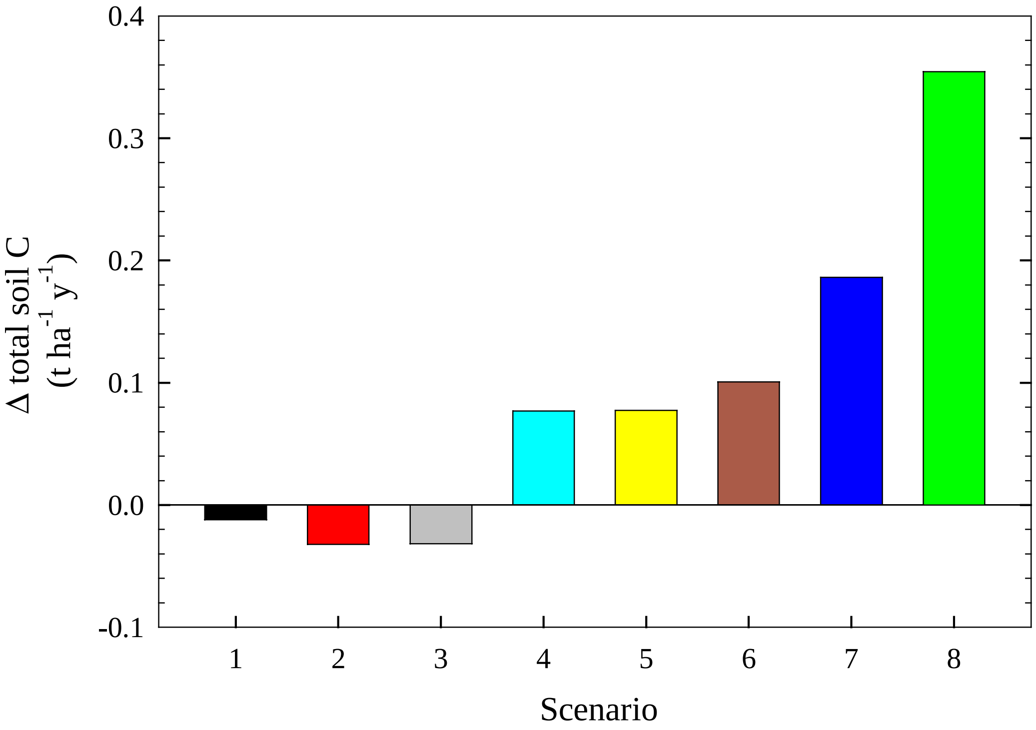

Figure N1b Average annual change in total soil carbon for Futchimiram settlement (CENTURY) scenarios described in Table N1b

Summary

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

ii) Kaska, Yobe Sate

This is a low intensity agro-pastoral 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 parametised for the last 50 years with a 7-year cycle of 4 years grazing and 3 years millet-cowpea-millet cropping. Farmyard manure (0.75 t ha^{-1}) was added in the first year of each cropping cycle. Cultivated soils have carbon contents of 4.5 – 7.0 t ha^{-1}. The CENTURY model calculates a current carbon content of 7.7 t ha^{-1} (Figure N2a), and RothC gives a similar result (Table N2a). Both models suggest that with current practice the system is close to steady state.

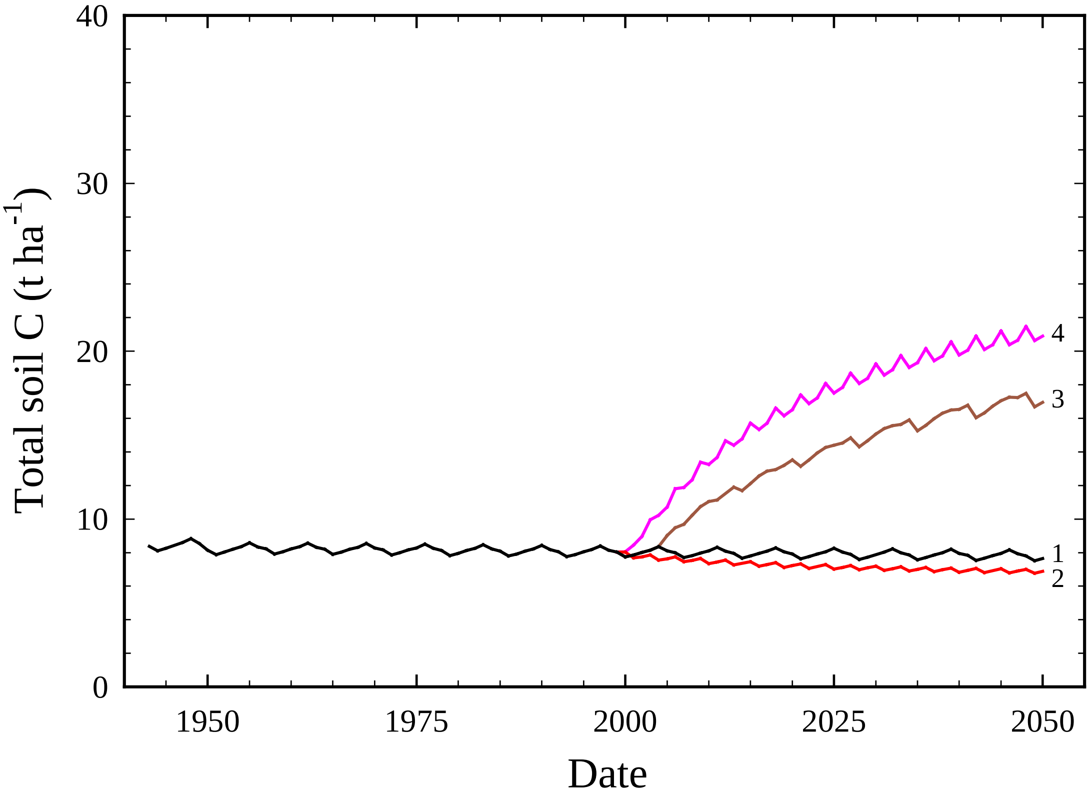

Figure N2a Total soil carbon for Kaska settlement (CENTURY)
scenarios described in Table N2b

Table N2a Total soil carbon (t ha^{-1}) for Kaska settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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 N2b

Table N2a Scenarios for modeling land management practices, Kaska settlement

Scenario	Land Management
1	current practice
2	continuous cultivation, millet-cowpea
3	cultivation-fallow, fym 3 t ha^{-1}, to millet
4	continous cultivation, fym 3 t ha^{-1}, to millet

Effects of fallows and organic inputs

Removing the fallow from the current practice (scenario 2) leads to a slight decline in soil carbon in subsequent years (Figures N2a,b). Applying 3 t ha^{-1} farmyard manure to each millet crop (average 1.3 t ha^{-1} y^{-1} over 7 year cycle) will produce a marked increase in soil carbon (Table N2a) representing a carbon sequestration rate of 0.18 t ha^{-1} y^{-1}, Figure N2b . This increase will be enhanced still further if the fallow is removed because the manure application rate will now average 2 t ha^{-1} y^{-1} (Figures N2a,b).

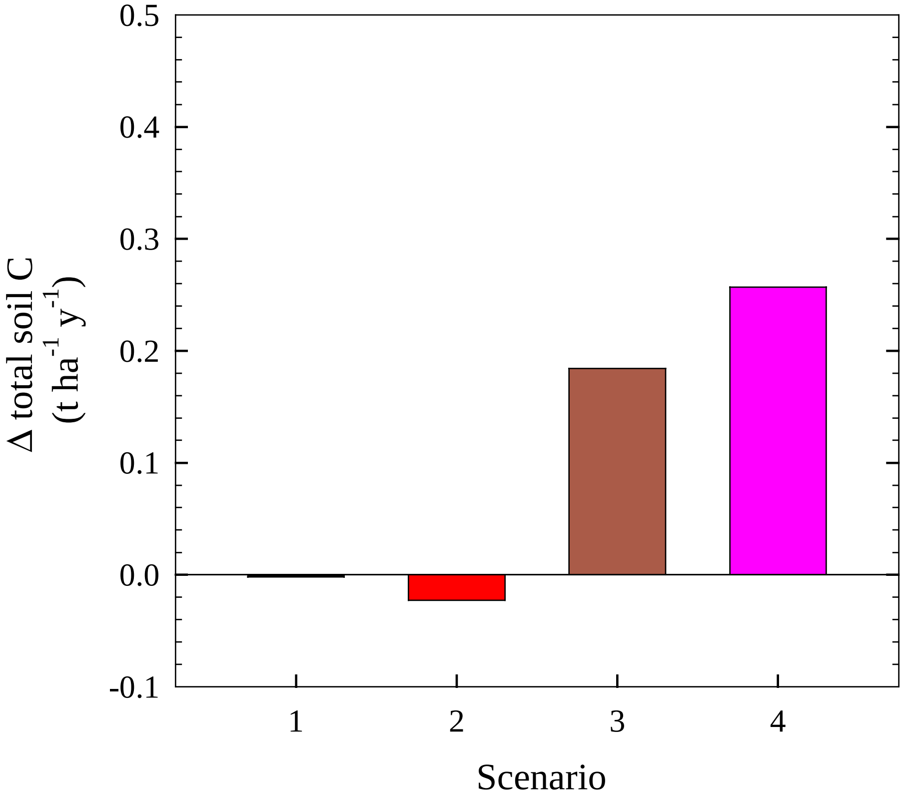

Figure N2b Average annual change in total soil carbon for Kaska settlement (CENTURY) scenarios – described in Table N2a

Summary

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

iii) Dagaceri, Jigawa state

This is a region undergoing rapid intensification. It is an agro-pastoral 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 increasingly rely upon manures to maintain soil fertility.

The parametisation 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 and 1.5 t ha^{-1} manure is added to each millet crop (average 0.64 t ha^{-1} over 7 year cycle).

The additional manure input associated with the increase in cropping intensity has resulted in an increase in soil carbon, predicted by both models, and this rise continues in subsequent years (Figure N3a, Table N3a). Field measurements vary according to previous cropping intensity and range between 3 and 17 t C ha^{-1}.

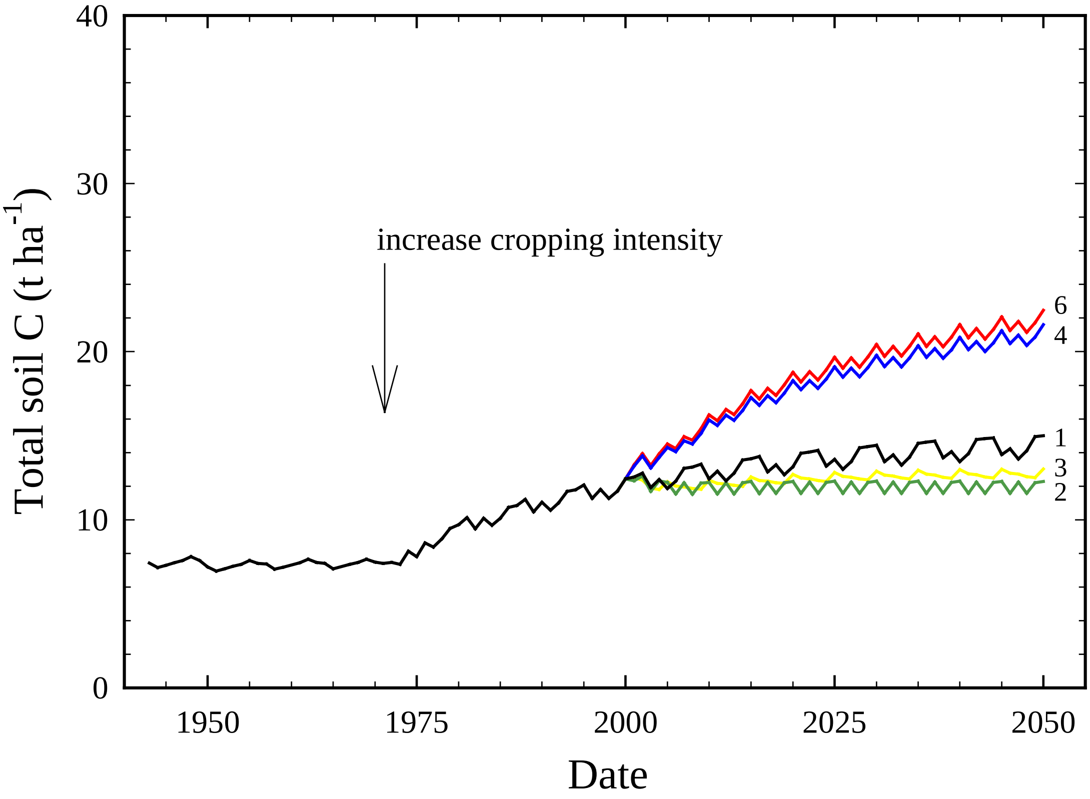

Figure N3a Total soil carbon for Dagaceri settlement (CENTURY)
scenarios described in Table N3b

Table N3a Total soil carbon (t ha^{-1}) for Dagaceri settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
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 N3b

Table N3b Scenarios for modeling land management practices, Dagaceri settlement

Scenario	Land Management
1	current practice
2	remove trees
3	no grazing of residues, harvest all above ground
4	continous cultivation, millet-cowpea
5	fym average 1.29 t ha^{-1} y^{-1},fallow, graze residues, harvest only grain
6	no grazing of residues, harvest only grain

Effects of fallows and organic inputs

The manure input to each millet crop is increased to 3 t ha^{-1} in all scenarios (2-6). Carbon sequestration rates of between 0.18 and 0.20 t ha^{1-} can be achieved, with slight differences occurring depending on whether or not the fallow is retained and crop residues grazed or un-grazed (scenarios 4-6, Figures N3a,b, Table N3a). However, if fallow elimination is accompanied by harvesting all above ground material (scenario 3), carbon sequestration is virtually halted even if manure application is maintained.

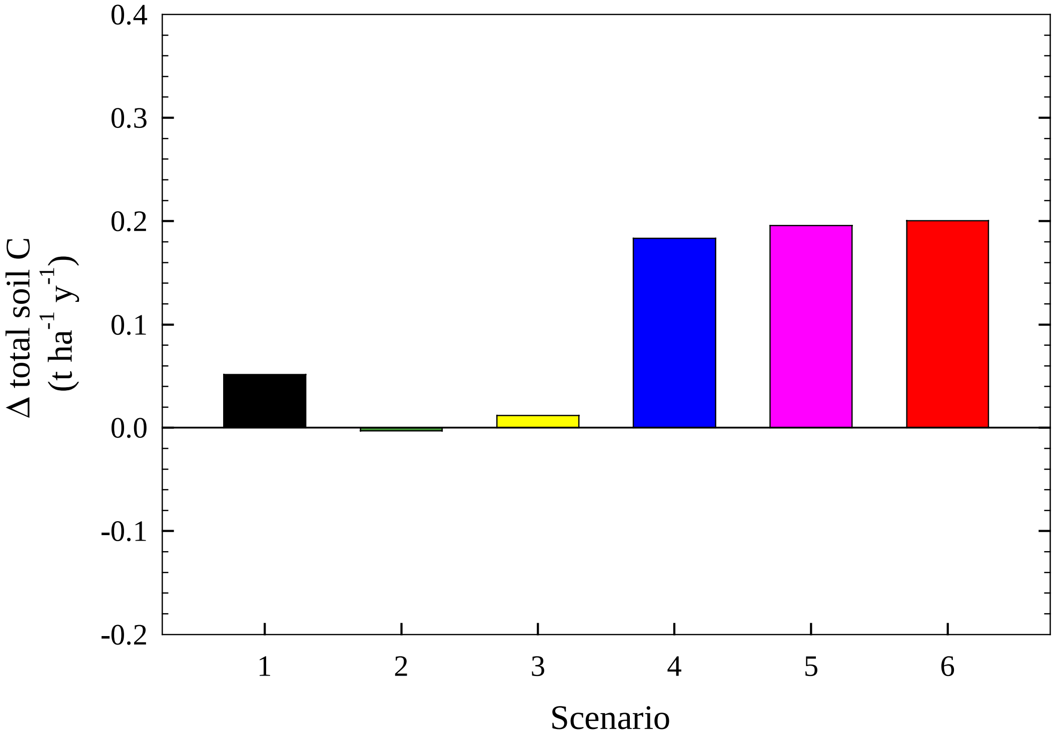

Figure N3b Average annual change in total soil carbon for Dagaceri settlement (CENTURY)

scenarios described in Table N3b

Effect of Trees

Completely removing trees from the system results in a net loss of soil carbon in spite of the increased application of manure.

Summary

This system shows that soil organic matter 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 (CSZ)

This is a highly intensive agricultural area. All the land is cultivated although degradation is reportedly less than 10% of the land area in this district. 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 be fed with crop residues and fodder grown on nearby fields.

CENTURY was run for the last 50 years with a millet-cowpea rotation, 6 t ha^{-1} manure applied to the millet (average 3 t ha^{-1} y^{-1}) and all above ground plant material harvested. This system is now close to steady state with soil C stocks at 9.8 t C ha^{-1} (Figure N4a). This compares with an average of 10.5 ± 1.7 t C ha^{-1} measured at cultivated sites. RothC calculates a value of 11.3 t ha^{-1} for 2000 but predicts that a higher soil carbon level will be reached by 2050 (Table N4a).

