# Estimated Changes in Soil Organic Carbon in the Upper Tana, Kenya

World Soil Information

Green Water Credits Report 13

N.H. Batjes

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## Estimating Changes in Soil Organic Carbon in the Upper Tana, Kenya

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# Foreword

ISRIC – World Soil Information has the mandate to create and increase the awareness and understanding of the role of soils in major global issues. As an international institution, ISRIC informs a wide audience about the multiple roles of soils in our daily lives; this requires scientific analysis of sound soil information.

The source of all fresh water is rainfall received and delivered by the soil. Soil properties and soil management, in combination with vegetation type, determine how rain will be divided into surface runoff, infiltration, storage in the soil and deep percolation to the groundwater. Improper soil management can result in high losses of rainwater by surface runoff or evaporation and may in turn lead to water scarcity, land degradation, and food insecurity. Nonetheless, markets pay farmers for their crops and livestock but not for their water management. The latter would entail the development of a reward for providing a good and a service. The Green Water Credits (GWC) programme, coordinated by ISRIC – World Soil information and supported by the International Fund for Agricultural Development (IFAD) and the Swiss Agency for Development and Cooperation (SDC), addresses this opportunity by bridging the incentive gap.

Much work has been carried out in the Upper Tana catchment, Kenya, where target areas for GWC intervention have been assessed using a range of biophysical databases, analysed using crop growth and hydrological modelling. While the GWC programme has focussed on the beneficial effects of improved *green water* management practices on reducing runoff, soil erosion and the siltation of reservoirs, as well as reducing non-productive evaporation, so far little attention has been paid to the possible beneficial effects of such practices on restoring or improving soil organic matter levels. Knowledge of how different land management practices affect agro-ecosystems, carbon stocks and greenhouse gas emissions, land degradation and sustainability remains far from complete. This reveals the need for a better understanding of the role of soils and the vegetation it supports, as natural regulators of greenhouse gas emissions and climate change. Depending on the objectives and overall data availability, such studies may be carried out using simple empirical models - or conceptually more elaborate and data demanding process-based models.

This study presents first estimates of possible soil organic carbon (SOC) gains upon improved *green water* management of current land use within areas identified as most suitable for GWC interventions in the Upper Tana basin; assessing the possible soil water and soil organic carbon gains may create new "win-win" scenarios for the various stakeholders.

Dr ir Prem Bindraban
Director, ISRIC – World Soil Information

# Key Points

- Large areas in the Upper Tana 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 basin earmarked as being the most promising for implementing Green Water Credits (GWC), an incentive mechanism to help farmers invest in specified land and soil management activities or "*green water* management" practices that affect all fresh water resources at source.

- These lands, covering some 580,000 ha, have been defined as having a biophysical suitability index (BSI) > 0.5, which corresponds to a high (modelled) cost-benefit ratio for the proposed *green water* management practices. Use of the recommended management practices can also help to restore SOM levels towards their natural level.

- Opportunities to increase soil organic carbon (SOC) stocks, for two broadly defined land utilisation types (LUT); namely croplands and plantations crops, with moderate levels of input, have been calculated using a simple empirical model, using various scenarios for the proportion of suitable land that may be treated with these practices (low scenario= 40%, medium or reference scenario= 60%, high scenario= 80%).

- The procedure is based on GIS overlays of BSI, land use, soil type, and agroclimatic zone maps for the GWC target area, combined with automated procedures for rating soil quality in the LUTs under consideration; feasible SOC change rates by LUT and agroclimatic zone are derived from the literature; possible SOC gains are calculated using an empirical model for the physically suited areas.

- For the reference scenario, corresponding with implementation on some 348,000 ha in the Upper Tana catchment, the eco-technologically possible SOC gains are estimated at 4.8 to 9.3 x $10^6$ tonnes (Tg= $10^{12}$ g) $CO_2$ 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 some US$ 48-93 million over a 20 year period of sustained *green water* management.

- This would correspond with a projected (potential) payment of some US$ 7-13 $ha^{-1}$ to farmers annually; this amount 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 realise from the impact on production of these practices themselves.

- 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.

