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PROJECTED CHANGES IN SOIL ORGANIC CARBON STOCKS UPON ADOPTION OF RECOMMENDED SOIL AND WATER CONSERVATION PRACTICES IN THE UPPER TANA RIVER CATCHMENT, KENYA

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ABSTRACT

Large areas in the Upper Tana river catchment, Kenya, have been over-exploited, resulting in soil erosion, nutrient depletion and loss of soil organic matter (SOM). This study focuses on sections of the catchment earmarked as being most promising for implementing Green Water Credits, an incentive mechanism to help farmers invest in land and soil management activities that affect all fresh water resources at source. Such management practices can also help restore SOM levels towards their natural level. Opportunities to increase soil organic carbon (SOC) stocks, for two broadly defined land use types (croplands and plantation crops, with moderate input levels), are calculated using a simple empirical model, using three scenarios for the proportion of suitable land that may be treated with these practices (low = 40 per cent, medium = 60 per cent, high = 80 per cent). For the medium scenario, corresponding to implementation on ~348 000 ha in the basin, the eco-technologically possible SOC gains are estimated at 4·8 to 9·3 × 10^6 tonnes (Mg) CO_2 over the next 20 years. Assuming a conservative price of US$10 per tonne CO_2-equivalent on the carbon offset market, this would correspond to ~US$48–93 million over a 20-year period of sustained green water management. This would imply a projected (potential) payment of some US$7–13 ha^{-1} to farmers annually; this sum would be in addition to incentives that are being put in place for implementing green water management practices and also in addition to the benefits that farmers would realize from the impact on production of these practices themselves. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: soil carbon; improved land management; carbon sequestration; carbon offsets; Green Water Credits; Upper Tana; Kenya; green water management

INTRODUCTION

Many areas in central and western Kenya are densely populated (500–1200 inhabitants/km^2). A large fraction of the population depends on subsistence agriculture: maize, rice, beans, bananas and cassava; the main export crops are tea and coffee. The most severe environmental issues include deforestation, overgrazing and increased cultivation in marginal areas leading to land degradation caused principally by soil erosion and consequent pollution of rivers and lakes, and loss of biodiversity (see Mathu and Davies 1996). Despite an increasing area under cultivation, decreasing soil fertility, particularly low availability of phosphorus and nitrogen, coupled with decreasing levels of soil organic matter in croplands (Kapkiyai *et al*., 1999; Gichuru *et al*., 2003), is blamed for a per capita decrease in food production. To a large extent, this situation can be remedied through adoption of recommended soil and water conservation (SWC) practices subject to the availability of adequate policies and socio-economic incentives (Koning *et al*., 2001; Ringius, 2002). Kenya's long history of state involvement in SWC and land management has been reviewed by Pretty *et al.* (1995). SWC programmes, however, were not always successful because of experts' negligence of the role of farmers in problem identification and conservation planning (Okoba and Sterk, 2010).

During the last decades, the use of blue water has received much attention in water resources research, whereas little attention has been paid to the quantification of green water in food production and food trade (Liu *et al*., 2009). *Green water* is defined as that fraction of rainfall that infiltrates into the soil and is available to plants; *blue water* comprises surface runoff, groundwater and stream base flow that can be used elsewhere and which supports aquatic and wetland ecosystems (Falkenmark and Rockström, 2005; Liu *et al*., 2009; Hoff *et al*., 2010). The Green Water Credits (GWC) project is developing a financial mechanism that supports upstream farmers to invest in improved green water management practices (Dent and Kauffman, 2007). Currently, such activities are unrecognized and unrewarded; direct reward will enable better management of the resource. GWC project activities in Kenya have focussed on the Upper Tana River catchment. These include participatory approaches to mobilize local communities for resource conservation, linking water users and suppliers

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with representatives of key Ministries and Water Authorities (Gicheru *et al*., 2006).

Differences between economic and ecological (biophysical) criteria for identifying, measuring and evaluating ecosystem services have been discussed by Sagoff (2011). So far, the GWC project has only considered the positive effects of improved SWC on green and blue water flows. To this avail, Hunink *et al*. (2011) used a distributed, watershed-scale modelling approach based on the Soil and Water Assessment Tool (SWAT; see Neitsch *et al*., 2002). Hydrological response units (HRUs) were defined on the basis of topography, soil distribution and characteristics, and land use. The analyses gave an insight in the spatial distribution of areas considered most appropriate for GWC interventions, for defined SWC practices. These areas were defined in terms of reduction in soil erosion (by water), increase in groundwater recharge, increase in crop transpiration (hence crop growth) and reduction in soil evaporation. The usefulness of the SWAT model for application at watershed scale in Kenya has been discussed by various authors (Githui *et al*., 2009; Gathenya *et al*., 2011; Mango *et al*., 2011).