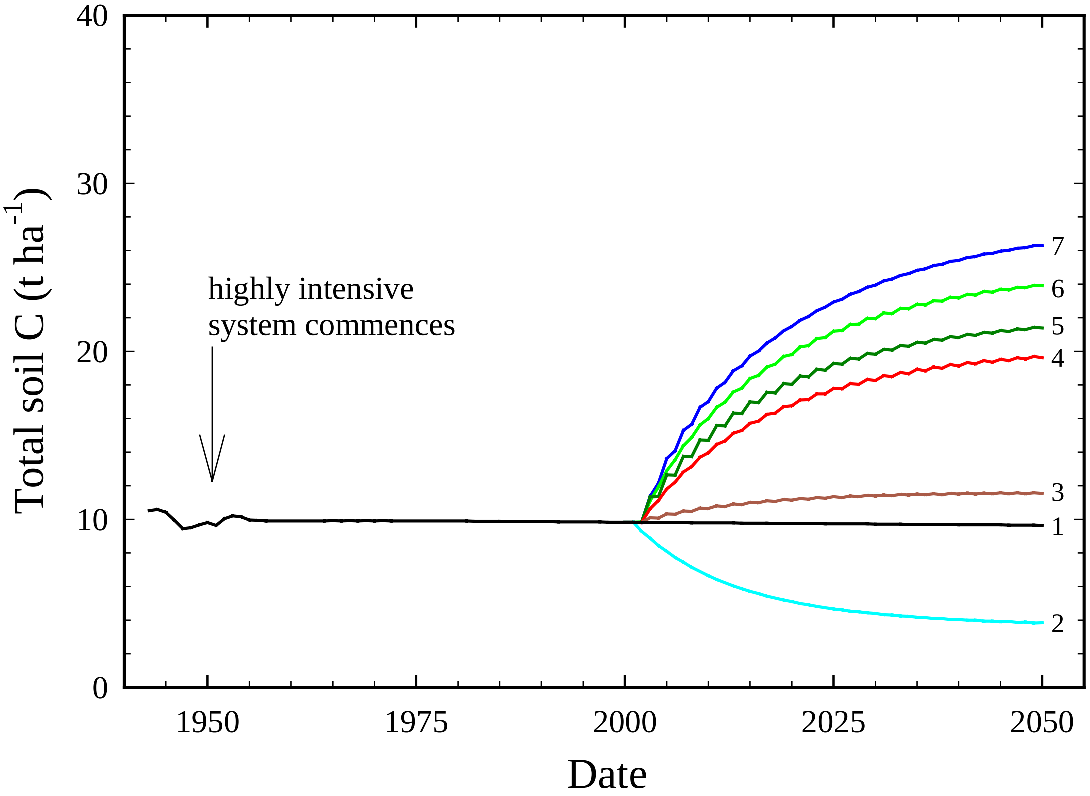

Figure N4a Total soil carbon for Tumbau settlement (CENTURY)
scenarios described in Table N4b

Table N4a Total soil carbon (t ha^{-1}) for Tumbau settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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

[1] scenarios described in Table N4b

Table N4a Scenarios for modeling land management practices, Tumbau settlement

Scenario	Land Management
1	current practice
2	inorganic fertilser (110 kg ha^{-1} urea)
3	fym 3.75 t ha^{-1} y^{-1}
4	fym 6.75 t ha^{-1} y^{-1}
5	fym 3.75 t ha^{-1} y^{-1}, add nitrogen-fixing trees
6	fym 6.75 t ha^{-1} y^{-1}, plant residues 2 t ha^{-1}
7	fym 6.75 t ha^{-1} y^{-1}, harvest only grain

Effects of organic inputs

Additional farmyard manure inputs have a marked impact on soil carbon, especially when they approach the maximum (7 t ha^{-1}) normally applied in this region, i.e. an annual input of 6.75 t ha^{-1} will result in the sequestration of 0.20 t C ha^{-1} y^{-1} over the next 50 years (Figure N4). Although adding nitrogen-fixing trees and plant residues to the fields will further increase soil carbon, the requirement of the former for livestock feed may exceed the capacity of the current farming system.

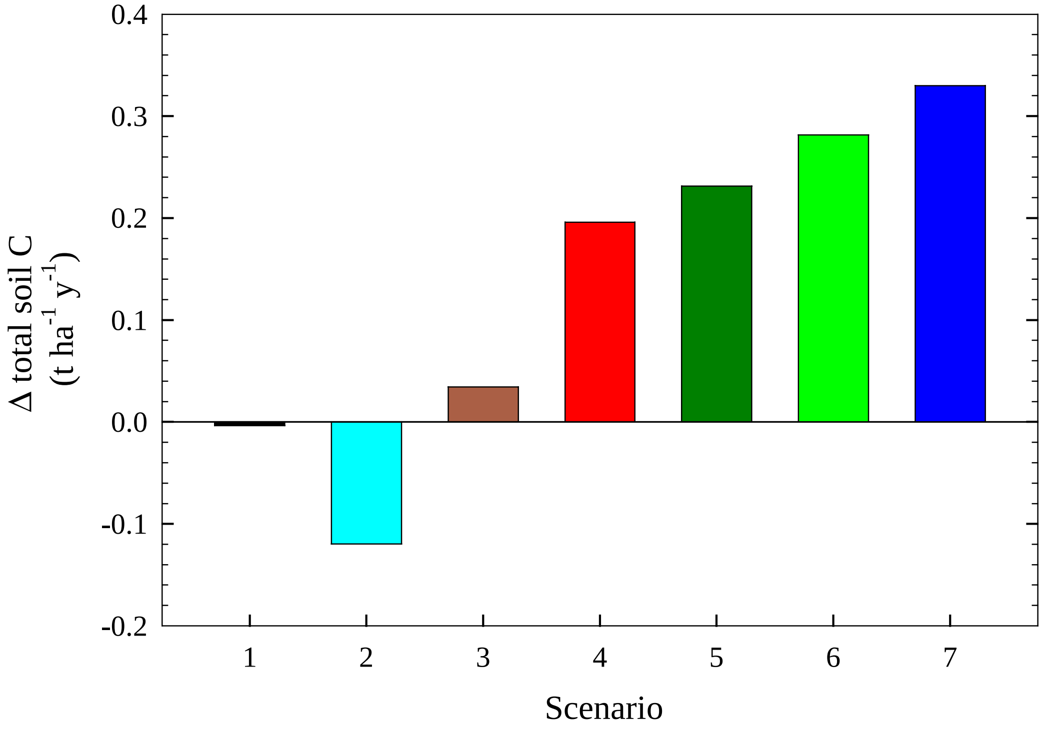

Figure N4b Average annual change in total soil carbon for Tumbau settlement (CENTURY) scenarios described in Table N4b

Effect of inorganic fertilizer

Replacing the manure input to this system with inorganic fertilizer (urea 100 kg ha^{-1}, scenario 2) results in a large reduction in soil carbon, with stocks falling by > 0.1 t C ha^{-1} y^{-1}.

Summary

Although cropping is intense, providing that adequate organic matter is returned to the soil these farm systems should maintain soil carbon and there is scope for carbon sequestration. These results are in agreement with findings in the field that provide no evidence for a decline in soil organic matter in spite of increased cultivation pressure. However, the ability to realise future carbon sequestration 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 most likely result in substantial losses of soil organic matter.

Conclusions from northern Nigeria cases

The modeling of farm data for the drylands of northern Nigeria shows that soil carbon stocks can be increased from a low base with a variety of technologies and practices already available to farmers.

The total amounts of carbon that can be sequestered with use of legumes, fallow periods, farmyard manure and retention of plant residues varies between 0.1 to 0.3 t C ha^{-1} y^{-1}. This rises when trees are also cultivated.

Soil carbon is again lost when only inorganic fertilizers are used to maintain soil fertility – some 0.1 t C ha^{-1} y^{-1} in the intense systems of the Kano CSZ. Continuous cultivation results in small year on year losses of carbon 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 is shown in these modeled scenarios.

Case Study 2
India - Andhra Pradesh and Karnataka States

Introduction

Over half of the farming population of India live in climatic 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 so inaccessible for the rural poor. This may also lead to declines in soil fertility, and are also dependent upon fossil fuel energy (Butterworth *et al.*, 2002). In fact, nearly two-thirds of the arable land in India remain solely dependent upon rainfall for agricultural production. The Natural Resources Institute (Chatham), the Deccan Development Society and BAIF Institute for Rural Development (India) have studied soil fertility management in the Medal district of Andhra Pradesh and the Tumkur district of Karnataka (Butterworth *et al.*, 2002). They have shown that there is an increasing awareness of technologies and practices for maintaining and improving soil fertility, identifying at least fourteen different practices from legume cultivation to vermicompost production. The majority of these involve maintaining and increasing the organic matter content of the soil. Consequently these studies provide an opportunity to investigate what effect these soil fertility improvement techniques may have on carbon sequestration.

Physical aspects

The 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 over 80% of rainfall occurs (kharif, June-October). Average rainfall is just below 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 between 120 and 150 days.

The major soils 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, including the black cotton soils are potentially more productive with a higher water-holding 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 this area is usually between 0.5% and 1% (K. Srinivas, pers. comm.). 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. The Medak district falls within zones III and IV of the agro-ecological zones classified in Andhra Pradesh, and Tumkur district in Karnataka falls within the south eastern dry zone.

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 agro-biodiversity that is combined with offfarm activities, particularly in Medak district. This makes for an efficient use of the limited land resources and acts as insurance against unpredictable weather conditions, a frequent problem in drylands. Farm sizes are small, on average just 2.6 ha (Butterworth *et al.*, 2002). The small and marginal farmers can grow at least 8-10 varieties of crops per half hectare. However 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 that bullocks make a vital contribution as draught animals, not least in the transport of farmyard manure. Tillage is commonly performed with very basic implements. The greatest shift towards mechanised cultivation has been in Karnataka.

The predominant crops grown in the Medak district are paddy, sorghum and maize whilst irrigated sugar cane is an important cash crop. Major crops grown in Karnataka are paddy, sorghum, finger millet, pearl millet, pigeon pea, green gram, groundnut, coconut, cotton, sugarcane, chilli and tobacco (Reddy, 2001).

Maintenance of soil fertility is given a high priority by farmers whilst inorganic fertilizers are ranked poorly in terms of maintaining soil quality. However, many farmers are forced to use them because organic alternatives are often unavailable and because the cost of inorganic fertilizers is subsidised. Still, the importance attached to soil fertility can have unforeseen consequences such as the sale of farmyard manure 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 at the expense of degrading neighboring areas.

Modelling soil carbon in the study villages

The CENTURY agro-ecosystem model was paramatised using climatic 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 slowly increased and by the commencement of the 20th century, cultivation periods of 4 years out of 10 were introduced. In the mid 20th century one year of grazed fallow was followed by 4 years cropping (sorghum-kharif, cowpea-rabi). Cultivation consisted of hand or bullock ploughing and hand hoeing. Average annual applications of farmyard manure (fym) were 2.1 t ha^{-1} averaged over the 5-year cycle and all above ground material was harvested. During the latter 30 years of the 20th century, cultivation was adjusted to reflect current practices. The RothC model was run to equilibrium in the mid 20th century, and then parametised using current practice and plant residue quantities calculated by CENTURY.

We present data on five types of farmer and location:

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

i) Analysis of land management by a large mixed farmer (5 ha), Lingampally village, Medak District

This is a large holding, just over 5 hectares in size, on predominantly black soils. 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 (ca. 2-3 t ha^{-1} y^{-1}), but in addition, inorganic fertilizer has been used during recent years (di-ammonium phosphate ca. 30-45 kg ha^{-1}). Crops modeled are sorghum (kharif May-Sept) and cowpea (rabi Oct-Jan).

CENTURY predicts that the current farming practice is resulting in a nearly stable soil carbon content of ca. 19 t ha^{-1} declining to 2050 by nearly 1.5 t ha^{-1} (Figure I1a). RothC shows a lower total soil carbon content of 16 t ha^{-1} in 2000, declining to 15 t ha^{-1} by 2050 (Table I1a). The scenarios in Figure I1a, detailed in Table I1b compare current practices with additions of inorganic fertilizer, farmyard manure, green manure, vermicompost, retained plant residues and cultivation of trees. Figure I1b indicates the average annual change of soil carbon over a 50 year period.

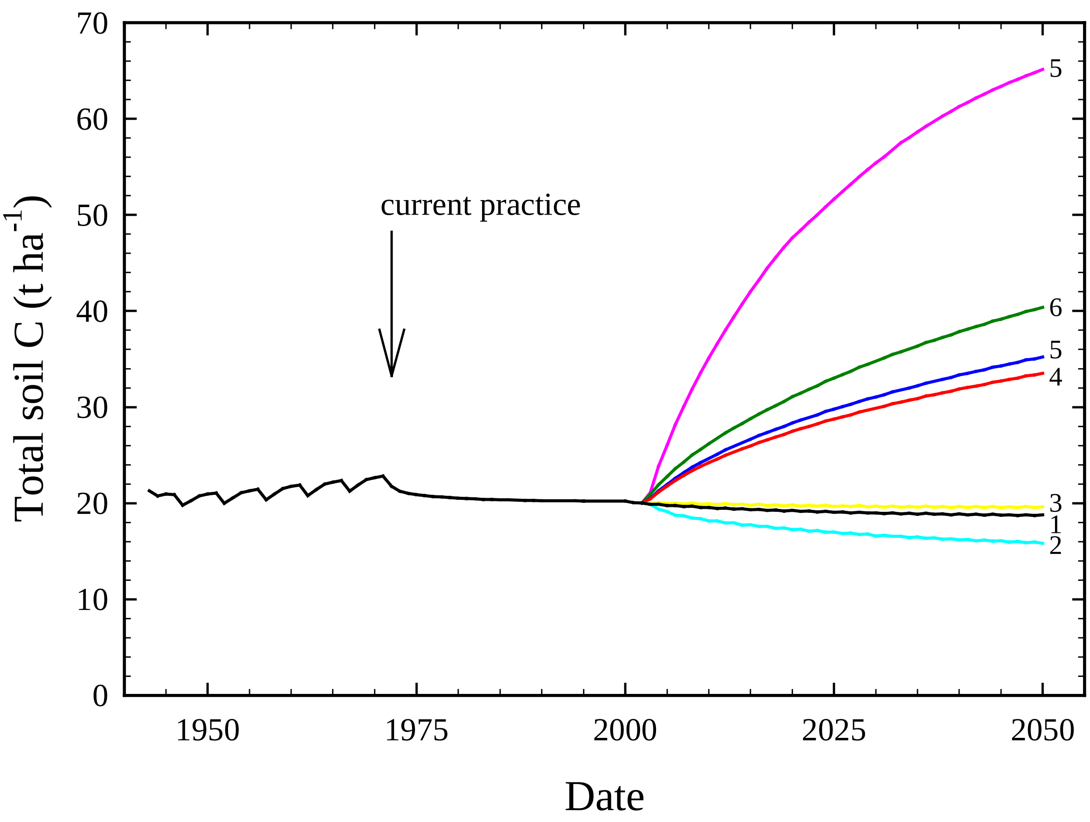

Figure I1a Total soil carbon for a large farmer (5 ha), Lingampally village (CENTURY)
scenarios described in Table 1b

Table I1a Total soil carbon for a large farmer (5 ha), Lingampally village (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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 I1b

Table I1b Scenarios for modeling land management practices, large farmer (5 ha), Lingampally village

Scenario	Land Management
1	current practice
2	inorganic fertilizer
3	replace inorganic fertilizer with fym
4	fym 6 t ha^{-1} y^{-1}
5	fym 6 t ha^{-1} y^{-1}, green manure 250 kg ha^{-1} y^{-1}, vermicompost 100 kg ha^{-1} y^{-1}
6	fym 6 t ha^{-1} y^{-1}, plant residues 2 t ha^{-1} y^{-1}
7	fym 6 t ha^{-1} y^{-1}, plant residues 2 t ha^{-1} y^{-1}, trees, e.g. *Glyricidia*

Effect of inorganic fertilizer

If the application of inorganic fertilizer was halted and the quantity of farmyard manure (fym) increased to replace the nitrogen input and maintain yields (increase manure application by 0.6 t ha^{-1}, scenario 3) soil carbon would only increase by 0.85 t ha^{-1} by 2050 (Figure I1a) and there would be no net gain in soil carbon (Figure I1b). Conversely, replacing all organic additions with inorganic fertilizer results in a decrease of soil carbon in excess of 4 t ha^{-1} by 2050, a loss of 0.09 t C ha^{-1} y^{-1} (scenario 2). Thus inorganic fertilizer results in a fall in soil carbon.