# Contents

# Acronyms and Abbreviations

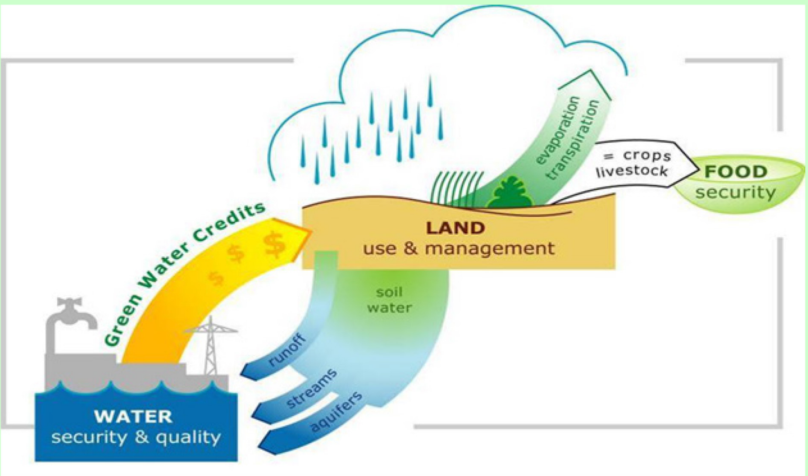
| | |
|---|---|
| ACZ | Agroclimatic zone |
| BSI | Biophysical Suitability Index |
| FAO | Food and Agriculture Organisation of the United Nations |
| GEFSOC | Global Environment Facility Soil Organic Carbon Stocks and Changes |
| GHG | Greenhouse Gas |
| GIS | Geographic Information System |
| GOFC-GOLD | Global Observation of Forest and Land Cover Dynamics |
| GWC | Green Water Credits |
| HRU | Hydrological Response Unit |
| IFAD | International Fund for Agricultural Development |
| LANDSAT | Land satelite imagery program |
| LUT | Land utilisation type |
| MVC | Monitoring, verification and certification |
| SDC | Swiss Agency for Development Cooperation |
| SOC | Soil Organic Carbon |
| SOM | Soil Organic Matter |
| SOTER | Soil and Terrain database |
| SOTER-UT | Soil and Terrain database – Upper Tana |
| SVM | Support Vector Machine |
| SWAT | Soil and Water Conservation Tool |
| SWC | Soil and water conservation |
| WOCAT | World Overview of Conservation Approaches and Technologies |

## Green Water Credits: the concepts

## *Green water, Blue water*, and the GWC mechanism

*Green water* is moisture held in the soil. *Green water* flow refers to its return as vapour to the atmosphere through transpiration by plants or from the soil surface through evaporation. *Green water* normally represents the largest component of precipitation, and can only be used *in situ*. It is managed by farmers, foresters, and pasture or rangeland users.

*Blue water* includes surface runoff, groundwater, stream flow and ponded water that is used elsewhere - for domestic and stock supplies, irrigation, industrial and urban consumption. It also supports aquatic and wetland ecosystems. *Blue water* flow and resources, in quantity and quality, are closely determined by the management practices of upstream land users.




*Green water* management comprises effective soil and water conservation practices put in place by land users. These practices address sustainable water resource utilisation in a catchment, or a river basin. *Green water* management increases productive transpiration, reduces soil surface evaporation, controls runoff, encourages groundwater recharge and decreases flooding. It links water that falls on rainfed land, and is used there, to the water resources of rivers, lakes and groundwater: *green water* management aims to optimise the partitioning between *green* and *blue water* to generate benefits both for upstream land users and downstream consumers.

*Green Water Credits* (GWC) is a financial mechanism that supports upstream farmers to invest in improved *green water* management practices. To achieve this, a GWC fund needs to be created by downstream private and public water-use beneficiaries. Initially, public funds may be required to bridge the gap between investments upstream and the realisation of the benefits downstream.

*The concept of green water and blue water was originally proposed by Malin Falkenmark as a tool to help in the understanding of different water flows and resources - and the partitioning between the two* (see Falkenmark M 1995 Land-water linkages. FAO Land and Water Bulletin 15-16, FAO, Rome).

# 1 Introduction

Many areas in central and western Kenya are densely populated (500-1200 inhabitants per $km^2$). A large fraction of the population depends on subsistence agriculture: maize, rice, beans, bananas, and cassava; 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 - with particularly low availability of phosphorus and nitrogen, coupled with decreasing levels of soil organic matter in croplands (Gichuru *et al.* 2003; Kapkiyai *et al.* 1999) - together with a high population growth rate - 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 – termed "*green water* management practices" under GWC - 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 both SWC and land management has been reviewed by Pretty *et al.* (1995). SWC programmes, however, were not always successful due to experts' negligence of the role of farmers in problem identification and conservation planning (Okoba and Sterk 2010).

The Green Water Credits (GWC) project is developing a financial mechanism that supports upstream farmers to invest in improved *green water* management activities (see "Green Water Credits: the concepts" on page 8 and Figure 1). Currently, such activities are unrecognised and un-rewarded; direct reward will enable better management of the resource (Dent and Kauffman 2007). GWC project activities in Kenya have focussed on the Upper Tana catchment (Droogers *et al.* 2006). GWC includes participatory approaches to mobilise local communities for resource conservation, linking water users and suppliers as well as representatives of key Ministries and Water Authorities (Gicheru *et al.* 2006).

Hunink *et al.* (2011) carried out a biophysical assessment to determine the impact of selected *green water* management practices on the *green* and *blue water* and sediment fluxes in the Upper Tana catchment. They used a distributed modelling approach, based on the Soil and Water Assessment Tool (SWAT) and 10-year average climatic data, for defined hydrological response units (HRUs). HRUs were defined based on topography, soil distribution and characteristics, and land use. The analyses give an insight into the spatial distribution of the most appropriate areas for GWC interventions, for defined *green water* management practices (Hunink and Droogers 2010). 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. Besides improving overall soil water conditions, the adoption of improved soil and water conservation practices (in other words improved *green water* management practices) may also lead to increased soil organic matter reserves (Batjes and Sombroek 1997; Lal 2004; Watson *et al.* 2000) but, so far, this aspect has not been considered explicitly in the GWC project. Differences between economic and ecological (biophysical) criteria for identifying, measuring, and evaluating ecosystem services have been discussed by Sagoff (2011).