Hunink *et al*. (2011) rated the projected biophysical suitability index (BSI) of a given HRU for green water management intervention from 0 to 1, where 1 points at the largest potential. For the purpose of the current assessment, HRU's with a BSI > 0·5—corresponding with a high (modelled) cost–benefit ratio for the proposed soil and water management practices—were selected as being most suited, from a biophysical point of view, for implementing SWC practices. Hereafter, the corresponding area is simply referred to as the *GWC target area*.

Besides improving overall soil water conditions, and crop production, the adoption of improved SWC practices (in other words improved *green water* management) may also have beneficial effects on soil carbon sequestration and net greenhouse gas emissions (Batjes and Sombroek, 1997; Watson *et al*., 2000; Lal, 2004; Powlson *et al*., 2011), opening further options for payment for environmental services. So far, however, possible effects on soil organic carbon (SOC) have not been considered explicitly in the GWC project.

The aim of this exploratory study to provide an *ex ante* assessment of feasible SOC gains in the GWC target area. First, however, it presents estimates of regional soil carbon stocks derived from a recent soil and terrain database for the Upper Tana river basin (Dijkshoorn *et al*., 2011) and simulation of synthetic soil profiles. Subsequently, possible gains in SOC stocks upon improved land management within land units identified as being biophysically most suited for GWC implementation, based on the preceding SWAT study (Hunink *et al*., 2011) and a physical land evaluation (FAO, 1976), are estimated using an empirical modelling approach to provide a first estimate of potential and eco-technologically possible SOC gains. This scenario approach builds upon earlier work for Africa (Batjes, 2004a) and Kenya (Batjes, 2004b). Finally, model projections are used to estimate possible annual rewards (US$) to small-scale farmers for avoided CO_2 emissions from the carbon offset market, subject to adoption of sustained use of the recommended green water management practices. Possible sources of uncertainty in the data and modelling approach are discussed.

DATA AND METHODS

Biophysical Data

The Upper Tana river basin is located some 50 km northeast of Nairobi and covers some 17 300 km^2 (approx. 0·2N/6·5E resp. 1·2S/38·8E, in decimal degrees). It covers 11 districts: Thika, Maragua, Muranga, Nyeri, Kirinyaga, Embu, Mbeere, Meru (South, Central and North) and Tharaka; some 3·1 million people live in the basin (WRI, 2007). Elevation ranges from over 4500 m, near Mount Kenya, to about 400 m a.s.l to the southeast. As a result, the catchment comprises a wide range of natural regions: from hot, semi-arid lowlands to cool, humid highlands with soils of widely differing potential for crop production (Sombroek *et al*., 1982).

The major limitations to maximum production per agro-climatic zone (ACZ), potential annual production, and likely risk of crop failure for an adapted maize crop are listed in Table I. Some 75 per cent of the basin has a *R*/*Et* ratio greater than 0·65, pointing at a medium to very high potential for crop growth (Sombroek *et al*., 1982). The effect of decreasing air temperature, between the semi-arid lowland and the very humid highlands, on potential production is small in comparison with that associated with possible water shortages.

Land use in the Upper Tana is changing rapidly with encroachment on forests and savannah land for agricultural and pastoral farming, wood fuel and timber for construction. Land cover/use data for this study are the result of recent fieldwork and satellite classification (Wilschut, 2010). Soil geographic and attribute data, in GIS format, were derived from a 1:250 000 scale soil and terrain (SOTER) database for the study area (Batjes, 2011b; Dijkshoorn *et al*., 2011).

Computing Soil Organic Carbon Stocks

Soil organic carbon stocks were calculated using procedures developed for the GEFSOC project (Batjes *et al*., 2007; Milne *et al*., 2007), using soil data derived from SOTER. The mapping approach takes into account regional differences in proportion of organic carbon, bulk density, volume of the fraction >2 mm, and thickness of layer within each SOTER map unit—which may comprise from one to four different soil units/components. Each soil component has been characterized by a single, so-called representative soil

Table I. Main characteristics of agro-climatic zones in the Upper Tana River basin (after Sombroek *et al.* 1982)