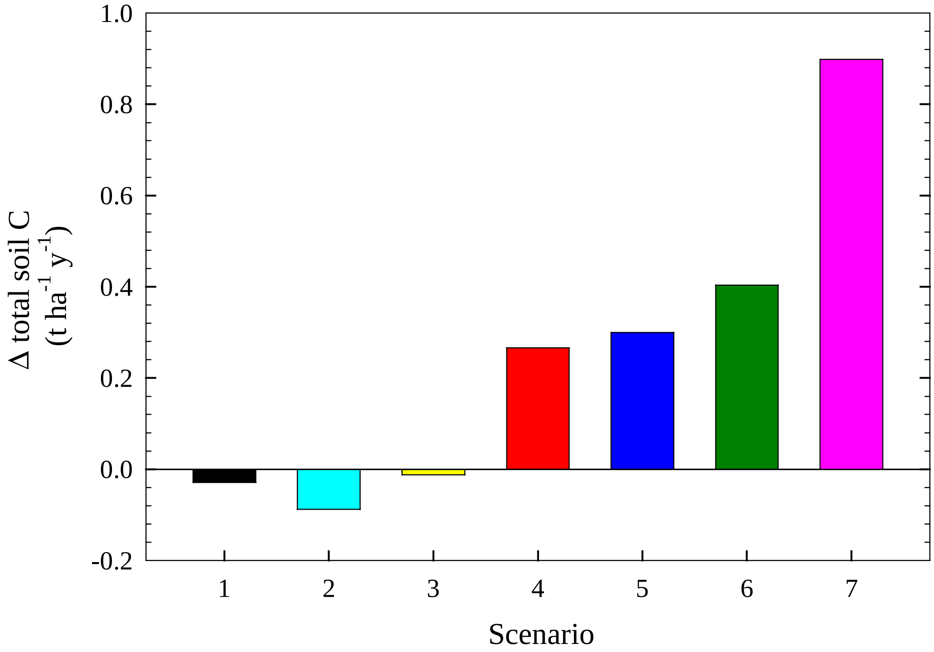

Figure I1b Average annual change (over 50 years) in total soil carbon for a large mixed farmer, Lingampally village (CENTURY)

scenarios – described in Table I1b

Effect of farmyard manure

Doubling the current annual input of farmyard manure (to 4-6 t ha^{-1}, scenario 4) without applying inorganic fertilizer has a marked effect on soil carbon: 0.27 t ha^{-1} y^{-1} is sequestered over the next 50 years (Figure I1b), with the system still not yet at steady state (Figure I1a). RothC similarly shows a continuing rise, reaching 28.3 t ha^{-1} by the same date (Table I1a).

Effect of other organic inputs

Adding only modest amounts of vermicompost (100 kg ha^{-1}) and green manure (250 kg ha^{-1}) in addition to the doubled farmyard manure scenario (5) have limited effect, whilst 2 t ha^{-1} plant residues makes a bigger contribution, 0.4 t ha^{-1} y^{-1} (Figure I1b).

Effect of trees

This farm has capacity for introducing nitrogen-fixing trees like *Glyricidia*. These have been added to the manure and plant residues scenario, creating scenario 7. After 10 years, the trees are cut annually for wood. The result is a very large increase soil carbon sequestration of 0.4 t ha^{-1} y^{-1} (Figure I1b). This increase exceeds that which would be obtained by increasing the manure application by four times.

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%) in soil carbon predicted over the next 50 years. However, cattle are currently being grazed on other land and consequently some carbon is effectively being mined from elsewhere.

A modest increase of organic material would be required to replace the inorganic fertilizers currently used. Further organic inputs could substantially increase soil carbon sequestration. Introducing trees is likely to have a marked effect on soil carbon and would simultaneously increase above ground carbon storage. However, the model may be introducing a greater proportion of trees than would be feasible and consequently may be over estimating the degree of carbon sequestration that is realistically practicable for this farming system.

ii) Analysis of land management by a small (1 ha) rainfed farmer, Lingampally village, Medak District

This holding is less than 1 hectare and the black soil has become very degraded. Animals were kept in the past but have been sold and currently sorghum is the only major crop being grown. All above ground material is harvested and removed. Some farmyard manure is applied at different times, equivalent to 3.9 t ha^{-1} y^{-1}.

The CENTURY model shows how current practices have produced a marked decline in soil carbon, reaching some 13 t ha^{-1} in 2000 (Figure I2a). However the system is reaching steady state and the current land management practice is not predicted to cause much further decline soil carbon during the next 50 years (Figure I2a). RothC yields a slightly higher carbon content in 2000 but is predicting a slightly greater decline (1.8 t ha^{-1}) by 2050 (Table I2a).

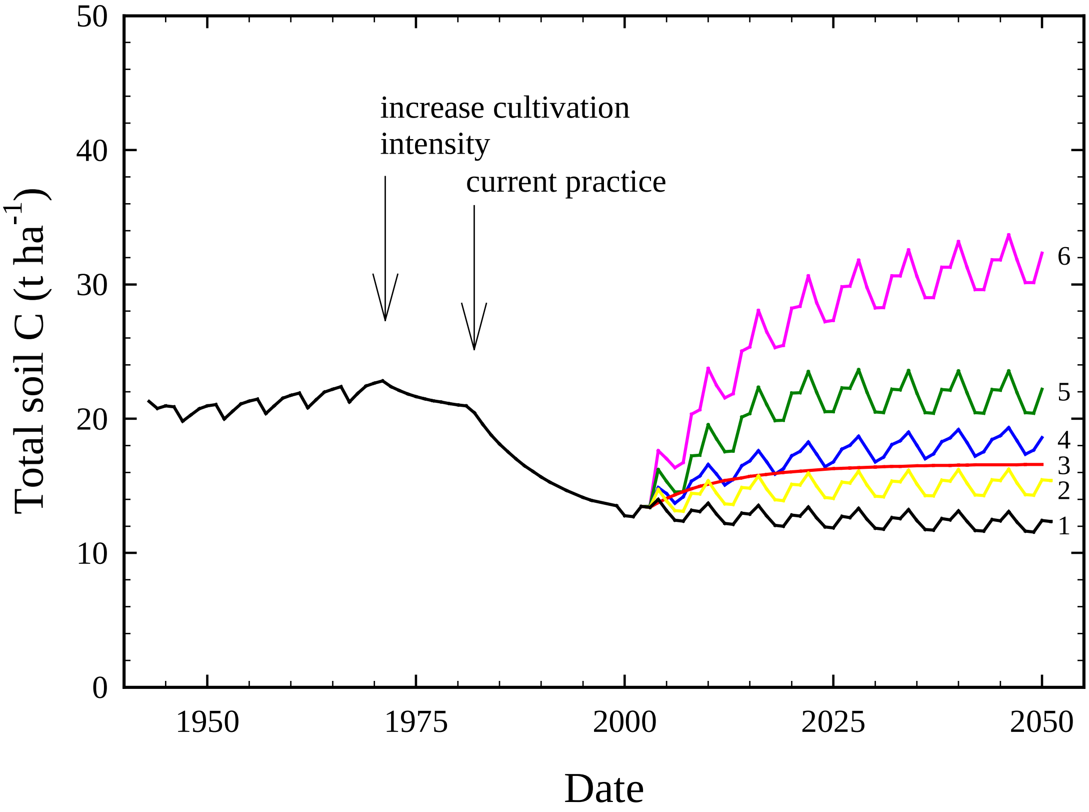

Figure I2a Total soil carbon for a small (1 ha) rainfed farmer, Lingampally village (CENTURY)
scenarios described in Table I2b

Table I2a Total soil carbon for a small (1 ha) rainfed farmer, Lingampally village (CENTURY and RothC)

Scenario*	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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 I2b

Table I2b Scenarios for modeling land management practices, for a small (1 ha) rainfed farmer, Lingampally village

Scenario	Land Management
1	current practice
2	harvest only grain
3	fym 6 t ha^{-1} y^{-1}
4	add legume (cowpea)
5	add trees, e.g. *Glyricidia*
6	all additions

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 t C ha^{-1} y^{-1} (Figure I2b, scenario 2).

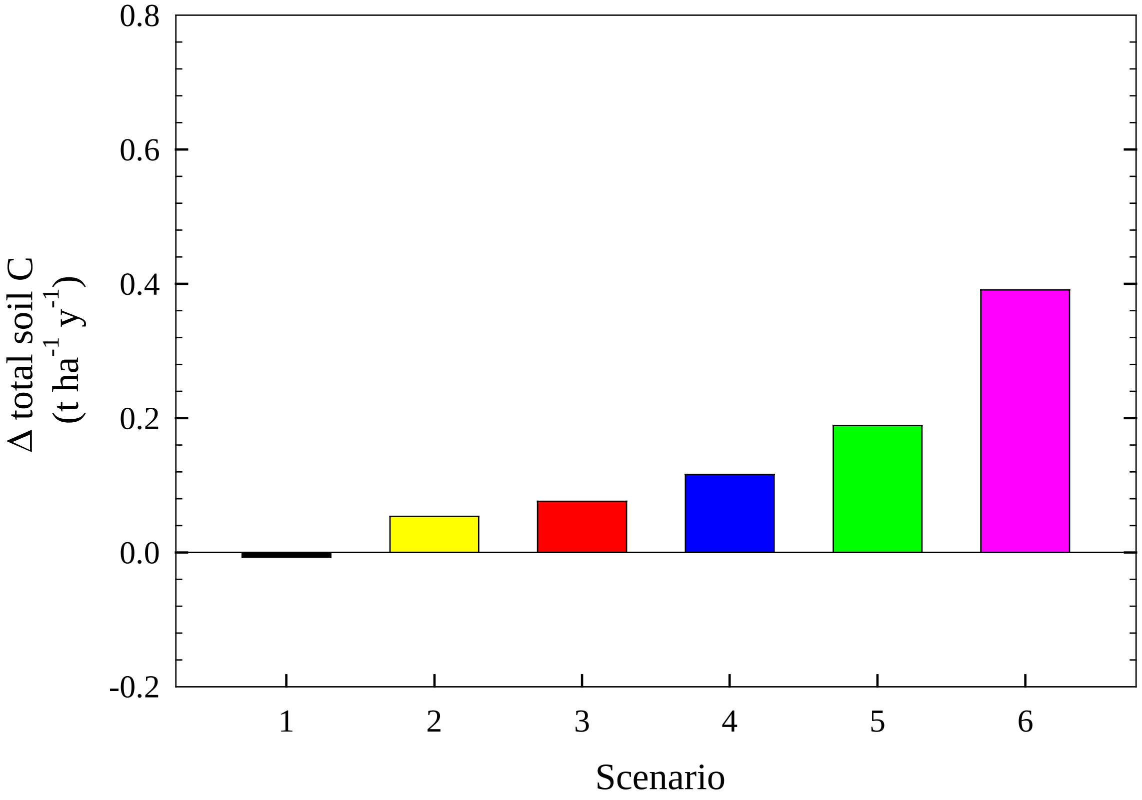

Figure I2b Average annual change in total soil carbon for a small rainfed farmer, Lingampally village (CENTURY)

scenarios – described in Table I2b

Effect of farmyard manure

Increasing the input of farmyard manure by 50% to 6 t ha^{-1} y^{-1} would increase soil carbon by 3.8 t ha^{-1} by 2050 (Figure I2b, scenario 3). RothC predicts a rise of 3.0 t ha^{-1} (Table I2a).

Effect of legume crops

Adding a legume to the rotation, cowpea, (fym 4 t ha^{-1}, harvesting only grain, scenario 4) would sequester 0.12 t C ha^{-1} y^{-1}. Introducing nitrogen-fixing trees (cut every 2 years after 10 years establishment) to the sorghum only system with fym 4 t ha^{-1}, would yield a sequestration rate of 0.19 t C ha^{-1} y^{-1} (scenario 5).

Combing all treatments would lead to a soil carbon sequestration rate of 0.39 t C ha^{-1} y^{-1} (scenario 6, Figure I2b).

Summary

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

iii) Analysis of land management for a large farmer (4.5 ha, crops only) using irrigation, Yedakulapaly village, Medak District

The farm comprises 4.5 ha of irrigated black soil. Water is pumped from a borehole. For the purposes of modelling, 5cm of water is applied when the soil water holding capacity is <

25% 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 used now - 650 kg ha^{-1} di-ammonium phosphate and 150 kg ha^{-1} of urea annually. Crops are grown in all 3 seasons (summer – sorghum, kharif – legume, rabi – legume) and all above ground material is harvested and removed. For the purpose of modeling, cowpea is used for the legume crop.

CENTURY calculates that current practices have depleted soil carbon to 13.26 t ha^{-1} but predicts no further reduction over the next 50 years (Figure I3a).

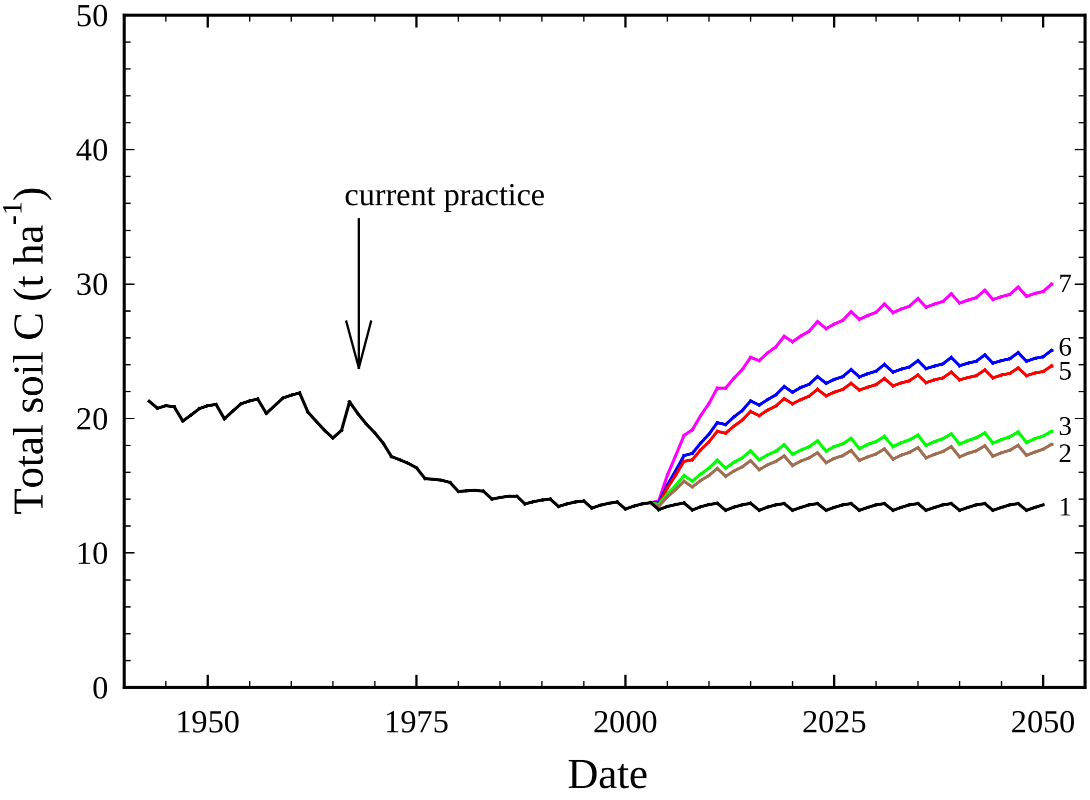

Figure I3a Total soil carbon for a large farmer (4.5 ha) using irrigation and cultivating three crops per year, Lingampally village (CENTURY)
scenarios described in Table I3a

Table I3a Scenarios for modeling land management practices, large farmer (4.5 ha) using irrigation, Lingampally village

Scenario	Land Management
1	current practice
2	fym 3 t ha^{-1} y^{-1}
3	fym 3 t ha^{-1} y^{-1}, green manure 500 kg ha^{-1} y^{-1}, vermicompost 250 kg ha^{-1} y^{-1}
4	as current practice but incorporate crop residues into soil
5	fym 3 t ha^{-1} y^{-1}, leave plant residues
6	fym 3 t ha^{-1} y^{-1}, plant residues, green manure, vermicompost
7	fym 6 t ha^{-1} y^{-1}, plant residues, green manure, vermicompost

Effect of organic inputs

Adding 3 t fym ha^{-1} y^{-1} (scenario 2) would increase soil carbon by 4.4 t ha^{-1} to 2050, sequestering 0.09 t C ha^{-1} y^{-1} (Figure I3b). Including 500 kg ha^{-1} y^{-1} of green manure and 250 kg ha^{-1} y^{-1} of vermicompost (scenario 3) would increase soil organic C by a further tonne, sequestering 0.11 t C ha^{-1} y^{-1} (Figure I3b). A similar increase in soil carbon can be obtained with no extra organic additions if only the grain is harvested and the crop residues are returned to the soil (Figure I3b). When 3 t fym ha^{-1} y^{-1} is applied and only the grain harvested (scenario 5), soil carbon increases by over 10 t ha^{-1} by 2050, equivalent to 0.20 t C ha^{-1} y^{-1}. Applying all the organic inputs and increasing the fym component to 6 t ha^{-1} would sequester 0.32 t C ha^{-1} y^{-1}.