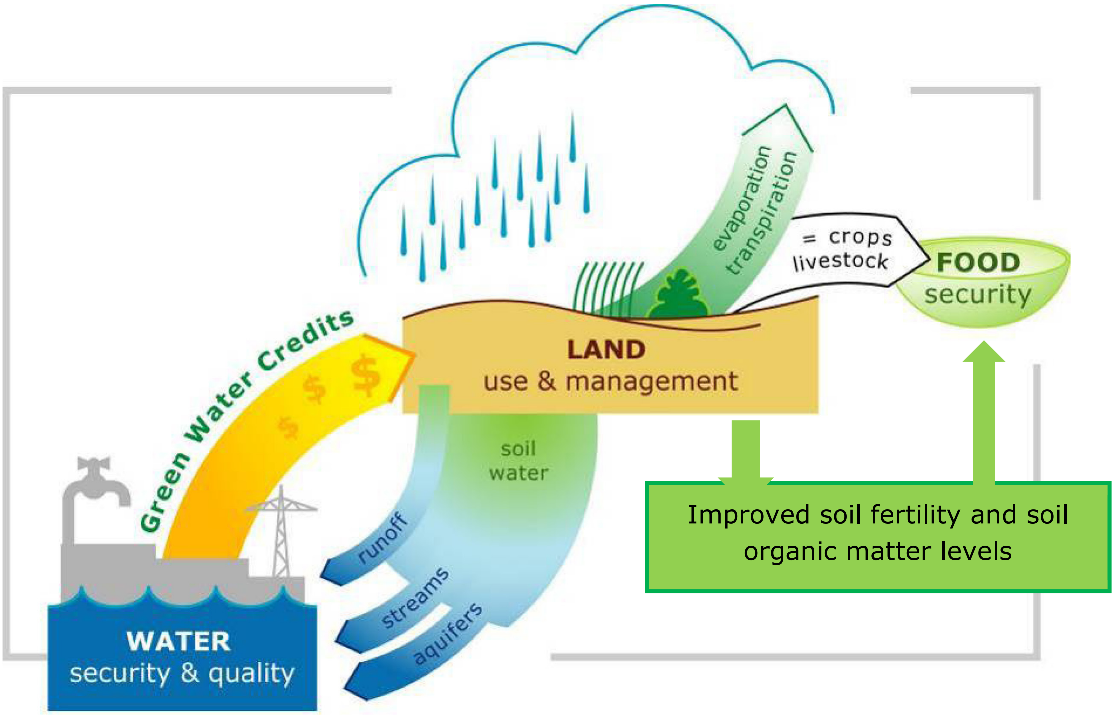



*Figure 1*
*Green Water Credits bridging the gap in the water cycle (After: Hunink et al. 2011)*

This study uses the Upper Tana river catchment as a test case for methodology development. First, it presents estimates of regional soil carbon stocks derived from a recent soil and terrain database for the region. Subsequently, possible gains in SOC stocks upon improved land management, within HRUs identified as being biophysically most suited for GWC implementation 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). Possible sources of uncertainty are discussed.

# 2 Data and methods

## 2.1 Biophysical data

The Upper Tana catchment has a wide range of natural regions: from hot, semi-arid lowlands to cool, humid highlands (Sombroek *et al.* 1982; Jaetzold and Schmidt 1983) with soils of widely differing potential for crop production (Table 1). Three main types of digital (GIS) data were used in this study: agroclimatic, land cover and soil and terrain data.

### 2.1.1 Agroclimatic zones

The major limitations to maximum production per agroclimatic zone (ACZ), potential annual production, and likely risk of crop failure for an adapted maize crop are listed in Table 1. Some 55% of the area has an R/Et ratio greater than 0.65, pointing to a medium to very high potential for crop growth. The effect of decreasing air temperature, between the semi-arid lowland and the very humid highlands, on potential production is small in comparison to that associated with possible water shortages.

*Table 1*
*Main characteristics of Upper Tana's agroclimatic zones (after Sombroek et al. 1982)*

| Agroclimatic Zone (ACZ) | Relative extent (%) [d] | R/Et [a] (%) | Potential production ($10^3$ kg dry matter ha$^{-1}$ yr$^{-1}$) | Risk of crop failure for an adapted maize crop (%) | Potential for crop growth[b] | Major limitations to maximum production[c] |
|---|---|---|---|---|---|---|
| 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] Ratio of mean annual rainfall (r) over evapotranspiration (Et).
[b] Assuming soil conditions are not limiting.
[c] Listed in approximate order of importance: DR= drainage; HU= husbandry; RA= rainfall; SF= soil fertility.
[d] Expressed as proportion of Upper Tana catchment (~ 17,300 km$^2$); water bodies cover rest of area, some 1.1%.

### 2.1.2 Land cover

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 data used for this study are the result of fieldwork and satellite classification in 2009. The resulting land cover/use map is based on support vector machine (SVM) classification, using LANDSAT images for 2000 (Wilschut 2010).