Agro-climatic zone (ACZ)	Relative extent (%)[a]	R/Et[b] (%)	Potential production (10^3 kg dry matter $ha^{-1} y^{-1}$)	Risk of crop failure for an adapted maize crop (%)	Potential for crop growth[c]	Major limitations to maximum production[d]
I—Humid	27·1	>100	>30	<1	Very high	SF, HU, DR
II—Sub-humid	11·9	80–100	20–30	1–5	High	SF, HU, DR
III—Semi-humid	15·9	65–80	12–20	5–10	Medium to high	SF, HU, RA
IV—Semi-humid to semi-arid	17·3	50–65	7–12	10–25	Medium	HU, RA, SF
V—Semi-arid	26·7	30–50	3–7	25–75	Medium to low	RA, HU, SF

[a]Expressed as proportion of the Upper Tana River basin (~17 300 km^2); water bodies cover the rest of the area, some 1·1%.
[b]Ratio of mean annual rainfall (R) over evapotranspiration (Et).
[c]Assuming soil conditions are not limiting.
[d]Listed in approximate order of importance: DR = drainage; HU = husbandry; RA = rainfall; SF = soil fertility.

profile that is considered to represent the modal properties for the corresponding soil component (van Engelen, 1999; Dijkshoorn *et al*., 2011). The use of single profiles, however, ignores the variability within land (map) units and their soil components. Ideally, this type of information should be derived from analysis of data for a range of profiles (>30) considered to be representative for a given soil component and selected using probabilistic sampling. In practice, however, such elaborate data sets are seldom available. A practical solution to this problem of data scarcity is to emulate the variation in soil properties within each soil component by using synthetic profiles. Various researchers have discussed the usefulness of proxy-based approaches to provide an approximation of possible effects of natural and man-induced soil variation in modelling studies (Bouma *et al*., 1998; Bouma, 2002; Ogle *et al*., 2010); nonetheless, the associated uncertainties remain large.

The simulated value of a soil attribute (Y), for example bulk density, for layer (k) of each synthetic profile (j) can be written as (Batjes 2004b)

$$Y_{jk} = X_{ik} + S \times (X_{ik} \times R \times V/100) \qquad (1)$$

Where: Y_{jk} is the value of the soil attribute for the kth layer of the simulated profile (j), X_{ik} is the value of the attribute for the kth layer of the representative profile (i), R is a random number from 0 to 1, V is the assumed maximum variation for the soil property in per cent, and S is a randomly determined sign (plus or minus). According to Landon (1991), the coefficients of variation of individual soil properties within soils mapped as single series commonly range from 20 to 70 per cent; this may be even more when soils are mapped at a higher hierarchical level (Spain *et al*., 1983; Eswaran *et al*., 1993). Variations tend to be largest for chemical properties, which are most readily modified by differences or changes in land management. Conservatively, a common within-class variance of 50 per cent was assumed here for the proportion of SOC and the content of fragments >2 mm to simulate plausible ranges for regional carbon stocks. As SOC content and bulk density are often correlated (Manrique and Jones, 1991; Bernoux *et al*., 1998), the possible variation in bulk density is not considered explicitly in the simulation (it is assumed to co-vary with the simulated SOC content).

The total content of SOC for each simulated (synthetic) profile, with k layers, was calculated using bulk density, the simulated data for proportion of carbon and proportion of the fraction >2 mm, and thickness of layers. For this study, the number of simulation runs was set at 1000 per profile (for each soil component); subsequently, 30 per cent thereof was randomly selected for further analysis ($n = 300$). The resulting information was linked to the soil geographic information (area of the corresponding soil component) to arrive at n realizations of carbon stocks for the Upper Tana basin. The resulting distribution showed the fluctuation arising from the model, approximating natural and man-induced soil variation. The quantiles of the observed values can serve as an estimate for the range in carbon content to the specified depths (Webster and Oliver, 2001). Confidence limits (95 per cent) for the population median were used in this study as the median is more robust than the mean and more resistant to erratic extreme observations (Snedecor and Cochran, 1980, p. 136–137).

Projected Changes in SOC Stocks

The semi-quantitative approach for assessing possible SOC gains considers differences in LUT, agro-climatic conditions and soil types, potential rates of SOC sequestration, a physical land evaluation and an empirical model (Figure 1). Details are provided in the following paragraphs.