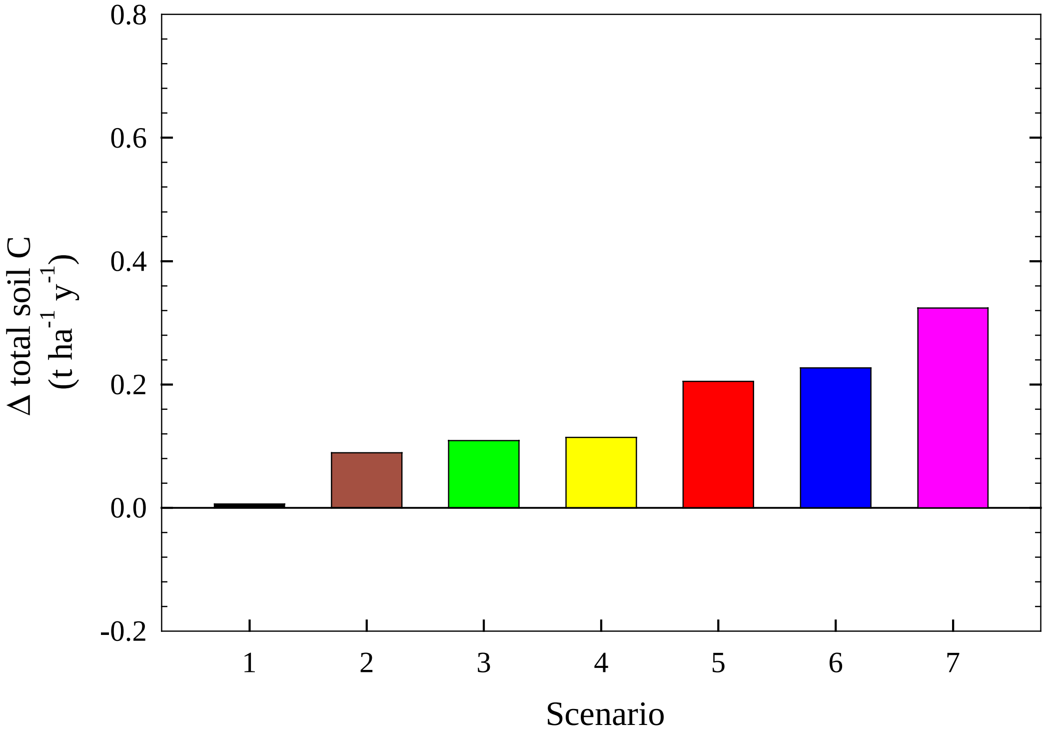

Figure I3b Average annual change in total soil carbon for a large farmer (4.5 ha, crops only) using irrigation, Lingampally village (CENTURY)
scenarios described in Table I3a

Summary

A combination of leaving crop residues and adding manure could make a significant contribution to soil carbon in this kind of farm 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 farmyard manure can offset the nutrients applied in inorganic fertilizers. For example removing inorganic fertilizer from scenario 6 maintains yield without affecting soil carbon. Removing irrigation from the above scenario does not have a detrimental effect on soil carbon but neither is there an apparent effect on yield.

iv) Analysis of land management for a small (2.7 ha) mixed crop and livestock farmer, Metalkunta village, Medak District

This land holding, 2.7 hectares, is small yet a very large variety of crops are grown on the lateritic red soil. Livestock are kept, a good cultivation pattern is practised and there are also many trees present around the farm. All above ground 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 at present is 2 t ha^{-1} and vermicompost is added to the land.

CENTURY was parametised 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 1960's. The model suggests that this system of land management would have approximately doubled the soil carbon content to nearly 25 t ha^{-1} by 2000 and would reach 26 t C ha^{-1} by 2050, Figure I4a. RothC predicts 25 t C ha^{-1} in 2000 rising to 29.1 t ha^{-1} in 2050 (Table I4a). Clearly this mixed cropping and livestock system has a substantial positive impact on soil carbon.

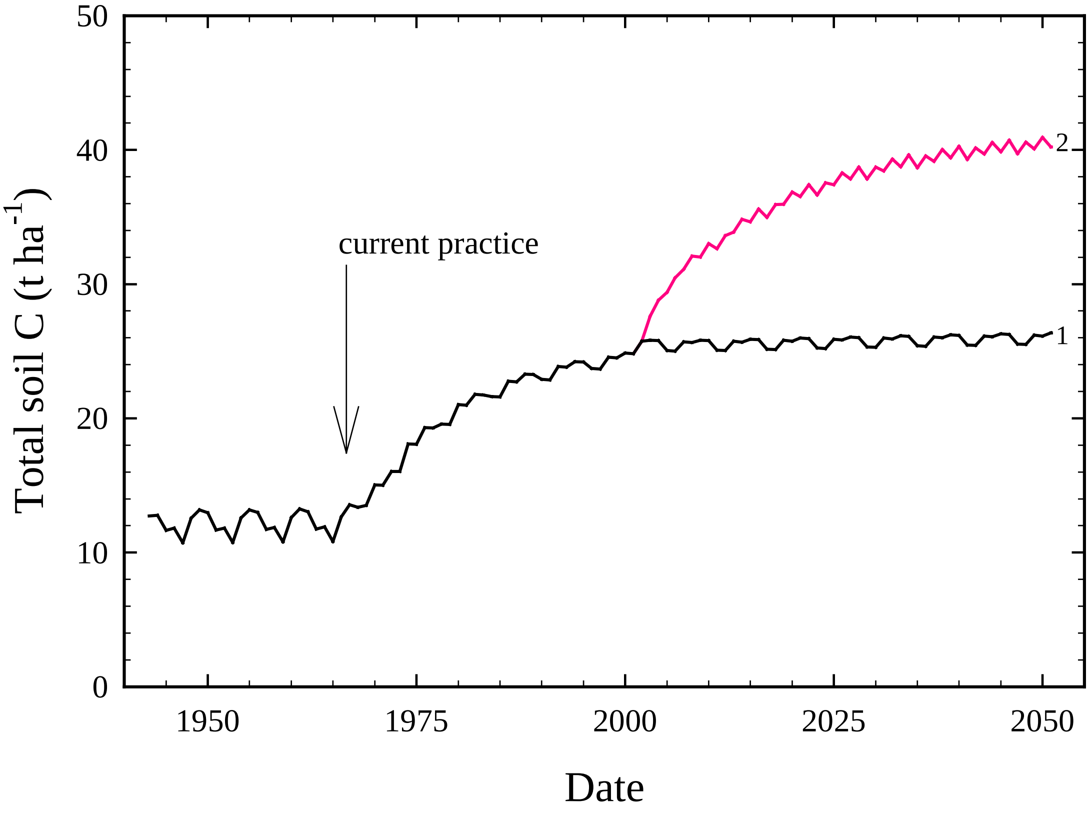

Figure I4a Total soil carbon for a small mixed crop and livestock farmer, Metalkunta village (CENTURY)

scenarios described in Table I4b

Table I4a Total soil carbon for a small mixed crop and livestock farmer, Metalkunta village (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
1	24.9	26.1	5.2	25.0	29.2	16.7
2		40.9	64.7		49.2	96.6

[1] scenarios described in Table I4b

Table I4b Scenarios for modeling land management practices, small mixed crop and livestock farmer, Metalkunta village

Scenario	Land Management
1	current practice
2	leave plant residues

Effects of retaining crop residues

Returning crop residues to the soil (scenario 2) would greatly increase the carbon content, sequestering 0.3 t C ha^{-1} y^{-1} over the next 50 years (Figure I4b), with the soil carbon content reaching 40.9 t ha^{-1} by 2050. RothC calculates that leaving crop residues would increase soil carbon to 49.2 t ha^{-1} (Table I4a).

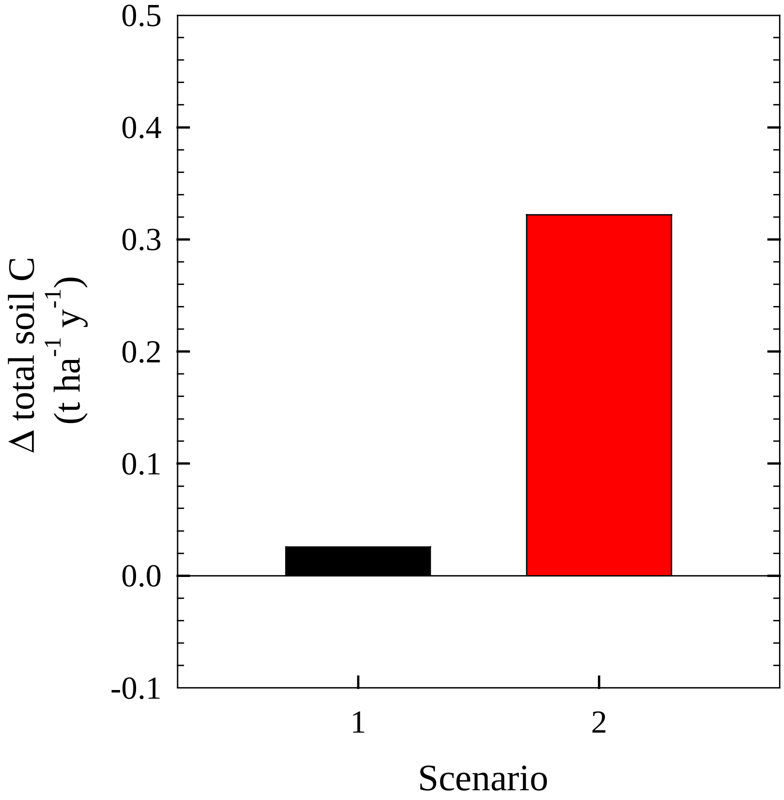

Figure I4b Average annual change in total soil carbon for a small mixed crop and livestock farmer, Metalkunta village (CENTURY)

scenarios described in Table I4b

Summary

This 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 partly being accomplished by grazing cattle on other lands and bringing in fodder. This means that carbon is effectively being mined from elsewhere. Thus although returning crop residues to the soil makes a further significant contribution to soil carbon, this would undoubtedly require importing more fodder to substitute for the plant residues, which again implies 'mining' carbon.

v) Analysis of land management for a small farmer, 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. Modeled kharif crops are sorghum and millet and the rabi crop is cowpea. On average 3 t ha^{-1} y^{-1} farmyard manure is applied. Inorganic fertilizers are also used: 75 kg ha^{-1} y^{-1} of di-ammonium phosphate and 75 kg ha^{-1} y^{-1} of urea.

Modeling with CENTURY shows that current practices are increasing soil carbon and that this will continue to rise by a further 2.7 t ha^{-1} over the next 50 years, reaching nearly 20 t C ha^{-1} in 2050 (Figure I5a). RothC also shows that current practice is increasing soil carbon but shows an enhanced effect. Soil carbon in 2000 is predicted to be 19.8 t ha^{-1}, rising to 24.3 t ha^{-1} in 2050, Table I5a.

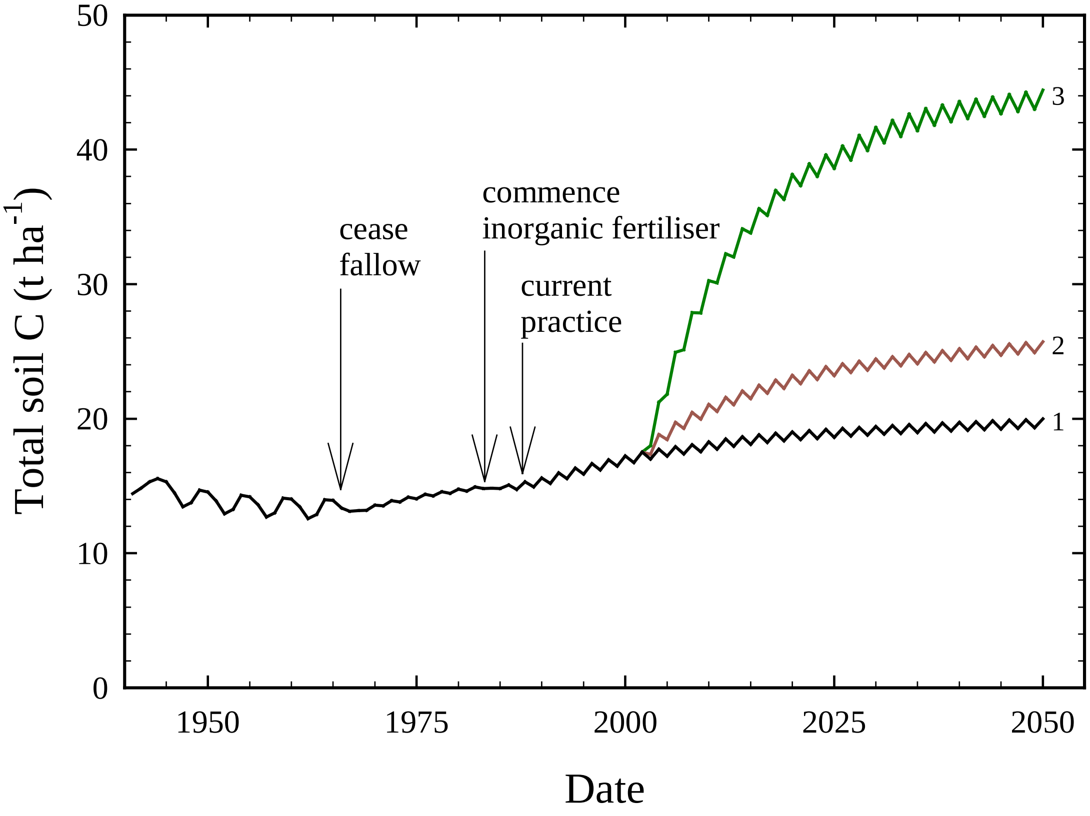

Figure I5a Total soil carbon for a small farmer, Malligere village, Tumkur District, (CENTURY)
[1] scenarios described in Table I5b

Table I5a Total soil carbon for a small farmer, Malligere village, Tumkur District (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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 I5b

Table I5b Scenarios for modeling land management practices, small farmer, Malligere village

Scenario	Land Management
1	current practice
2	replace inorganic fertiliser with farmyard manure
3	add trees, *Glyricidia*

Effect of organic additions

Inorganic fertilizer again has a carbon cost, and so replacing the nitrogen supplied by the inorganic fertilizer with manure (annual addition 6.3 t ha^{-1}) enhances the carbon sequestration rate to 0.17 t C ha^{-1} y^{-1} so that the soil level reaches 25.7 t ha^{-1} by 2050 (Figure I5b, Table I5a, scenario 2). RothC predicts a much bigger effect of replacing the fertilizer with fym: soil C is predicted to rise to 34.2 t ha^{-1} by 2050.

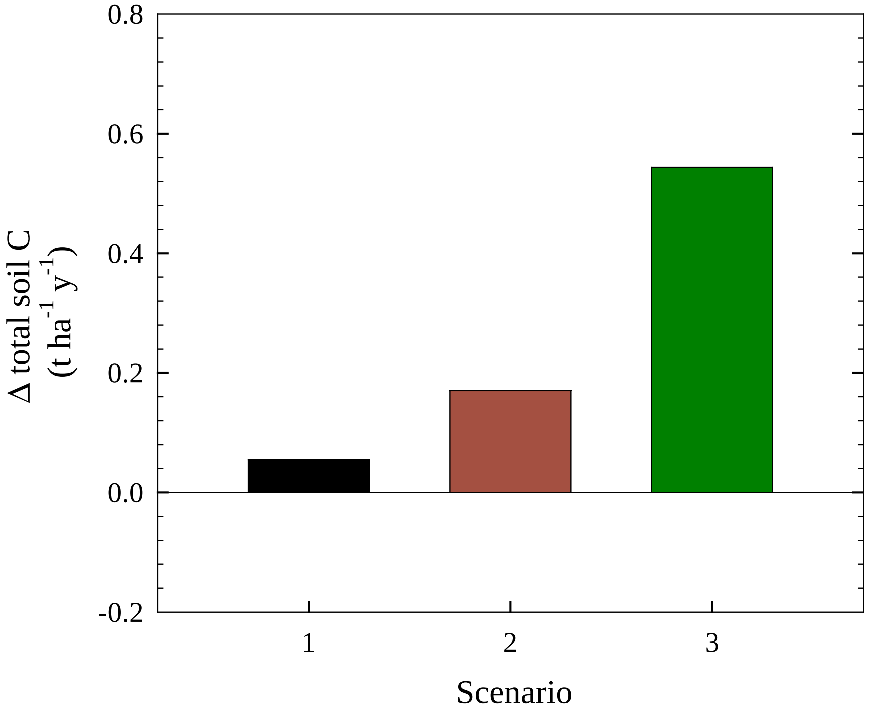

Figure I5b Average annual change in total soil carbon for a small farmer, Malligere village, Tumkur District (CENTURY)

scenarios described in Table I5b

Effect of trees

Adding trees such as *Glyricidia* to the system (scenario 3), which are cropped annually for wood after 10 years growth, makes a very large difference, increasing carbon sequestration to 0.54 t C ha^{-1} y^{-1} (Figure I5b).

Summary

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

Conclusions from India cases

The modeling 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.

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 t C ha^{-1} y^{-1}, whereas the use of either farmyard manure, green manures, vermicompost and/or plant residues produces increases of 0.2 to 0.4 t C ha^{-1} y^{-1}. The use of agroforestry substantially increases below ground carbon sequestration to 0.9 t C ha^{-1} y^{-1}.