### 2.1.3 Soils

An updated version of the 1:250,000 soil and terrain database (SOTER-UT) for the Upper Tana river catchment provided the primary soil attribute data (Dijkshoorn *et al.* 2011). Each SOTER unit has a unique identifier linking it to the attribute data for its constituent terrain, terrain component, and soil component(s). Each soil component was characterised by a single profile. These were selected by national experts as being regionally representative of the corresponding soil unit classified according to FAO (1988). Most profiles have been collated from reconnaissance and semi-detailed surveys, carried out between 1970 and 2003. Several attributes, notably bulk density and water retention, have not been measured routinely; therefore, a standard procedure was used to fill gaps in the measured data (Batjes *et al.* 2007). The resulting, secondary data set provided the soil geographic and attribute data for this study (Batjes 2011).

## 2.2 Computing soil carbon stocks

Differences in mapping approaches, selection of representative profiles and calculation methods affect estimates of regional carbon stocks (Batjes 2000; Bernoux *et al.* 2002; Liebens and VanMolle 2003). Soil organic carbon (SOC) stocks for the Upper Tana basin were calculated using the procedure developed for the GEFSOC project (Batjes 2004b; Batjes *et al.* 2007). 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, for a given representative profile (soil component), for each SOTER unit. Further, the method emulates the variability in soil conditions within a soil component, using n (300) runs; details are given in Batjes *et al.* (2007). The information resulting from the simulations was linked to the soil geographic information to arrive at n realisations of regional carbon stocks. The resulting distribution showed the fluctuation arising from the model and emulates natural soil variation. As indicated by Webster and Oliver (2001), quantiles of the observed values can provide a reasonable estimate for the range in carbon content, to the specified depth; 95% confidence intervals for median carbon stocks were calculated according to Snedecor and Cochran (1980).

## 2.3 Assessing changes in soil carbon stocks

The semi-quantitative approach for assessing possible SOC gains, within target areas identified as being most suited for adoption of *green water* management practices (see Hunink and Droogers 2010; Hunink *et al.* 2011), considers differences in land use type, agroclimatic conditions and soil types. The procedure (Figure 2) elaborates on earlier work for Africa (Batjes 2004a) and Kenya (Batjes 2004b); details are provided in the following sections.

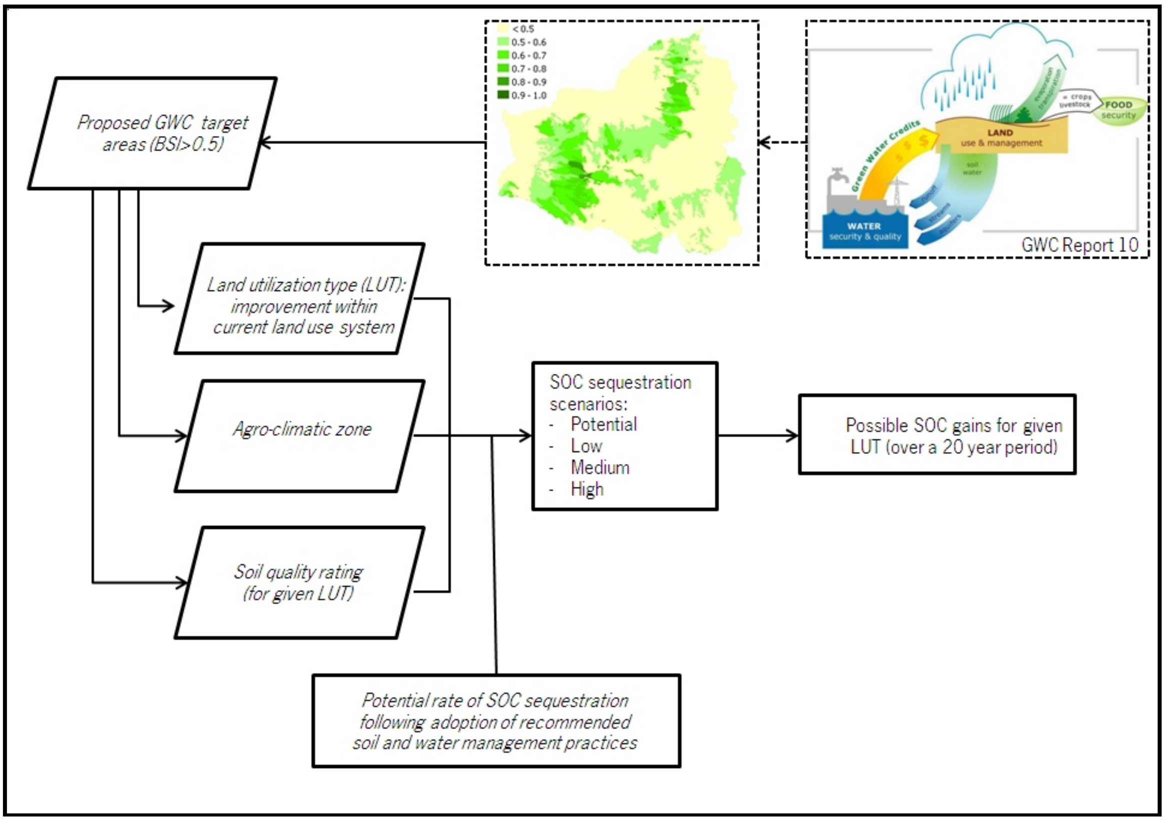



*Figure 2*

*Procedure estimating possible SOC gains upon improved management or restoration within current land use systems, for GWC target areas*