For Africa, the average annual decrease of topsoil organic matter associated with soil nutrient depletion has been estimated at $-0{\cdot}22$ Mg C ha^{-1} (Sanchez *et al*., 1997). The possible increase in organic carbon stocks in response to adoption of best management practices will vary with land

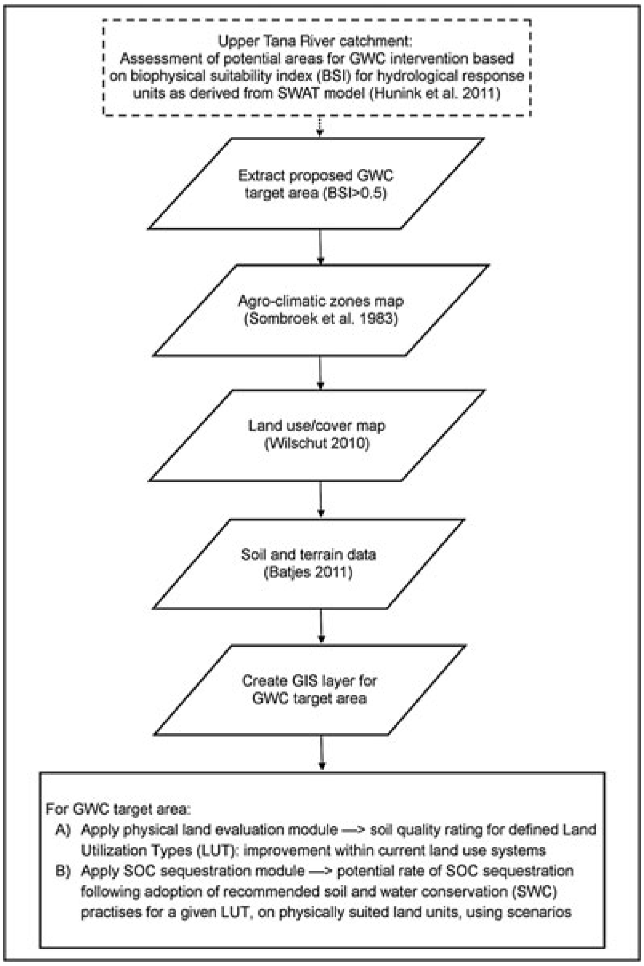

Figure 1. Procedure for estimating possible SOC gains upon improved management or restoration within current land use systems for the GWC target area.

use history and climate as well as current soil conditions and types of management measures adopted. The latter will depend strongly on prevailing socio-economic conditions and policy incentives (e.g. Izac, 1997; Koning *et al*., 2001; Smith, *et al*., 2007b; Henry *et al*., 2009). At the present low prices for carbon, main mitigation options are those consistent with existing production systems, such as changes in tillage, fertilizer application, erosion control and manure management (Smith *et al*., 2007a).

Best management practices to increase soil carbon reserves within present land use systems, such as croplands, must be site specific (e.g. Paustian *et al*., 1998; Bruce *et al*., 1999; Smith *et al*., 2007a). They should include an adroit combination of (a) conservation tillage in combination with planting of cover crops, green manure and hedgerows; (b) organic residue and fallow management; (c) water conservation and management; (d) soil fertility management, including use of chemical fertilizers, organic manures and liming; (e) introduction of agro-ecologically and physiologically adapted crop/plant species, including agroforestry; (f) adopting crop rotations, with avoidance of bare fallow; and (g) stabilization of slopes and terraces to reduce risk of erosion by water. Options that both reduce GHG emissions and increase productivity are more likely to be adopted than those which only reduce emissions (Gisladottir and Stocking, 2005; Smith *et al*., 2007a).

The magnitude of change in carbon stocks for a given practice depends on three factors (Sampson and Scholes, 2000): the average rate of carbon stock change per unit area after adoption of the practice, the time required for new steady state levels to occur and the total area over which the activity is applied. Table II lists estimates of carbon sequestration rates by ACZ for cropland and plantation crops. These rates are lower—hence more conservative—than those from published studies, which often report measurements for time intervals shorter than needed to reach a new equilibrium. Overall, uncertainties remain high, generally in the order of ±50 per cent (Sampson and Scholes, 2000) or even more (Smith *et al*., 2007a). Therefore, SOC sequestration rates in Table II should be revised as data from long-term field observations become available for the Upper Tana basin.

The rate of carbon gain will decrease over time and level off after 20–50 years, depending on land use, management, climatic conditions and soil quality, as the system approaches a new steady state (Sampson and Scholes, 2000). A time horizon of 20 years is considered appropriate in the context of this exploratory study. This is also the default for empirical, IPCC Tier-1 level calculations (e.g. IPCC, 2006; Smith *et al*., 2007a; Bernoux *et al*., 2011). A linear rate of change over the 20-year period was assumed, which is a simplification.

Variations in SOC sequestration rates due to climate change and increase in atmospheric CO_2 concentration were assumed to be much smaller than those associated with the proposed changes in land use and management, over the 20-year reference period.