The models show substantial declines in soil C on small farms cultivating only sorghum and those intensively cultivating three irrigated crops per year – a loss of 5 t C ha^{-1} over a 25 year period, and that these falls can be quickly reversed within 5-10 years with adoption of legumes in rotations, the addition of fym 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 t C ha^{-1} to 24.8 t C ha^{-1} over 25 years, and can increase this to over 40 t C ha^{-1} during the next 50 years if plant residues are added to the soil.

For full accounting of the carbon used or sequestered in these farms, it is important to consider the high energy cost of nitrogen fertilizer manufacture (65.3 MJ kg^{-1} for N, 7.2 MJ kg^{-1} for P, 6.4 MJ kg^{-1} for K – Pretty *et al.*, 2002), the use of mechanised operations on farms, and the issue of the transfer of carbon 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 carbon if leguminous crops are included in rotations and trees cultivated in agroforestry systems.

Case Study 3

Kenya – Makueni District (formerly part of Machakos District)

Introduction

Arid and semi-arid lands occupy approximately two-thirds of Kenya (Nandwa *et al.*, 1999). 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 (KARI, 1999). A detailed research programme examining the sustainability of farming systems in semi-arid Kenya has been conducted by Drylands Research. This study has recorded physical aspects of the environment together with land management practices in four villages of Makueni District. These span a range of settlement times from the 1950s through 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 characterised by two rainy periods: the short rains, which deliver most precipitation during October to December, and the long rains which run from March to May. However, superimposed on the average annual rainfall (600 mm to 670 mm) is the periodic occurrence of drought (Gichuki, 2000). Annual mean temperature is in the range 21°C - 24°C. Elevation is between 800m and 1600m, 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 ferrolsols (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 (M. Mortimore, pers. comm.). Each year covers two cropping seasons. The major crops are maize and pulses, with millet and sorghum recommended as drought crops. Yields vary greatly between years depending on rainfall; on average maize will give 1 t ha^{-1}, though some modern varieties achieve 4 t ha^{-1} 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. There is little investment made in the grazing lands and during the wet season animals are usually kept in pens. Very little fertilizer is used, especially since drought causes ‘burning’ of the crops. Crop residues are either burnt, fed to animals or ploughed into the soil. Tillage is accomplished by using simple ridging ploughs pulled by oxen whilst hand hoeing and digging are also common. Labour is in short supply and so is 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 *et al.*, 1995; Gichuki, 2000).

Woodland is continually 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 10 years and major fires every 30 years.

i) Darjani

This settlement lies within the agro-ecological zone, lower midland 5. The primary crops are millet, sisal, cowpea and sorghum and the natural pasture can support low intensity grazing. Settlement took place in the 1960s. Average soil carbon content of bush soils is 37.6 ± 7.5 t ha^{-1}, and for cultivated soils it is slightly less - 33.7 ± 2.8 t ha^{-1} (Mbuvi, 2000).

Once run to equilibrium CENTURY gave a value for soil carbon of 31.0 t ha^{-1} 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 6-year cycle of 4 years alternate maize and millet crops followed by 2 years fallow. Cultivation was accomplished using a steel ridging plough and hand weeding was included. Crop residues were burnt. In 1971 farmyard manure additions commenced averaging 1.5 t ha^{-1} over the 6-year cycle as soil fertility and conservation measures began to be adopted. In 1983 the fallow period was reduced to 1 year out of 6 and by 2000 the modeled soil carbon was some 24 t ha^{-1} (Figure K1a). This reduction of 7 t ha^{-1} from the level modeled for the uncultivated bush soil is greater than the 5 t ha^{-1} decline measured in the field. Continuation of this land management practice is predicted to lead to a further loss of 1.3 t C ha^{-1} by 2050 (Figure K1a).

RothC was run to equilibrium using the current level of bush soil carbon and then used to predict the effect of land management using plant inputs calculated by CENTURY. RothC predicted soil carbon to be 34.6 t ha^{-1} in 1999, which is within 1 t ha^{-1} of the measured value. Over the next 50 years RothC predicts a further decline of 0.6 t C ha^{-1} (Table K1a).

Table K1a Total soil carbon (t ha^{-1}) for Darjani settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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

[1] scenarios described in Table K1b

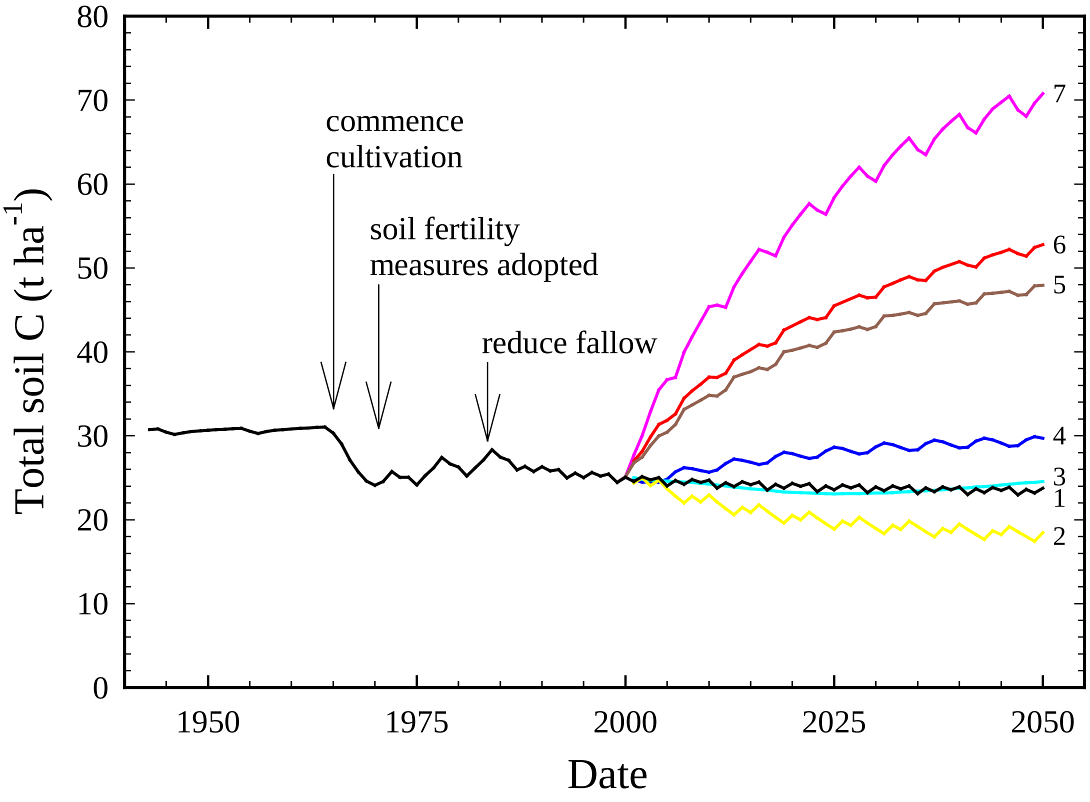

Figure K1a Total soil carbon for Darjani settlement (CENTURY)
scenarios described in Table K1b

Table K3b Scenarios for modeling 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 t ha^{-1} y^{-1}, burn residues, fallow
6	fym 4.5 t ha^{-1} y^{-1}, do not burn residues, fallow
7	fym 6.75 t ha^{-1} y^{-1}, do not burn residues, fallow

Effect of fallow removal

CENTURY predicts that removing the fallow from the current practice will result in a reduction in soil carbon (6.6t ha^{-1}) by 2050 (scenario 2, Figure K1a).

Effect of organic inputs

Adding an average 4.5 t ha^{-1} y^{-1} fym over the 6-year cropping-fallow cycle leads to a carbon sequestration rate of 0.5 t ha^{-1} y^{-1} (scenario 5, Figure K1b). If the crop residues are returned to the soil rather than burnt a further 4.9 t C ha^{-1} can be accumulated by 2050 representing a sequestration rate of 0.6 t ha^{-1} y^{-1} (Figures K1a,b). RothC predicts similar increases (Table K1a). Increasing the fym input to 6.75 t ha^{-1} y^{-1} will increase the sequestration rate to 0.9 t C ha^{-1} y^{-1} (Figure K1b).

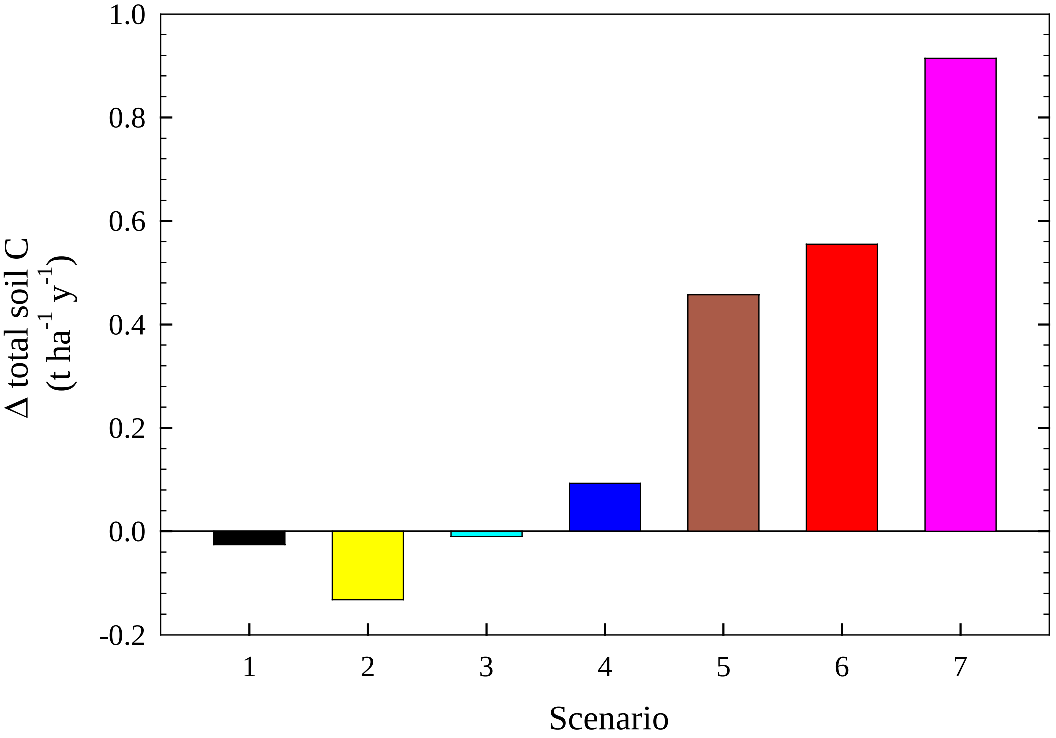

Figure K1b Average annual change in total soil carbon for Darjani settlement (CENTURY) scenarios described in Table K1b

Effect of inorganic fertilizer

Replacing all organic inputs with inorganic fertilizer (100 kg N ha^{-1} y^{-1}, scenario 4) results in only a moderate increase in soil carbon sequestration (0.09 t ha^{-1} y^{-1}). However, the quantity of nitrogen applied is equivalent to approximately 5 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 nitrogen that is applied.

Summary

The importance of fym manure 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 lead to an increase in carbon sequestration, the increase in carbon per unit of nitrogen added is much less efficient than if fym is added. The indirect energy embodied in manufactured nitrogen fertilizer is an additional carbon cost.

ii) Kaiani

This settlement is also located in lower midland zone 5, and has a similar farming system to Darajani. CENTURY underestimated the current bush content of soil carbon, yielding nearly 32 t ha^{-1} compared with measured values of 41.5 ± 3.1 t ha^{-1}. 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 t ha^{-1} manure applied once in the 6-year cycle. There was one year of fallow. Cultivation is calculated to have reduced soil carbon to 28.1 t ha^{-1} by 2000 which compares with a measured value for cropped soil of 30.5 ± 4.8 t ha^{-1}. Soil carbon is then predicted to decrease by just over 1 t ha^{-1} during the next 50 years (Figure K2a, Table K2).

After parametisation with the carbon content for bush soil soils, RothC, shows very little effect of cultivation when using plant inputs calculated by CENTURY. Contrary to CENTURY, this model predicts a slight rise in soil carbon by 2050 (Table K2a).

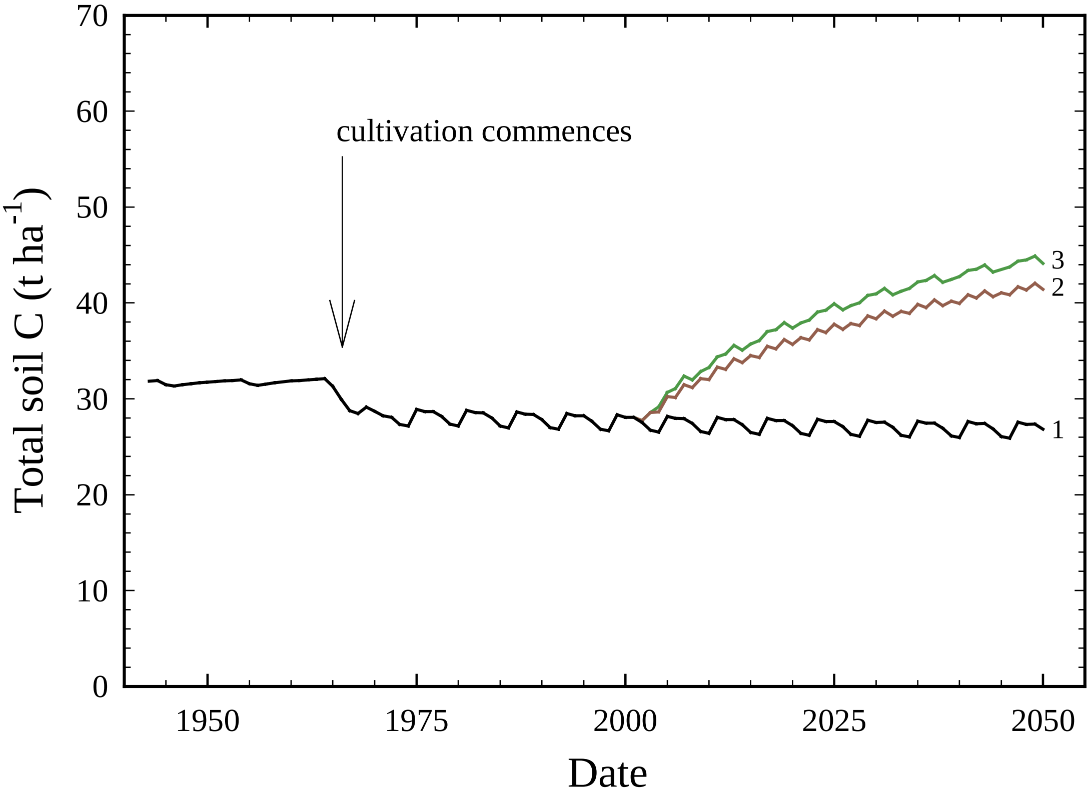

Figure K2a Total soil carbon for Kaiani settlement (CENTURY)
scenarios described in Table K2b

Table K2b Total soil carbon (t ha^{-1}) for Kaiani settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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

[1] scenarios described in Table K2b

Table K2b Scenarios for modeling land management practices, Kaiani settlement

Scenario	Land Management
1	current practice
2	fym 2 t ha^{-1} y^{-1}
3	fym 2 t ha^{-1} y^{-1}, plant residues 0.3 t ha^{-1} y^{-1}

Effect of organic inputs

Modest increases in the application rate of farmyard manure (0.75 t ha^{-1} y^{-1} to 2 t ha^{-1} y^{-1}) result in quite marked accumulation of soil carbon (Figures K2a,b). Adding additional plant residues further increase the sequestration rate to 0.3 t C ha^{-1}. RothC predicts very similar proportional increases in soil carbon (Table K2a).