### 2.3.1 Carbon sequestration rates

For Africa, the average annual change of topsoil organic matter associated with soil nutrient depletion has been estimated at -0.22 Mg C $ha^{-1}$ (1 Mg= $10^6$ g= 1 tonne) (Sanchez *et al.* 1997). The possible increase in organic carbon stocks in response to adoption of best management practices will depend on land 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. Henry *et al.* 2009; Izac 1997; Koning *et al.* 2001; Smith *et al.* 2007b). 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, livestock diet formulation and manure management (Smith *et al.* 2007a).

Best management practices to increase soil carbon reserves within defined land use systems, such as crop lands, must be site specific (e.g. Batjes 1999; Bruce *et al.* 1999; Paustian *et al.* 1998; 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) stabilisation of slopes and terraces to reduce risk of erosion by water. Options that both reduce greenhouse gas (GHG) emissions and increase productivity are clearly 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 2 lists estimates of carbon sequestration rates by agroclimatic zone for "crop land" and "plantation crops". Rates in Table 2 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% (Sampson and Scholes 2000) or even more (Smith *et al.* 2007a). SOC sequestration rates in Table 2 should be revised as data from long-term field observations become available for the Upper Tana region.

*Table 2*

*Indicative rates of soil carbon sequestration upon introduction of improved management within agricultural lands in the Upper Tana basin by agroclimatic zone*

| Land use | Carbon sequestration rates by agroclimatic zone[a] (Mg C $ha^{-1}$ $yr^{-1}$) | | |
|---|---|---|---|
| | I – II | III – IV | V |
| Crop lands | 0.30–0.50[b] | 0.15–0.30 | 0.05–0.15 |
| Plantationl crops[c] | 0.25–0.50 | 0.10–0.25 | 0.05–0.10 |

[a] Agroclimatic zones are characterised in Table 1.

[b] Indicative rates for annual mitigation potential, based on data from Bruce *et al.* (1999), Lal *et al.* (2002), Sampson and Scholes (2000) 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 1.

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 linear rate of change over the period was assumed here, which is a simplification. A time horizon of 20 years was considered appropriate in the context of this exploratory study; this is also the default for empirical, IPCC Tier-1level calculations (e.g. Bernoux *et al.* 2011; IPCC 2006; Smith *et al.* 2007a).

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.

### 2.3.2 Physical land evaluation

A preceding modelling study (see Hunink and Droogers 2010; Hunink *et al.* 2011) has assessed the projected biophysical suitability index (BSI) of a given HRU, or map unit having similar land use, soil and slope, for GWC intervention. The projected biophysical suitability index (BSI) of a given HRU, or map unit having similar land use, soil and slope, for GWC intervention has been rated from 0 to 1, where 1 represents the greatest potential. The BSI index, however, does not provide any indication about the proportion (relative extent) of the HRU to which this rating applies nor information about other possible soil limitation for a given land use (e.g. high acidity).

For the purpose of this exploratory assessment, HRUs 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 best suited, from a biophysical point of view, for implementing *green water* management practices. Land use/cover types reported for the HRUs with BSI > 0.5 are listed in Table 3. For the purpose of this assessment, they have been clustered into two broad land utilisation types (FAO 1976): crop lands (comprising land cover classes AGRL and CORN) and plantation crops (TEA and COFF) with moderate levels of inputs assumed.

*Table 3*

*Proportion of agroclimatic zones and land use/cover classes with BSI > 0.5 in the Upper Tana catchment*

| 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] Agroclimatic zones, for details see Table 1.
[b] Combined code for ACZ and land use/cover (LU) classes (Wilschut 2010): AGRL stands for croplands (undefined), COFF for coffee plantations, CORN for maize cultivation, and TEA for tea plantations.
[c] Proportions are derived from GIS overlays.

The capacity for increasing crop production and humus levels upon improved management within a given land use system and agroclimatic zone will vary with the quality of the soil, type of crops grown, and overall input levels. Soil quality, for defined land utilisation types (LUT), was rated using soil layer data (respectively, soil pH and cation exchange capacity as proxies for soil fertility; and, 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. The necessary data were derived from the *secondary* SOTER-UT database (Batjes 2011).

Tea and coffee plantations predominate in the more humid uplands, while rainfed croplands are the dominant land use in the semi-humid and semi-arid parts of the Upper Tana basin (with BSI > 0.5). 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 or degrading (Figure 3). Contrastingly, the soil's surface is generally well protected under established tea plantations with prunings, and water erosion is rare; as such, there will be less scope for increasing SOC stocks under established and well-managed tea plantations (Figure 4). Alternatively, when soils in the "tea zone" are left uncovered, erosion by water can be high, especially on steep slopes (Wilschut 2010).