Table II. Indicative rates of soil carbon sequestration upon introduction of improved management within agricultural lands in the Upper Tana River basin, by agro-climatic zone

Land use	Carbon sequestration rates by agro-climatic zone[a] ($Mg\,C\,ha^{-1}\,y^{-1}$)		
	I–II	III–IV	V
Croplands	0·30–0·50[b]	0·15–0·30	0·05–0·15
Plantation crops[c]	0·25–0·50	0·10–0·25	0·05–0·10

[a]Agro-climatic zones are characterized in Table I.
[b]Indicative rates for annual mitigation potential, based on data from Bruce *et al*. (1999), Sampson and Scholes (2000), Lal *et al*. (2002) and Ramachandran Nair *et al*. (2010).
[c]Refers to improved soil and water management of mainly coffee plantations (see text); overall, zone V is not considered biophysically suited for rainfed plantations of coffee and tea, see Table I.

Assessing Land Suitability for Specific Uses

Tea and coffee plantations predominate in the more humid uplands, whereas rainfed croplands are the dominant land use in the semi-humid and semi-arid parts of the GWC target area. According to Wilschut (2010), there is much scope for improving the management of land currently under maize and coffee, significant portions of which are poorly managed and degraded. Contrastingly, the soil's surface is generally well protected under established tea plantations with pruning's and water erosion is rare; as such, there will be less scope for increasing SOC stocks under established and well-managed tea plantations (see Table II). Alternatively, when soils in the 'tea zone' are left uncovered, erosion by water can be high especially on steep slopes (Wilschut, 2010). Further, for example, soil acidity may be limiting for some crops, such as maize, on soil types such as Acrisols and humic Cambisols.

The capacity for increasing crop production and humus levels upon adoption of improved soil and water management *within* a given land use system and ACZ will vary with the quality of the soil, type of crops grown and overall input levels. For this study, these aspects were rated using physical land evaluation (FAO, 1976; Sys *et al*., 1993; FAO, 2007). To this avail, land use/cover types for the GWC target area (Table III) were clustered into two broadly defined LUTs, namely rainfed croplands (comprising land cover classes AGRL and CORN) and plantation crops (TEA and COFF), with moderate levels of inputs and technology. It has been assumed that some N–P–K fertilizers are applied, crop residues are left on the ground, and appropriate SWC technologies are adopted. Crops grown include staple foods (maize, beans, banana and cassava), and overall biophysical requirements are assumed to correspond to those of a maize crop. For plantation crops, the biophysical requirements are assumed to correspond to those of coffee and tea.

Table III. Proportion of agro-climatic zones and land use/cover in the Upper Tana GWC target area

ACZ[a]	ACZ_LU[b]	Proportion (%)[c]
I—Humid	I/COFF	10·2
	I/CORN	7·3
	I/TEA	8·1
II—Sub-humid	II/COFF	9·3
	II/CORN	15·7
	II/TEA	0·2
III—Semi-humid	III/AGRL	0·4
	III/COFF	5·8
	III/CORN	17·4
IV—Semi-humid to semi-arid	IV/AGRL	0·5
	IV/COFF	0·3
	IV/CORN	3·4
V—Semi-arid	V/AGRL	21·0
	V/CORN	0·2
Water	Water	0·2

[a]Agro-climatic zones; for details, see Table I.
[b]Combined code for ACZ and land use/cover (LU) classes (Wilschut, 2010): AGRL = croplands (undefined); COFF = coffee plantations; CORN = maize cultivation; TEA = tea plantations.
[c]Proportions are derived from GIS overlays; totals may differ from 100% because of rounding.

Soil quality, for the above LUTs, was rated using soil layer data (soil pH and cation exchange capacity as proxies for soil fertility; soil texture and proportion of coarse fragments as proxies for rating ease of soil workability), soil profile data (rootable soil depth, soil drainage, water holding capacity) and slope data held in SOTER (Batjes, 2011b). For each soil component (different soil type within a given soil mapping unit), the abovementioned land characteristics were rated according to whether they were considered to be non-limiting (s1, rated 1·0), slightly limiting (s2, rated 0·8), moderately limiting (s3, rated 0·6) or strongly limiting (n, rated as 0·2) for the given LUT. Criteria for rating the absence of limitations, or reduction factors, were derived from various sources (FAO, 1983; Landon, 1991; Sys *et al*., 1993) and discussed in a technical report (Batjes, 2011a); inherently, such class limits are fuzzy, not crisp (Burrough, 1989).