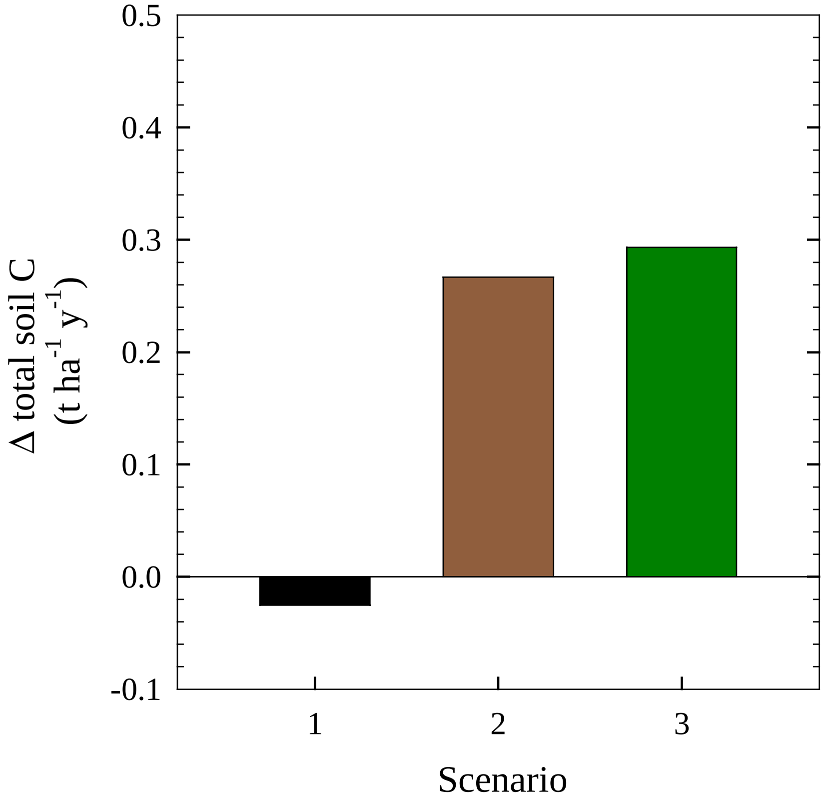

Figure K2b Average annual change in total soil carbon for Kaiani settlement (CENTURY) scenarios described in Table K2b

Summary

The models suggest that the current system is at or near steady-state. Consequently it is possible to achieve reasonable rates of carbon sequestration (0.3 t C ha^{-1} y^{-1}) with modest increases in organic manure inputs.

iii) Kymausoi

Kymausoi is situated in lower midland zone 4 which is a marginal cotton zone where maize, pigeon pea and sisal are also be grown. Cattle ranching is practised and the village was settled in the 1950s. Average soil carbon content for bush soils here is 38.4 ± 4.8 t ha^{-1}, while for cultivated soils the average is 33.5 t ha^{-1} with a range of 17.4-38.9 t ha^{-1}. The CENTURY agro-ecosystem model was run to equilibrium and gave a bush soil carbon level of 28.5 t ha in 1955, which is below the average concentration for soils in this area (Figure K1a).

The model was then run to reflect the current 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 t ha^{-1} y^{-1}. Soil conservation and fertility management commenced in the late 1960s, the average annual manure application rate being increased to

1 t ha^{-1} to reflect this. By 2000 CENTURY estimated soil carbon to be 17.8 t ha^{-1}, which is at the lower end of measured values. A decline of < 1 t C ha^{-1} is predicted to occur over the next 50 years.

RothC, after being run to equilibrium for current bush soils and then parametsised with plant inputs from CENTURY calculated a 3.4 t ha^{-1} reduction of soil carbon resulting from cultivation and like CENTURY suggests a further decline of < 1 t ha^{-1} by 2050 (Table K3a).

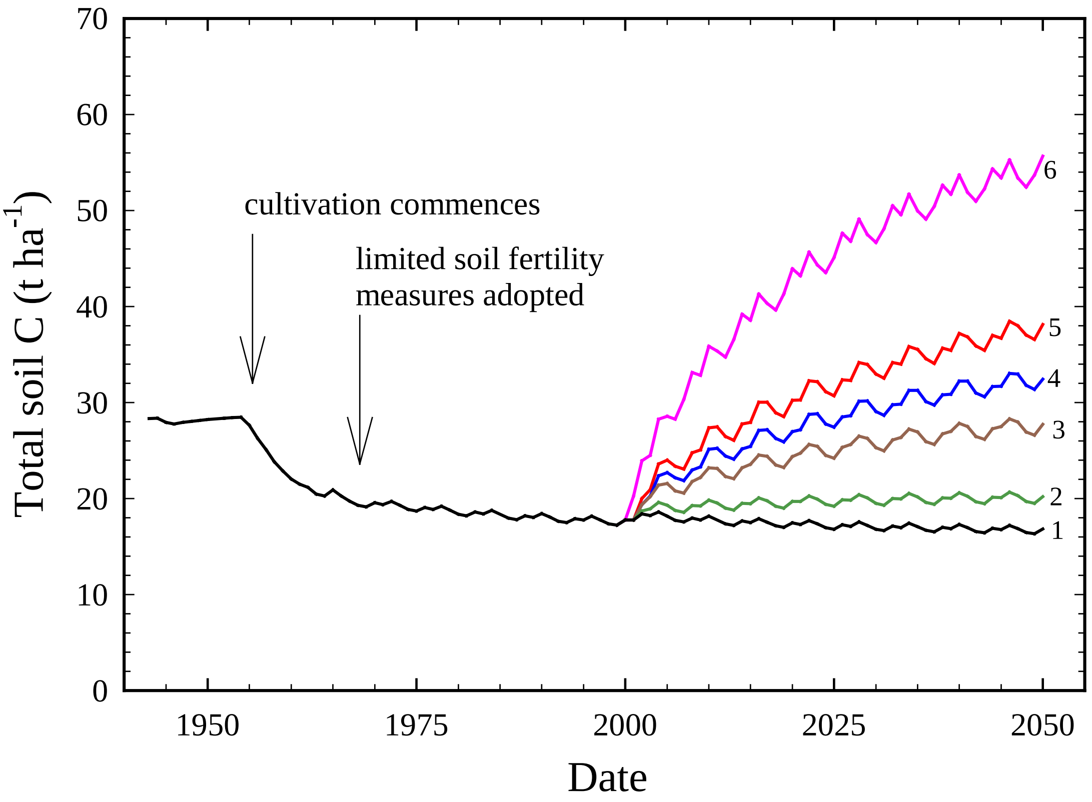

Figure K3a Total soil carbon for Kymausoi settlement (CENTURY)
scenarios described in Table K3b

Table K3a Total soil carbon (t ha^{-1}) for Kymausoi settlement (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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

[1] scenarios described in Table K3b

Table K3b Scenarios for modeling land management practices, Kymausoi settlement

Scenario	Land Management
1	current practice
2	plant residues 0.3 t ha^{-1} y^{-1}
3	fym 1.5 t ha^{-1} y^{-1}, plant residues 0.6 t ha^{-1} y^{-1}
4	fym 1.5 t ha^{-1} y^{-1}, plant residues 0.6 t ha^{-1} y^{-1}, legume (cowpea)
5	fym 2 t ha^{-1} y^{-1}, plant residues 0.6 t ha^{-1} y^{-1}, legume (cowpea)
6	fym 4 t ha^{-1} y^{-1}, plant residues 0.6 t ha^{-1} y^{-1}, legume (cowpea)

Effect of organic inputs

Adding additional plant residues and increasing the farmyard manure application rate to 1.5 t ha^{-1} y^{-1} (scenarios 2, 3) will increase soil carbon levels by at least 50% (Table K3).

Effect of legume crop

Introducing a leguminous crop into the system, such as cowpea, can make a significant improvement to carbon sequestration (scenarios 4-6, Figures K3a,b), increasing the rate from 0.2 to 0.3 t C ha^{-1} y^{-1} at the same rates of fym application.

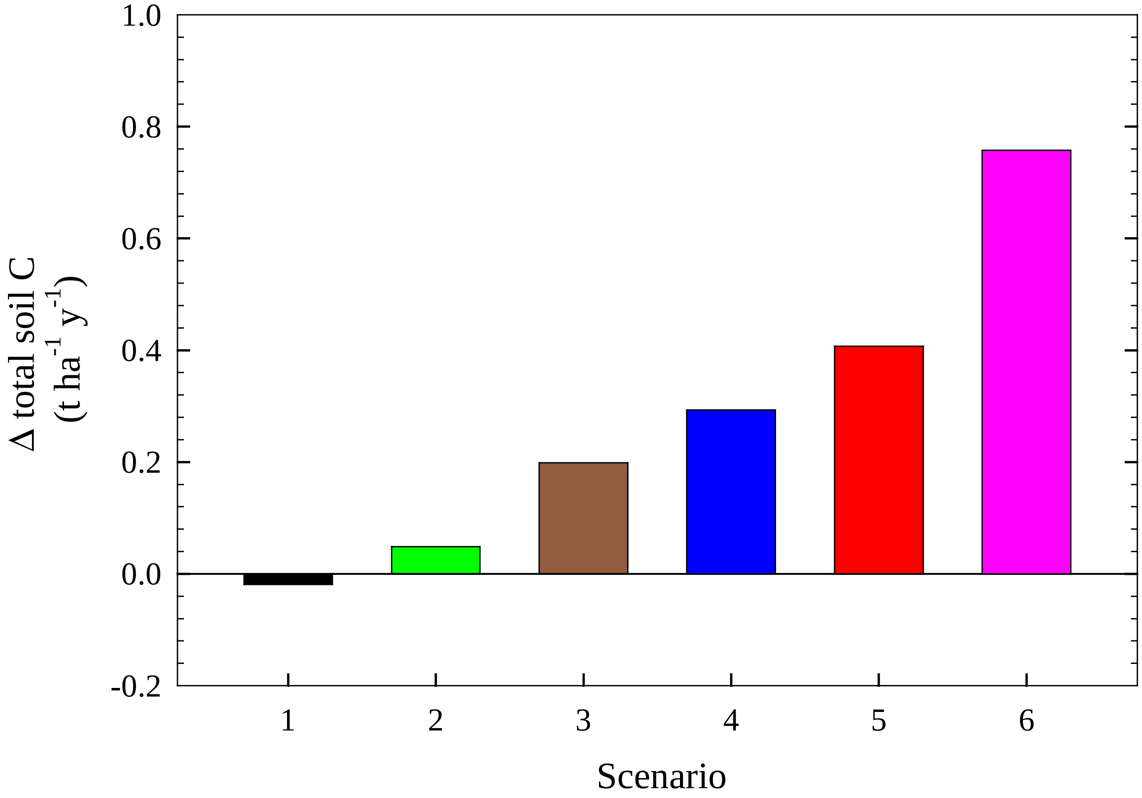

Figure K3b Average annual change in total soil carbon for Kymausoi settlement (CENTURY) scenarios described in Table K3b

Summary

This example illustrates the advantage that can be had if leguminous crops are included in the planting rotation. A farm system using 4 t ha^{-1} y^{-1} of FYM, maintaining plant residues in the field, and with a legume in the rotation, can accumulate 0.7 t C ha^{-1} y^{-1}. 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. This is the most recently settled village, being established in the 1970s. CENTURY was parametised for the commencement of cropping / grazing during the last 30 years. Millet was grown and an average of 0.75 t ha^{-1} manure applied during the last 6 years.

The value for soil carbon modeled by CENTURY matched the current bush level (33.2 ± 3.2 t C ha^{-1}). When settlement commenced, CENTURY calculated a decline in soil carbon of some 9 t ha^{-1} over 25 years. Again this is very close to the actual measurements that show cultivated soils on average contain 24.0 ± 3.0 t C ha^{-1}. Continuing this scenario into the 21st century suggests that the system has nearly reached a new steady state (Figure K4a). RothC calculates a smaller effect of cultivation on soil carbon, predicting a value of 29.7 t C ha^{-1} in 2000, and a slight decline over the next 50 years (Table K4a).

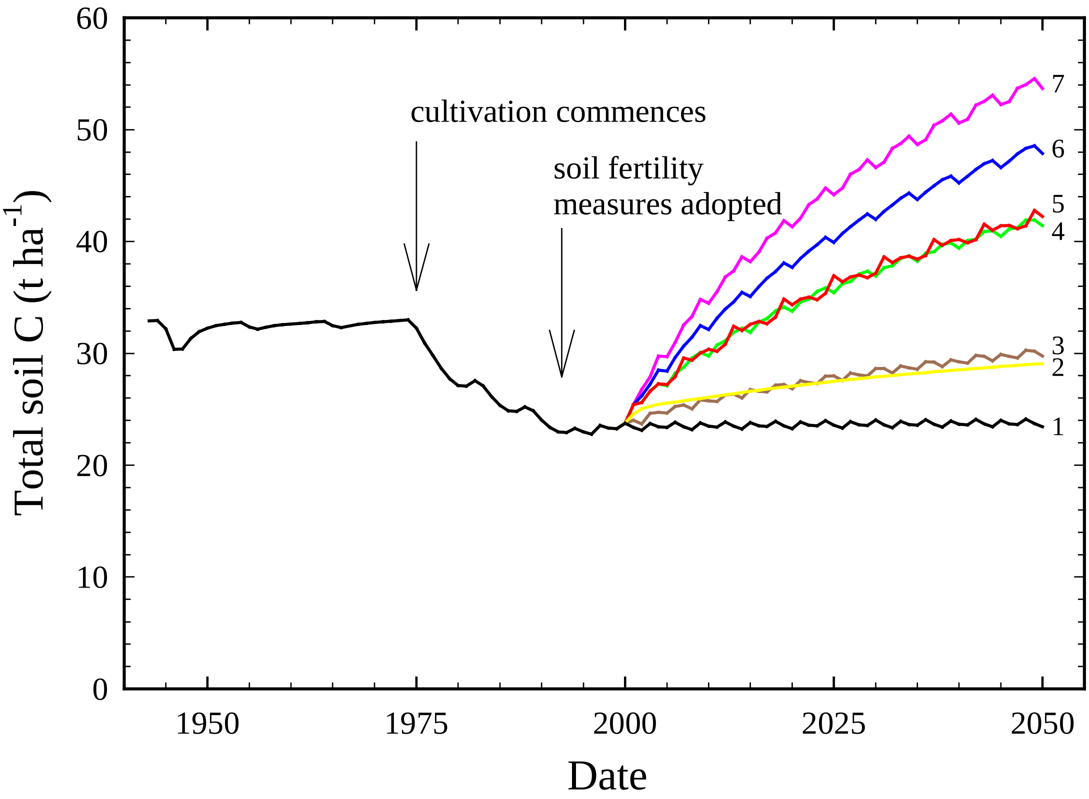

Figure K4a Total soil carbon for Athi Kamunyuni settlement (CENTURY)
scenarios described in Table K4b

Table K4a Total soil carbon (t ha^{-1}) for Athi Kamunyuni settlement (CENTURY and RothC)

Scenario1	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
1	23.75	23.45	-1.3	29.68	28.29	-4.7
2		29.09	22.5		31.4	5.8
3		29.77	25.3		42.76	44.1

[1] scenarios described in Table K4b

Table K3b Scenarios for modeling land management practices, Athi Kamunyuni settlement

Scenario	Land Management
1	current practice
2	grazing
3	fym 1.25 t ha^{-1} y^{-1}
4	fym 2.25 t ha^{-1} y^{-1}
5	fym 2.27 t ha^{-1} y^{-1}, fallow reduced to 1 year
6	fym 3.3 t ha^{-1} y^{-1}
7	fym 3.9 t ha^{-1} y^{-1}, plant residues 0.3 t ha^{-1}

Effect of organic inputs

Increasing the current average application rate of farmyard manure from 0.75 t ha^{-1} y^{-1} to 1.25 or 2.25 t ha^{-1} y^{-1} (scenarios 3, 4) increases rates of carbon sequestration between 0.12 – 0.37 t ha^{-1} y^{-1} (Figures K4a, b). Further additions of organic inputs, if available, could yield substantial increases in carbon sequestration rates, rising to 0.6 t ha^{-1} y^{-1}.

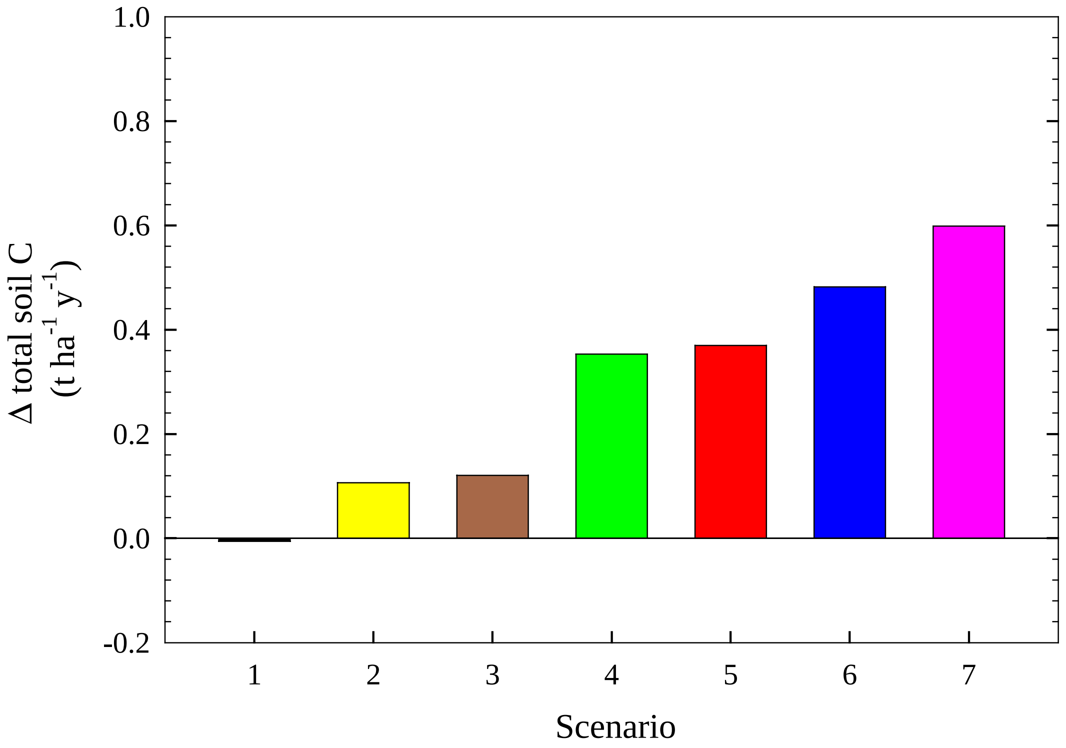

Figure K4b Average annual change in total soil carbon for Athi Kamunyuni settlement (CENTURY)
scenarios described in Table K3b

Effect of fallows

Reducing the fallow period from 2 to 1 year (scenario 5) has very little effect on soil carbon providing the organic inputs are maintained. Using this location solely for ranching would result in an increase in soil carbon as the system returns to similar conditions that existed before cultivation commenced (scenario 2). The rate of carbon sequestration is very similar to scenario 3, where an average of 1.25 t ha^{-1} farmyard manure was added annually. RothC predicts a much smaller increase in soil carbon on return to ranching but this reflects the fact that this model initially calculated a much smaller decline in total soil carbon following the commencement of cultivation.