***Figure 3***
*Soil degradation on poorly maintained terraces in a coffee plantation, Upper Tana, leads to loss of soil organic matter (Photo credit: L. Wilschut 2009)*

***Figure 4***
*Established tea plantations provide good ground cover (Photo credit: L. Wilschut 2009)*

In view of the 1:250,000 scale of the soil database, the assessment is made for two broadly defined land use type (LUT): namely rainfed crops and plantation crops with moderate levels of inputs and technology. It has been assumed that some NPK fertilizers are applied, crop residues are left on the ground, and appropriate soil and water conservation technologies are adopted. Crops grown include staple foods (maize, beans, bananas, and cassava) and overall biophysical requirements are assumed to correspond with those of a maize crop. For plantation crops the biophysical requirements are assumed to correspond with those of coffee and tea.

For each soil component, 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); inherently, such class limits are fuzzy, not crisp (Burrough 1989). The final suitability rating, ranging from 1 for no limitations to 0 for severe limitations, for a given soil component and LUT was solved using an approach that integrates the various subratings into one single, weighted land suitability index (after Batjes *et al.* 1987). The procedure (Eq. 1) 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).

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

where *S-index* is the aggregated suitability rating, *Sr* is the subrating for relief (slope), *Sp* is the subrating for "whole profile" properties (i.e., drainage class, depth of soil, and soil moisture holding capacity; Eq. 2), *Sc* is the depth-weighted subrating for soil horizon properties (i.e., particle size class, proportion of mineral fraction > 2 mm, cation exchange capacity, and $pH_{water}$) down to 60 cm depth (Eq. 3).

Subratings for *Sp* and *Sc* are determined as:

$$Sp = ((Rating_{most\_limiting\_factor}) * (\Sigma ratings_{two\_remaining\_factors})) / 2 \qquad \text{[Eq. 2]}$$

and

$$Sc = Avg(Sc_i), \text{ with} \qquad \text{[Eq. 3]}$$

$$Sc_i = ((Rating_{most\_limiting\_factor}) * (\Sigma rating_{three\_remaining\_factors})) / 3 \text{ for layer } i$$

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) ranges from one (highly suitable) to zero (not suitable). This type of weighted-approach is commensurate with the procedure that has been used to classify the biophysical suitability of the potential target areas for GWC interventions in the Upper Tana catchment (see Hunink and Droogers 2010).

Possible SOC sequestration has been assessed, for the various scenarios described earlier, for soil types identified as being at least marginally suitable for the LUT under consideration; this corresponds with areas having an *S-index* > 0.4 (as well as BSI > 0.5), or some 33% of the Upper Tana catchment.

### 2.3.3 Potential versus possible SOC gains

Potential SOC sequestration refers to application of the recommended *green water* management practices on 100% of the target area. In practice, however, due to 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% here forming the medium or *reference* scenario. In addition to this, a low (40%) and high (80%) scenario were introduced to present a range of opportunities for the possible SOC gains.

Field studies will be needed to fine-tune these assumptions and to support more elaborate modelling studies. Overall, sustainable land management projects should be encouraged to use the most accurate methods possible, given the resources available and project objectives (Milne *et al.* 2010a; Milne *et al.* 2010b).

# 3 Results and discussion

## 3.1 Soil organic carbon content

The dominant major FAO (1988) soil groups in the whole basin are Nitosols (~30%), followed by Andosols (13%), Acrisols (12%), Cambisols (11%), Luvisols (8%), Regosols (7%), Vertisols (6%), and Ferralsols (5%), with smaller extents (<2% each) of Leptosols, Planosols, Arenosols, Phaeozems, Alisols, Fluvisols, Gleysols and Lixisols. The distribution of these major soil groups varies widely within and between ACZs (Table 4). Relatively fertile Andosols and Nitosols are predominant in the humid zone, while less fertile Acrisols and Cambisols predominate in the semi-arid section of the basin; many of these soils are degraded to a certain extent (Wilschut 2010).

*Table 4*
*Dominant major soil groups in the Upper Tana basin per agroclimatic 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.

The area-weighted SOC content for the Upper Tana basin, expressed as 95% 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 5). SOC content 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 as well as humic members of Acrisols and Cambisols in the Upper Tana.

*Table 5*
*Area-weighted content of soil organic carbon per agroclimatic zone (ACZ) of the Upper Tana 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 | 5.3–5.4 | 7.7–7.9 |
| V – Semi-arid | 2.6–2.7 | 3.9–4.0 | 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, see text.

On average, some 44–50% of the SOC stock is stored in the upper 30 cm, the layer most vulnerable to changes in land use or management, and about 65–70% in the top 50 cm.

## 3.2 Soil organic carbon stocks

Based on the available historic soil data (Batjes 2011; Dijkshoorn *et al.* 2011), total SOC stocks for the Upper Tana are estimated to be 114.9–117.3 Tg C (Tg= $10^{12}$ g C; 0-30 cm), 167.8–170.8 Tg C (0-50 cm), and 240.8–243.8 Tg C (0-100cm; expressed as 95% confidence limits for the median). This corresponds with some 6% of the total SOC stock to a depth of 1 m reported for Kenya (Batjes 2004b), while the Upper Tana accounts for some 3% of the country's land area; this is a direct reflection of the relatively fertile nature of the soils in the basin (see Table 4).