The final suitability rating, ranging from 1 for no limitations to 0 for strong limitations, for a given soil component and LUT was assessed using an approach that integrates the various subratings into one single, weighted land suitability index. The procedure (2) accounts for the fact that physical soil limitations, such as a shallow depth or poor drainage conditions, are considered to pose a greater obstacle to (most) farmers than would limiting soil chemical properties, which can be redressed more readily using agricultural interventions (at the moderate input levels assumed here, assuming adequate socio-economic incentives).

$$S\text{-}index = Sr^*[(2^*Sp + 1^*Sc)/3] \tag{2}$$

Where: S-index is the aggregated suitability rating, *Sr* is the subrating for relief (slope), *Sp* is the subrating for 'whole profile' properties (drainage class, depth of soil, and soil moisture holding capacity; see Equation 3), *Sc* is the depth-weighted subrating for soil horizon properties (particle size class, proportion of mineral fraction >2 mm, cation exchange capacity, and pH_{water}; see Equation 4) down to 60-cm depth. Subratings for *Sp* and *Sc* are determined as

$$Sp = \left[\left(Rating_{most\_limiting\_factor}\right) * \left(\sum ratings_{two\_remaining\_factors}\right)\right]/2 \tag{3}$$

and

$$Sc = \mathrm{Avg}(Sc_i), \text{ with} \tag{4}$$

$$Sc_i = \left[\left(Rating_{most\_limiting\_factor}\right)^*\left(\sum rating_{three\_remaining\_factors}\right)\right]/3 \quad \text{for layer } i$$

Where: i is the soil layer ($i = 1$ to 3, resp. 0–20, 20–40 and 40–60 cm).

The final *S-index* for each map unit (i.e. combination of LUT, soil type and agro-ecological zone) was rated from 1 (highly suitable) to 0 (not suitable). This type of weighted approach is commensurate with the procedure that Hunink *et al*. (2011) have used to map possible target areas for GWC interventions in the Upper Tana basin.

Finally, the projected SOC sequestration for the GWC target area was computed for tracts of land rated as being at least marginally suitable (defined as *S-index* > 0·4) for the LUT under consideration.

RESULTS AND DISCUSSION

Soil Organic Carbon Content

The dominant major FAO (1988) soil groups in the basin are Nitosols (~30 per cent), followed by Andosols (13 per cent), Acrisols (12 per cent), Cambisols (11 per cent), Luvisols (8 per cent), Regosols (7 per cent), Vertisols (6 per cent) and Ferralsols (5 per cent), with smaller (<2 per cent each) extents of Leptosols, Planosols, Arenosols, Phaeozems, Alisols, Fluvisols, Gleysols and Lixisols. The distribution of these major soil groups varies widely within and between ACZs (Table IV). Relatively fertile Andosols and Nitosols are predominant in the humid zone, whereas less fertile Acrisols and Cambisols predominate in the semi-arid section of the basin; many of these soils are degraded to a certain extent.

The area-weighted SOC content for the Upper Tana River basin, expressed as 95 per cent confidence limits for the median, is 6·6–6·9 kg C m^{-2} for 0–30 cm, 9·7–10·0 kg C m^{-2} for 0–50 cm, and 14·0–14·2 kg C m^{-2} for 0–100 cm (Table V); the simulated ranges (min–max) for the present simulation run are 5·6–8·3 (0–30 cm), 8·4–11·7 (0–50 cm) and 12·2–15·9 (0–100 cm) kg C m^{-2}. Inherently, similar (although slightly different) values would be obtained for a new series of 'randomized runs'. Further, it should be noted that wider confidence intervals than shown in Table V would probably be obtained when analyses can be based on a range of real profiles (e.g. >30) for each soil component, rather than the currently used, simulated synthetic profiles. In practice, however, the necessary field data are rarely available (or freely accessible) for inclusion in SOTER and similar subnational, national and continental scale databases. The need for sustained data collection activities that include both soil legacy (historic) data and newly collected soil data to better address a range of global issues, including food security and adaptation and mitigation to climate change, at various scale levels has been discussed by various authors (Sanchez *et al*., 2009; Nachtergaele *et al*., 2011; van Wesemael *et al*., 2011; Panagos *et al*., 2012).

Soil organic carbon density to 100-cm depth is highest in the humid zone (26·7–27·4 kg C m^{-2}) and lowest in the semi-humid to semi-arid zone (5·7–5·9 kg C m^{-2}). These values are similar to those reported earlier by ACZ for the whole of Kenya (Batjes, 2004b), except for the humid zone of the Upper Tana. The larger value reported here for the humid zone is related to the predominance of umbric and mollic Andosols, humic Nitosols and humic members of Acrisols and Cambisols in the Upper Tana. On average, some 44–50 per cent of the SOC content is stored in the upper 30 cm, the layer most vulnerable to changes in land use or management, and about 65–70 per cent in the top 50 cm.