Summary

The level of soil carbon in this recently settled system could be restored to pre-settlement levels and then above by the addition of farmyard manure. Conditions at this location are not ideal for cropping and a return to a grazing-only system should also restore soil carbon to its pre-settlement level.

Conclusions from Kenya cases

The modeling of farm data from four communities of semi-arid Makueni District in Kenya 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 farmyard manure and plant residues can lead to carbon sequestration, 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 t C ha^{-1} y^{-1}, and inorganic fertilizers are again an inefficient choice for plant nutrients when soil carbon is a concern. Burning plant residues is not desired.

The combination of legumes in rotations, 2-4 t ha^{-1} y^{-1} of fym in addition to 0.6 t ha^{-1} y^{-1} of plant residues results in the highest rate of carbon sequestration in all the dryland cases – 0.7 t C ha^{-1} y^{-1}. At lower levels of fym and maintenance of fallows, together with legumes in rotations, increases in soil C of 0.3 to 0.4 ha^{-1} y^{-1} can be achieved.

Case Study 4
Argentina – Tucuma, Catamarca and Cordoba Provinces

Introduction

In recent years, Argentina has experienced a rapid growth in adoption of reduced and zero-tillage systems, especially in dryland regions. This change has been brought about by a deterioration in soil quality and associated crop yields. Many Argentine soils are not suited to the heavy tillage and cropping practices introduced by European settlers.

The Argentine Pampa now has very little natural vegetation remaining. In the most arid areas xerophytic vegetation such as *Prosopis algarrobilla* and *Larrea divaricata* can still be found. Agricultural practices commenced with the arrival of colonists in the 16th century. Ungulates were introduced to graze the grasslands, which have now been mostly re-sown, and 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 1990's but since then there has been a marked increase in the cultivation of summer annuals, such as maize, sunflower and soybean (Diaz-Zorita *et al.*, 2002). The Argentine Pampa has been recognised as a region with potential for increased production, if soils can be improved (Alvarez, 2001).

Crop yields have, however, declined in many areas, and this has been closely correlated with a reduction in soil organic matter content (Diaz-Zorita *et al.*, 2002). This has prompted the need for change in existing land management practices. The negative effects that heavy tillage has on soil organic matter led to the commencement of zero-till experiments in the 1960s in an attempt to produce a more sustainable agricultural system. Now some 13 million hectares, or about half of the agricultural production area in Argentina, is under some form of reduced-tillage system (R. Peiretti, pers. comm.). Fertilisation of crops is primarily achieved through the use of inorganic fertilizers with organic material tending to be conserved for use in horticultural farming systems (E. Rienzi, pers. comm.).

Zero-tillage modelling studies

We use three case studies to model soil carbon under a variety of conventional and zero-tillage systems in Tucuman, Catamarca and Cordoba Provinces.

i) Monte Redondo, Tucuman Province

This is a semi-arid area that naturally supports xerophytic vegetation. The agricultural practices include grazed prairie lands and row cropping; the two systems are often rotated. The studied site consists of 7 years cropping followed by 4 years of prairie grassland. The crop sequence is wheat/soybean, maize, soybean, wheat/soybean, maize, soybean, wheat, and 4 years of prairie. Both conventional tillage and zero-till cultivation are represented. In the tillage system disc and chisel plough are used for soil preparation whilst the zero-till system uses the same cropping sequence without tillage.

After an equilibrium phase of grassland and trees with fire every 60 years, CENTURY was parametised to run with improved prairie grassland from the mid 19th century. The model predicts that the prairie system is losing carbon at the rate of 0.06 t ha^{-1} y^{-1} under the current regime, but at stocks of 55.4 t C ha^{-1} is overestimating the current measured level of 48.8 t C ha^{-1}.

Cultivation is scheduled to commence in the 1950s. Fertilizer applications of 110 kg ha^{-1} urea begin in 1980. Two scenarios compare the effect of conventional tillage with that of no-tillage. The model predicts a consistent difference between the two systems of < 3 t C ha^{-1} (Figure A1a). This is less than the 6 t C ha^{-1} difference 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 carbon. 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 carbon but predicts a greater differential of 6 t ha^{-1} by 2050, mainly through a higher loss of carbon from the tilled system (Table A1a).

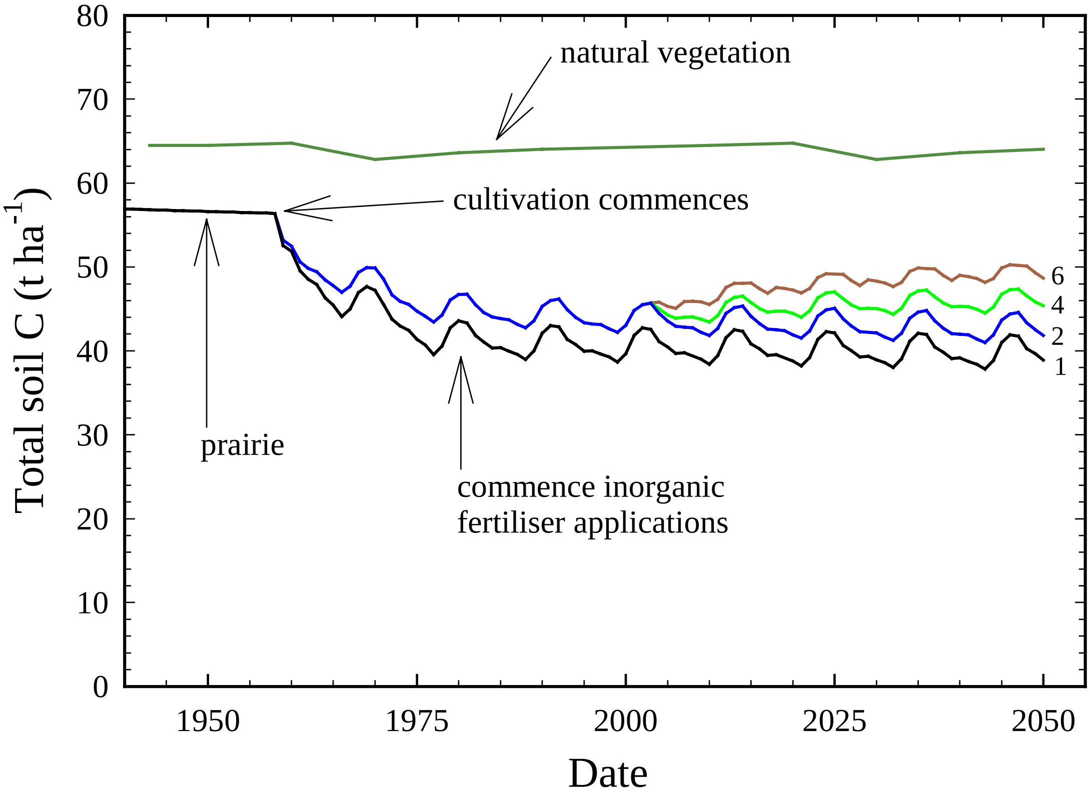

Figure A1a Total soil carbon for Monte Redondo (CENTURY)
scenarios described in Table A1b

Table A1a Total soil carbon (t ha^{-1}) for Monte Redondo (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
prairie	55.40	54.50	-1.6	43.95	43.21	-1.7
conventional 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

[1] scenarios described in Table A1b

Table A1b Scenarios for modeling land management practices, Monte Redondo

Scenario	Land Management
1	conventional tillage, inorganic fertiliser
2	zero-till, inorganic fertiliser
3	zero-till, fym 1.5 t ha^{-1} y^{-1}, inorganic fertiliser
4	zero-till, green manure 10 t ha^{-1} $crop^{-1}$, inorganic fertiliser
5	zero-till, fym 1.5 t ha^{-1} y^{-1}, green manure 10 t ha^{-1} $crop^{-1}$, no inorganic fertilser
6	zero-till, fym 3.3 t ha^{-1} $crop^{-1}$, no inorganic fertiliser

Effect of zero-tillage and organic additions

Additions of green manure (10 t ha^{-1} $crop^{-1}$) or farmyard manure (1.5 t ha^{-1} each cropping year) to the no-till system both lead to increases in carbon sequestration (scenarios 3, 4; 0.029 – 0.034 t c ha^{-1} y^{-1}) (Figure A1b). A combination of these inputs without inorganic fertilizer yields a similar result, scenario 5.

Cessation of inorganic fertilizer usage and using farmyard manure as a replacement source of nitrogen results in the greatest rate of carbon sequestration, scenario 6, 0.1 t C ha^{-1} y^{-1} (Figure A1b).

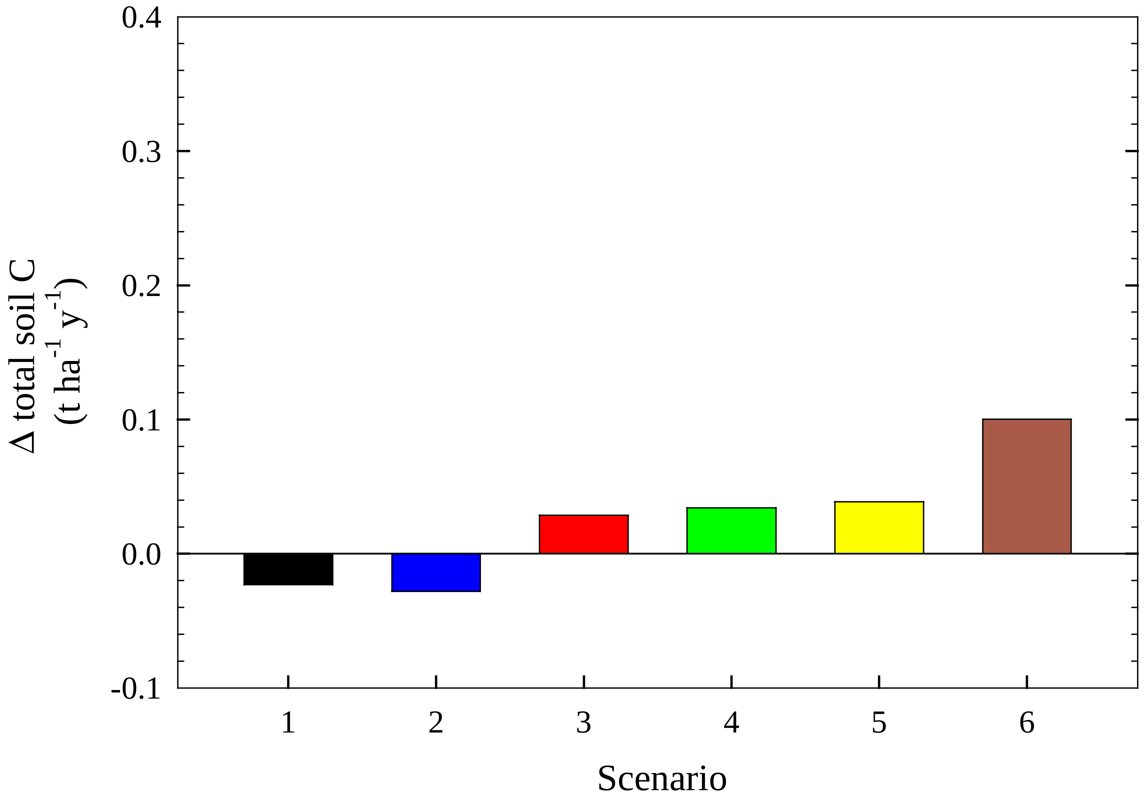

Figure A1b Average annual change in total soil carbon for Monte Redondo (CENTURY) scenarios described in Table A1b

Summary

Both models register the improvement that zero-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 prarie content in the rotation also will increase soil carbon stocks.

ii) Santa María river valley, Catamarca province

This is an arid region, with annual rainfall of 400mm and temperatures ranging from 7-32°C. The native vegetation is xerophytic 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%.

After reaching equilibrium with natural vegetation, CENTURY was run with a prairie scenario from the mid 19th century and cultivation commenced in the late 1950's using conventional tillage (disc plough). A cotton barley rotation commenced in 1980. CENTURY calculates that by 2000, soil carbon had decreased to two-thirds of its initial value (Figure A2a). Measurements in the region confirm declines in soil carbon in cultivated areas between 33% and 66%. The model estimate is therefore at the top of this range. However, the system is predicted to be reaching a new steady state and the decline in soil carbon is estimated to be just 3 t ha^{-1} over the next 50 years.

RothC, parametised with the higher, measured level of soil carbon and using quantities of plant inputs calculated from CENTURY shows a proportionately smaller effect of the current cultivation practice on soil carbon (Table A2a).

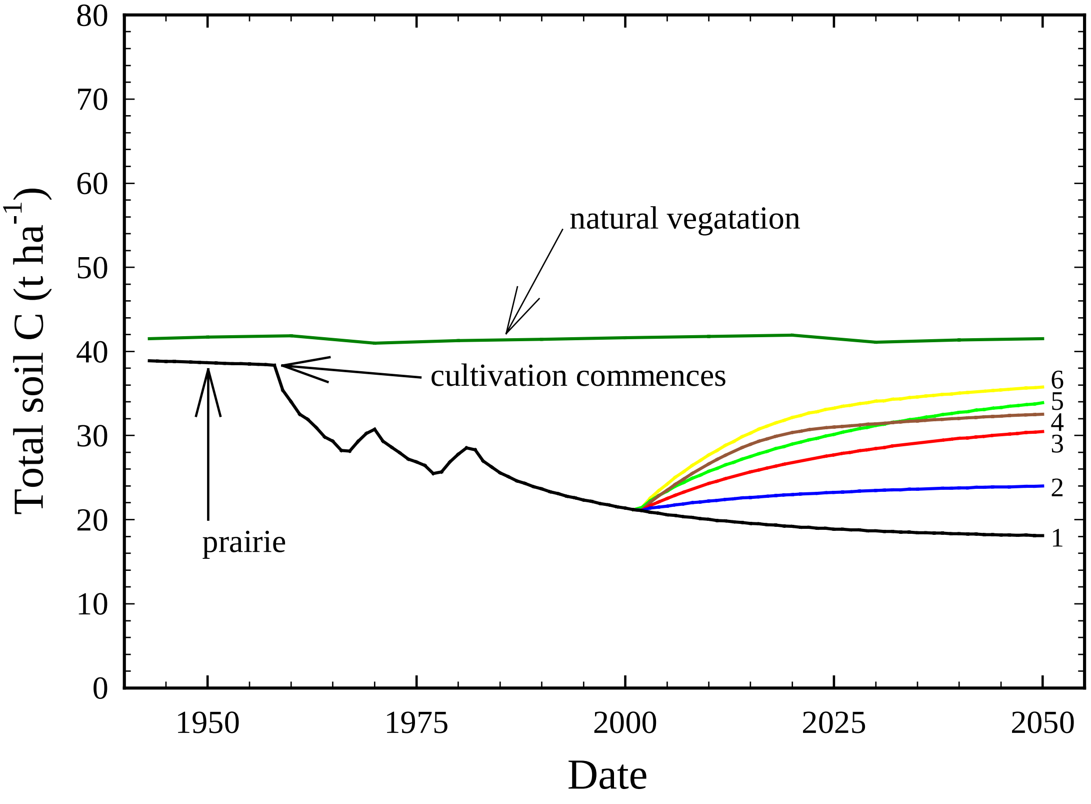

Figure A2a Total soil carbon for Santa Maria (CENTURY)
scenarios described in Table A2b

Table A2a Total soil carbon (t ha^{-1}) for Santa Maria (CENTURY and RothC)

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% change
prairie	37.11	35.75	-3.7	70.68	74.71	5.7
conventional 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

[1] scenarios described in Table A2b

Table A2b Scenarios for modeling land management practices, Santa Maria

Scenario	Land Management
1	conventional tillage, inorganic fertiliser
2	zero-till, inorganic fertiliser
3	zero-till, fym 1.5 t ha^{-1} y^{-1}, inorganic fertiliser
4	zero-till, fym 3.3 t ha^{-1} $crop^{-1}$, no inorganic fertiliser
5	zero-till, green manure 10 t ha^{-1} $crop^{-1}$, inorganic fertiliser
6	zero-till, fym 1.5 t ha^{-1} y^{-1}, green manure 10 t ha^{-1} $crop^{-1}$, no inorganic fertilser

Effect of zero-tillage

Adopting a zero-tillage system not only halts the loss of soil carbon predicted by CENTURY, but leads to a low sequestration rate of 0.05 t C ha^{-1} y^{-1} over the next 50 years (Figures A2a,b). The RothC model is less sensitive to this scenario although only change in plant inputs could be modeled (Table A2a).