## 3.3 Projected SOC gains

Table 6 shows modelled increases in SOC content over a 20-year period of improved management for land currently under cropland respectively plantation crops, for the selected target areas (i.e., BSI > 0.5 and *S-index* > 0.4). Various scenarios are considered; details and assumptions are given in Section 2.3.3

*Table 6*

*Simulated increase in organic carbon content over 20 years of sustained improved green water management within GWC target areas of the Upper Tana (Tg C)*

| Land utilisation type | Scenario [a] | | | |
|---|---|---|---|---|
| | Potential | Low | Medium | High |
| Crop lands | 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] Analyses are for areas with BSI >0.5 and S-index >0.4; see Section 2.3 for details. 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); the potential scenario assumes that improved *green water* management and SOC maintenance practices can be implemented on 100% of the land mapped as being most suited for GWC interventions (BSI >0.5 and S-index >0 .4), 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 ACZ in consideration and the land use, and the second for the upper value (see Table 2).

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, over a 20-year period of sustained improved management (Table 6). By comparison, based on the available historic soil data, SOC stocks for the selected target areas (with BSI > 0.5 and S-index >0.4) to 30 cm depth are estimated at 36.2-37.1 Tg C; this would correspond to a projected increase of some 5% 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 - though not if justified by production gains and supported by GWC incentives or other mechanisms for rewarding farmers for the environmental services they provide.

## 3.4 Carbon offset markets

Background information describing principles and mechanisms of the carbon offset market may be found elsewhere (e.g. Kollmuss *et al.* 2008); consistent monitoring, verification and certification (MVC) standards are always needed to ensure that C-offset projects perform as projected during the project design (e.g. GOFC-GOLD 2009; Ravindranath and Ostwald 2008). Carbon market programs include regulatory/compliance as well as voluntary offset markets; in a competitive market, offset prices are a function of supply and demand. Overall, the attractiveness of 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)[1], carbon offset prices are in the order of US$ 5 to 30 per tonne $CO_2$, depending on the adopted standards and criteria for verification.

[1] EcobusinessLinks 2010. *How much does carbon offsetting cost?* http://www.ecobusinesslinks.com/carbon offset wind credits carbon reduction.htm

For this *ex-ante* study, a price of US$ 10 per tonne $CO_2$-equivalent has been assumed to provide a conservative estimate of possible carbon credits for the medium scenario. Using the conversion factor of 1 Tg C = 3.66 Tg $CO_2$, 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 x $10^6$ tonnes $CO_2$. At US$ 10 per tonne $CO_2$, this would correspond to some US$ 48-93 x $10^6$ over a 20-year period of sustained management. The area under consideration (BSI > 0.5 and S-index>0.4) covers some 33% of the Upper Tana basin (about 580,000 ha). For the medium scenario, implementation of best soil and water management practices is assumed to be feasible for some 60% of this area, corresponding to some 348,000 ha. Over 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.

# 4 Conclusions

The present approach for estimating possible soil organic carbon gains for defined land utilisation types, subject to adoption of broadly defined recommended *green water* management practices, for areas identified earlier as being most suited for Green Water Credits interventions, is considered appropriate for rapid, exploratory, *ex-ante* assessments. It can be readily adapted to accommodate a wider range of land utilisation types, subject to the availability of published data on SOC sequestration rates for these systems and supporting information on their land use requirements.

Various uncertainties are associated with the current projections, as discussed earlier. Further, for example, 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. Other adverse side effects will include $CO_2$ generated from the energy requirements of manufacturing and distributing fertilizers, or transfer of produce to urban and international markets.

Actual areas for implementing *green water* management practices in the Upper Tana still need to be identified. Once this has been done, more elaborate studies of carbon stock changes, both in vegetation and soil, that consider full carbon and greenhouse gas accounting should be considered. However, there remain significant limitations in the biophysical data necessary to underpin more detailed inventories. 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.* 2010b).

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# Annex 1 System for rating land characteristics by land use type

| Land use type | Soil characteristics | Degree of limitation[a] | | | | | | | Units |
|---|---|---|---|---|---|---|---|---|---|
| | | n | s3 | s2 | s1 | s2 | s3 | n | |
| *Crop land* | Soil pH | <4.5 | 4.5-5.0 | 5.0-5.5 | 5.5-7.3 | 7.3-8.0 | 8.0-8.5 | >8.5 | pH |
| | $CEC_{soil}$ | <4 | 4-16 | 16-24 | >=24 | - | - | - | $cmol_c$/kg |
| | Soil texture | | V[b], O | F | M, C or Z | - | - | - | class |
| | Coarse fragments | >55 | 35-55 | 15-35 | ≤15 | - | - | - | vol. % |
| | Profile AWC[c] | <50 | 50-75 | 75-100 | ≥100 | - | - | - | mm/m |
| | Rootable depth | <25 | 25-50 | 50-75 | ≥ 75 | - | - | - | cm |
| | Soil drainage[e] | V | P, I | M | W, S, E | | | | class |
| | Slope | >30 | 16-30 | 8-16 | ≤8 | - | - | - | % |
| *Plantation crops* | Soil pH[f] | <4.0 | 4.0-4.5 | 4.5-5.5 | 5.5-6.5 | 6.5-7.3 | 7.3-8.0 | >8.0 | pH |
| | $CEC_{soil\ (}$ | <4 | 4-8 | 8-16 | >=16 | - | - | - | $cmol_c$/kg |
| | Soil texture[g] | - | O | V[d] | M, C, F, Z | - | - | - | class |
| | Coarse fragments | 60-100 | 40-60 | 20-40 | ≤20 | - | - | - | vol. % |
| | Profile AWC | <40 | 40-80 | 80-120 | ≥120 | - | - | - | mm/m |
| | Rootable depth | <50 | 50-75 | 75-100 | ≥ 100 | - | - | - | cm |
| | Soil drainage | V, P | I | M | W, S, E | | | | class |
| | Slope | >30 | 16-30 | 8-16 | ≤8 | - | - | - | % |