Soil Organic Carbon Stocks

With the available historic soil data and simulation runs, the SOC stocks for the Upper Tana basin are estimated to be 114–118 Tg C (Tg = 10^{12} g C; 0–30 cm), 167–171 Tg C (0–50 cm) and 240–244 Tg C (0–100 cm; expressed as 95 per cent confidence limits for the median), whereas the range is 97–143 (0–30 cm), 144–201 (0–50 cm) and 210–274 (0–100 cm) Tg C. This corresponds to some 6 per cent of the total SOC stock to a depth of 1 m reported for Kenya (Batjes 2004b), whereas the Upper Tana accounts for some 3 per cent of the Country's land area; this is a direct reflection of the relatively fertile nature of the soils in the basin (see Table IV).

Projected SOC Gains

Table VI shows projected increases in SOC content over a 20-year period of improved management for land currently under cropland respectively plantation crops, for sections of the GWC target area identified as being at least

Table IV. Dominant major soil groups in the Upper Tana River basin per agro-climatic zone

ACZ	Dominant major soil groups[a]
I—Humid	AN > NT >> RG >> AC > PH > CM
II—Sub-humid	NT >>> AN > CM >> LV > AC > PL > AL > PH
III—Semi-humid	NT >>> CM > FR > AC > VR > RG > LV > PL > LP > AR
IV—Semi-humid to semi-arid	LV > FR > NT > CM > VR > AC > PL > RG > LP > AR
V—Semi-arid	AC > CM > LV > VR > RG > AR > LP > NT > FR

[a]Major soil groups are listed for a given ACZ if their total extent exceeds 0·1% of the total area. The cumulated area of major soil groups listed for a given ACZ account for >90% of the total extent of said agro-climatic zone. Abbreviations for major soil groups: AN = Andosols; AC = Acrisols; AL = Alisols; AR = Arenosols; CM = Cambisols; FR = Ferralsols; LP = Leptosols; LV = Luvisols; PH = Phaeozems; PL = Planosols; NT = Nitosols; RG = Regosols; VR = Vertisols; see FAO (1988) for details.

Table V. Area-weighted content of soil organic carbon per agro-climatic zone (ACZ) of the Upper Tana river basin

ACZ	Organic carbon ($kg\,C\,m^{-2}$)[a]		
	0–30 cm	0–50 cm	0–100 cm
I—Humid	13·3–13·9	19·3–19·9	26·7–27·4
II—Sub-humid	6·9–7·1	10·3–10·5	15·7–16·1
III—Semi-humid	5·1–5·3	7·6–7·8	11·5–11·8
IV—Semi-humid to semi-arid	3·6–3·8	5·3–5·5	7·7–7·9
V—Semi-arid	2·6–2·7	3·9–4·1	5·7–5·9
All	6·6–6·9	9·7–10·0	14·0–14·2

[a]Results are 95% confidence intervals for the median for the simulated synthetic profiles; see text for a discussion of the associated uncertainties.

marginally suited (*S-index* > 0·4) for the LUT under consideration. Potential SOC sequestration refers to application of the recommended SWC practices to 100 per cent of the target area. In practice, however, because of socio-economic and policy constraints, or lack of farmer participation, it is likely that only a portion of the corresponding land area will benefit from improved soil and water management. Conservatively, this portion has been set at 60 per cent here forming the *reference* or medium scenario. In addition to this, low (40 per cent) and high (80 per cent) scenarios were introduced to present a range of opportunities for the projected SOC gains.

The medium scenario gives a possible increase of 1·31–2·53 Tg C, with a lower limit of 0·87 Tg C and upper limit of 3·38 Tg C for the other scenarios, over a 20-year period of sustained *green water* management (Table VI). By comparison, with the best available historic soil data, SOC stocks (for the GWC target area) to 30-cm depth are estimated at some 36·5 Tg C; this would correspond to a projected increase of some 5 per cent in SOC stocks over a 20-year period (for the medium scenario). However, a time horizon of 20 years may be too long for small-scale farmers in the context of proposed carbon sequestration projects although not if justified by production gains and supported by GWC incentives or other mechanisms for rewarding farmers for the environmental services they provide.