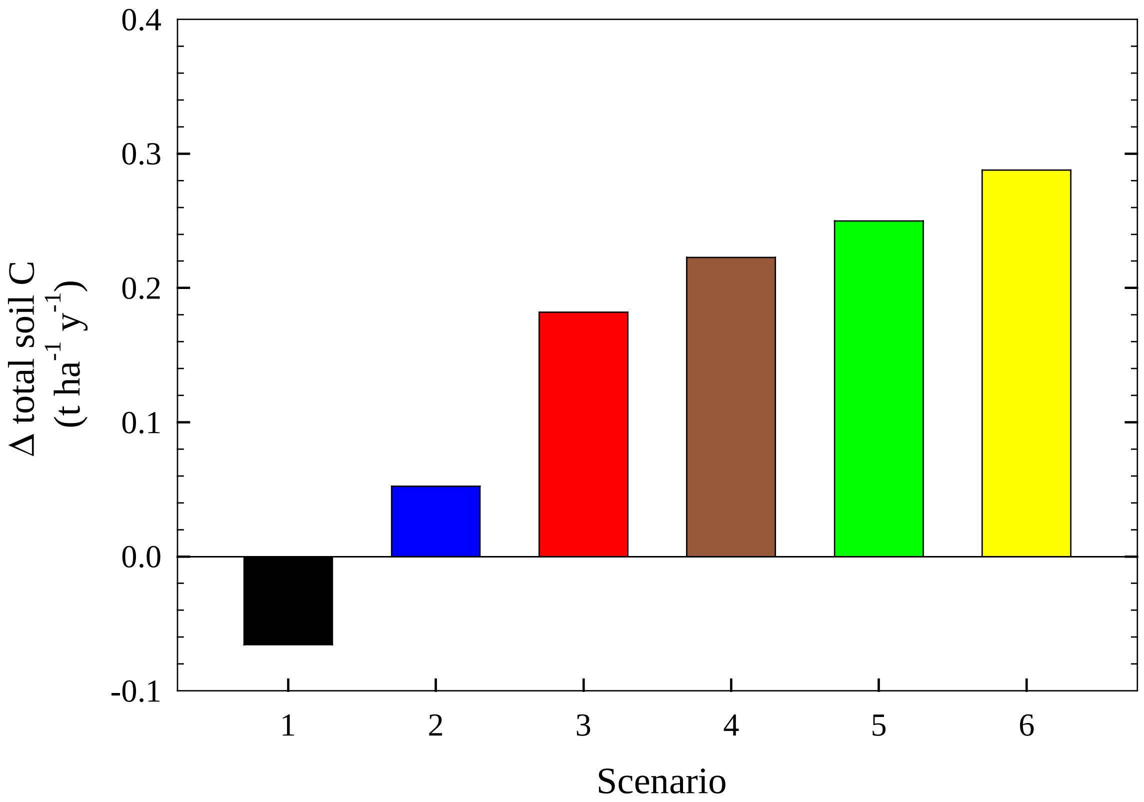

Figure A2b Average annual change in total soil carbon for Santa Maria (CENTURY) scenarios described in Table A2b

Effect of organic additions

Additions of farmyard manure and green manure (scenarios 3, 5) both lead to marked increases in carbon sequestration rates in the region of 0.18 – 0.25 t C ha^{-1} y^{-1} (Figures 2Aa,b). RothC again shows a smaller effect (Table A2a).

Effect of inorganic fertilizer

Replacing inorganic fertilizer with farmyard manure (scenario 4) promotes carbon sequestration (0.22 t ha^{-1} y^{-1}, scenario 4) while combing the green manure and farmyard manure applications gives the best carbon accrual rate, 0.29 t ha^{-1} y^{-1} (scenario 6, Figures A2a,b). Inorganic nitrogen fertilizer is further inefficient owing to the high energy cost of manufacture

Summary

Both models suggest that adopting zero-tillage will halt the decline in soil carbon. However, to increase carbon sequestration rates organic additions are necessary (green manures, farmyard manure), and these can be used to replace the inorganic fertilizer applications.

iii) Southern Cordoba province, north-west Buenos Aires province, and north-east La Pampa province

Following an equilibrium period with natural vegetation and subsequent prairie conditions from the mid 1800s, CENTURY was parmetised with a cultivation regime commencing in the 1950's. This included a 4 year cropping (wheat-soybean-maize-soybean), 4 year prairie cycle with inorganic fertilizer applications (100 kg ha^{-1} 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-4 years prairie-winter forage-wheat-soybean-maize-soybean-maize-prairie. The non-rotated crop sequence was similar but without the prairie interludes.

Modeled results for the non-rotated crop system show an initial steep fall in soil carbon to 37 t ha^{-1} in 2000 and further losses over subsequent years (Figure A3a). RothC estimates a proportionately larger fall from a higher base (Table A3a). The rotated crop-prairie system does not show the same sharp decline in soil carbon as the non-rotated system did and oscillates around a level of just over 40 t ha^{-1} (Figure A3a). However, RothC estimates a slightly larger proportionate decline in carbon for the rotated crop system. Both models calculate smaller differences between the rotated and non-rotated cropping systems in 2000 compared with the 8.5 t ha^{-1} difference measured in the field.

Table A3a Total soil carbon (t ha^{-1}) for rotated and non-rotated plots, modelled with CENTURY and RothC

Scenario[1]	CENTURY			RothC		
	2000	2050	% change	2000	2050	% 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

[1] scenarios described in Table A3b

Table A3b Scenarios for modeling land management practices, Santa Maria

Scenario	Land Management
1	non-rotated plots, inorganic fertiliser
2	rotated plots, inorganic fertiliser
3	rotated plots, zero-till, inorganic fertiliser
4	rotated plots, zero-till, fym 1.5 t ha^{-1} y^{-1}, green manure 10 t ha^{-1} crop^{-1}, no inorganic fertilser
5	zero-till, fym 1.5 t ha^{-1} y^{-1}, inorganic fertiliser
6	zero-till, green manure 10 t ha^{-1} crop^{-1}, inorganic fertiliser
7	zero-till, fym 3.3 t ha^{-1} crop^{-1}, no inorganic fertiliser

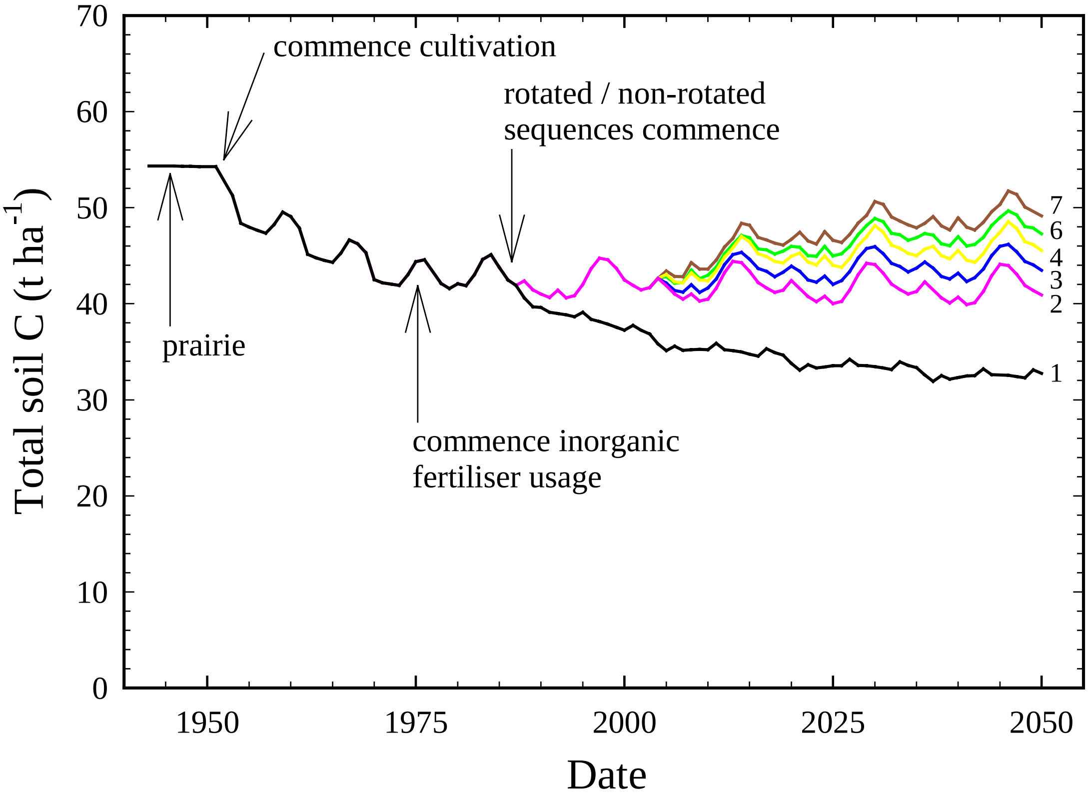

Figure A3a Total soil carbon for rotated and non-rotated plots (CENTURY)
scenarios described in Table A3b

Effect of zero-tillage

Adoption of a zero-tillage regime for the rotated-plots system increases soil carbon by 2.5 t ha^{-1} over the next 50 years, representing a carbon sequestration rate of 0.02 t ha^{-1} y^{-1} (Figure A3b). The rate increases to about 0.1 t C ha^{-1} y^{-1} if green manures and farmyard manure are used instead of fertilizers.

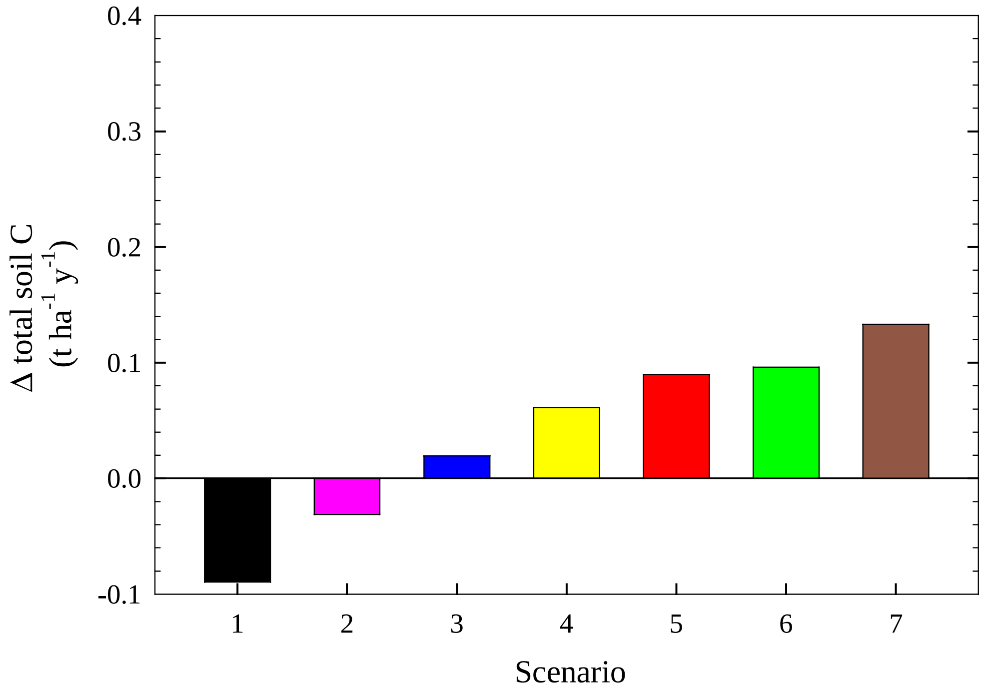

Figure A3b Average annual change in total soil carbon for rotated and non-rotated plots (CENTURY)

scenarios described in Table A3b

Effect of organic inputs

Additions of green manure and farmyard manure with or without inorganic fertilizer can lead to carbon sequestration rates of between 0.06 and 0.13 t ha^{-1} (Figures A3a,b). Inorganic fertilizer can be successfully replaced with organic material.

Summary

The inclusion of prairie interludes in the cropping system is an important factor for reducing the decline in soil carbon but the models show that zero-tillage and organic inputs are required if carbon is to be sequestered in this system.

Conclusions from Argentina cases

The modeling of farm data from three dryland provinces of Argentina shows that carbon tocks 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 ca. 15 t ha^{-1}. However, the adoption of zero-tillage systems in recent years has halted these declines and, on their own, result in small annual increases in soil carbon of the order of 0.02 t ha^{-1} y^{-1}. Rotations with significant periods for return to prairie grassland (eg 4 years in 11) result in further increases in soil carbon.

The highest rates of sequestration (0.1 to 0.25 t ha^{-1} y^{-1}) occur when zero-tillage systems also include cultivation of green manures and additions of farmyard manure.

References

Alvarez R (2001) Estimation of carbon losses by cultivation from soils of the Argentine Pampa using the Century Model. *Soil Use and Management* 17, 62-66.

Breman H, De Wit C T (1983) Rangeland productivity and exploitation in the Sahel. *Science* 221, 1311 - 1347

Butterworth J A, B Adolph, PV Satheesh, GNS Reddy, B Suresh Reddy, V Murali, V Srinivas, V Karoshi, Ganesh Keremane K Ravi, M N Kulkarni, T K Geetarani, B S Ramachandra, Iranna Umrani (2002). Human and social capital aspects of soil nutrient management, India. Working Document, Natural Resources Institute, Chatham, UK Deccan Development Society, Hyderabad / Pastapur, Andhra Pradesh, BAIF Institute of Rural Development, Tiptur / Lakihalli, Karnataka.

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

Diaz-Zorita M, Duarte GA, Grove JH (2002) A review of non-till systems and soil management for sustainable crop production in the sub-humid and semiarid Pampas of Argentina. *Soil and Tillage Research* 65, 1-18

Falloon P, Smith P (2002) Simulating SOC changes in long-term experiments with RothC and CENTURY: a model evaluation for a regional scale application. *Soil Use and Management* 18, 101-111

FAOCLIM 2 (2000) World-Wide Agroclimatc Database. FAO Agrometeorology Group

Gichuki FN (2000) Makueni district profile: rainfall variability, 1950-1997. Drylands Research Working Paper 2. Drylands research, Crewkerne, UK.

Harris F (2000) Changes in soils fertility under indigenous agricultural intensification in the Kano region. Drylands Research Working Paper 36. Drylands research, Crewkerne, UK.

Humphries SW Long SP (1995) WIMOVAC: a software package for modelling the dynamics of plant leaf and canopy photosynthesis. *Cabios* 11, 361-371

Jenkinson DS and Rayner JH (1977) The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science* 123, 298-305

KARI (1999) Soil Fertility and Plant Nutrition. Annual Report, Kenya Agricultural Research Insitute, Nairobi.

Mbogoh S (2000) Makueni district profile: crop production and marketing 1988-1999. Drylands Research Working Paper 7. Drylands research, Crewkerne, UK.

Mbuvi JP (2000) Makueni district profile: soil fertility management. Drylands Research Working Paper 6. Drylands research, Crewkerne, UK.

Mortimore M (1989) The causes, nature and rate of soil degradation in the northern most states of Nigeria and an assessment of the role of fertilizer in counteracting the problems of degradation. Environment Department Working Paper no. 17, The World Bank, Washington DC.

Mortimore M (2000) Profile of rainfall change and variability in the Kano-Maradi region, 1960-2000. Drylands Research Working Paper 25. Drylands research, Crewkerne, UK.

Nandwa SM, Gicheru PT, Qureshi JN, Kibunja C, Makokha S (1999) Kenya – country report. In Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and East Africa, Proceedings of the Expert Consultation, Harare, Zimbabwe, December 1997. Eds. H. Nabhan, A.M. Mashali, A.R. Mermut. FAO, Rome.

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America Journal* 51, 1173-1179

Parton WJ, Stewart JWB, Cole CV (1988) Dynamics of C, N, P, and S in grassland soils: A model. *Biogeochemistry* 5, 109-131

Pretty J N, Thompson J and Kiara J K. 1995. Agricultural regeneration in Kenya: The Catchment Approach to soil and water conservation. *Ambio* XXIV (1), 7-15

Pretty J N, A.S. Ball, Li Xiaoyun and N.H. Ravindranath. 2002. The role of sustainable agriculture and renewable resource management in reducing greenhouse gas emissions and increasing sinks in China and India. *Trans. Roy. Soc. Lond A (Mathematical, Physical and Engineering Sciences)* 360, 1741-1761

Pound B (2000) Visit report, March 12-30, 2000. Karnataka Watershed Development Society, Bangalore.

Reddy GNS (2001) Human and social capital aspects of soil nutrient management, India Annex D: Karnataka fieldwork report. BAIF Institute for Rural Development, Tiptur, Karnataka, India.

Smith P, Powlson DS, Smith JU, Elliot ET (1997) Evaluation and comparison of soils organic matter models using datasets from seven long-term experiemts. *Geoderma* 81 (special issue) 225