Payment for Environmental Services: Carbon Offset Markets

Background information describing principles and mechanisms of the carbon offset market may be found in Kollmuss *et al.* (2008); consistent monitoring, reporting and verification (MRV) standards are always needed to ensure that C-offset projects perform as anticipated during the project design (e.g. Ravindranath and Ostwald, 2008; GOFC-GOLD, 2009; de Brogniez *et al.*, 2011). Carbon market programmes include regulatory/compliance as well as voluntary offset markets; in a competitive market, offset prices are a function of supply and demand. Overall, the interest for a project will depend on the buyer's objectives, and these will be different for a compliance buyer or voluntary buyer. According to Kolmuss *et al.* (2008) and EcobusinessLinks (2010), carbon offset prices are in the order of US$5 to 30 per tonne CO_2-equivalent, depending on the adopted standards and criteria for verification.

For this *ex ante* study, a price of US$10 per Mg or tonne CO_2-equivalent has been assumed to provide a conservative estimate of possible carbon credits for the medium scenario. With the use of the conversion factor of 1 g C = 3·66 g CO_2, the medium scenario would lead to a sequestration, or reduced emission, of some 4·8 to 9·3 Tg CO_2 or 4·8–9·3 × 10^6 tonnes CO_2. At US$10 per tonne CO_2-equivalent, this would correspond to some US$48–93 × 10^6 over a 20-year period of sustained management. The section of the GWC target area with *S-index* > 0·4 covers some 33 per cent of the Upper Tana River basin (some 580 000 ha in total). For the medium scenario, implementation of green water management practices is assumed to be feasible for some 60 per cent of that area, corresponding to some 348 000 ha. Over

Table VI. Simulated increase in organic carbon content over 20 years of sustained improved management within the Upper Tana GWC target area (Tg C)

Land utilization type	Scenario[a]			
	Potential	Low	Medium	High
Croplands	1·29–2·44[b]	0·52–0·98	0·78–01·46	1·03–1·95
Plantation crops	0·88–1·79	0·35–0·72	0·53–1·07	0·70–1·43
Total	2·17–4·23	0·87–1·70	1·31–2·53	1·73–3·38

[a]The medium scenario or *reference* assumes that 'best management practices' can be introduced on 60% of current croplands and cropland plantations (resp. 40% for the low and 80% for the high scenario) in the corresponding area; the potential scenario assumes that improved GWC and SOC maintenance practices can be implemented on 100% of the corresponding land, which is considered unrealistic in view of possible socio-economic and policy constraints.
[b]The first figure is the estimate for the lower rate assumed for feasible SOC increase for the considered ACZ and land use and the second for the upper value (see Table II).

20 years, this would correspond to some US$137–267 ha^{-1} or approximately US$7–13 ha^{-1} annually associated with carbon credits only; these would serve to supplement payments for GWC services *sec*. Higher market prices for CO_2-equivalents than that assumed here would probably allow for a more rapid implementation of the proposed agricultural mitigation measures

Sources of Uncertainty

Like all model-based approaches, the current projections will entail uncertainties (see Raupach *et al*., 2005; Larocque *et al*., 2008; Grimm and Behrens, 2010; Nol *et al*., 2010). These may relate to the measured and simulated soil data, land use data, scale level, assumptions for feasible SOC sequestration rates for defined agro-ecological zones, criteria used in the quantified land evaluation procedure, assumptions for scenarios considered in the empirical SOC model, and the type and structure of the model. Results of Manna *et al*. (2009) and Ogle *et al*. (2010) contradict the simplified view on the overall better performance of more complex and data demanding mechanistic methods. Overall, sustainable land management projects should be encouraged to use the most accurate forecasting methods possible, ranging from empirical to process-based models, given the resources available and project objectives (Milne *et al*., 2010).

Further, the anticipated increase in use of fertilizers associated with the recommended land management practices may result in greater emissions of N_2O, itself a potent greenhouse gas, which would lead to lower net C gains. Other adverse side effects may include CO_2 generated from the energy requirements of manufacturing and distributing fertilizers, or transfer of produce to urban and international markets.

CONCLUSIONS

The present approach for estimating possible SOC gains for defined LUTs, subject to adoption of broadly defined recommended *green water* management practices, is considered appropriate for rapid, exploratory, *ex ante* assessments in the framework of the GWC programme. It can be readily adapted to accommodate a wider range of LUTs, as may be encountered in future GWC project areas, subject to the availability of published data on SOC sequestration rates for these systems and supporting information on their land use requirements.

Actual areas where GWC practices are to be implemented in the Upper Tana River catchment still need to be identified by the various stakeholders (S. Kauffman, pers. comm.). Once this has been performed, more elaborate modelling studies of C stock changes, both in vegetation and soil, that consider full carbon and GHG accounting should be considered. However, there remain significant limitations in the biophysical and activity data necessary to underpin such more detailed inventories; field studies will be needed to fine-tune the assumptions, evaluate the various models and reduce the associated uncertainties.

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