[a] Degree of limitation for given land use type: s1= none to slight; s2= moderate; s3= severe; n= very severe. Indicative class limits were taken from various sources (FAO 1983; Landon 1991; Sys *et al.* 1993). Ratings for the different limitation levels, or factor ratings, are: 1.0 for s1, 0.8 for s2, 0.6 for s3 and 0.2 for n thereby permitting a combined limitation-parametric rating of the combined limitations into overall suitability classes for the given land use type, for the assumed input levels (see text for details). The effect of climate is rated separately by land utilisation type, according to agroclimatic zone.

[b] If texture is very fine (V) and soil is a Nitosol or a Ferralsol then rated as s2.

[c] Available water capacity (AWC) is defined as the amount of water held in the soil between -33kPa and -1500 kPa (USDA-NRCS 2008[2]).

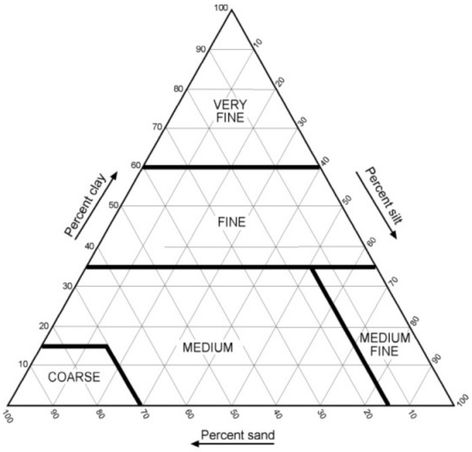
[d] If texture is very fine (V) and soil is Nitosol or Ferralsol then rated as s1; else if soil is Vertisol, the texture is rated as s3.

[e] Soil drainage classes (FAO 2006): V= very poorly drained; P= poorly drained; I= imperfectly drained; M= moderately well drained; W= well drained; S= somewhat excessively drained; E= excessively drained.

[g] Coffee and tea are very sensitive to elevated $CaCO_3$ levels, which may induce lime-induced chlorosis.

[f] Soil texture classes: C= Coarse; M= Medium; Z= Medium Fine; F= Fine; V fine; for details see Figure below.

[2] USDA-NRCS 2008. *NSSC Soil Survey Laboratory Soil Characterization Database*, United States Department of Agriculture, Natural Resources Conservation Service, Lincoln: http://ssldata.nrcs.usda.gov/




*Soil texture classes*

## GWC Reports Kenya

| | | |
|---|---|---|
| GWC K1 | *Basin identification* | Droogers P and others 2006 |
| GWC K2 | *Lessons learned from payments for environmental services* | Grieg Gran M and others 2006 |
| GWC K3 | *Green and blue water resources and assessment of improved soil and water management scenarios using an integrated modelling framework.* | Kauffman JH and others 2007 |
| GWC K4 | *Quantifying water usage and demand in the Tana River basin: an analysis using the Water and Evaluation and Planning Tool (WEAP)* | Hoff H and Noel S 2007 |
| GWC K5 | *Farmers' adoption of soil and water conservation: the potential role of payments for watershed services* | Porras IT and others 2007 |
| GWC K6 | *Political, institutional and financial framework for Green Water Credits in Kenya* | Meijerink GW and others 2007 |
| GWC K7 | *The spark has jumped the gap. Green Water Credits proof of concept* | Dent DDL and Kauffman JH 2007 |
| GWC K8 | *Baseline Review of the Upper Tana, Kenya* | Geertsma R, Wilschut LI and Kauffman JH 2009 |
| GWC K9 | *Land Use Map of the Upper Tana, Kenya: Based on Remote Sensing* | Wilschut LI 2010 |
| GWC K10 | *Impacts of Land Management Options in the Upper Tana, Kenya: Using the Soil and Water Assessment Tool - SWAT* | Hunink JE, Immerzeel WW, Droogers P, Kauffman JH and van Lynden GWJ 2011 |
| GWC K11 | *Soil and Terrain Database for the Upper Tana, Kenya* | Dijkshoorn JA, Macharia PN, Huting JRM, Maingi PM and Njoroge CRK 2010 |
| GWC K12 | *Inventory and Analysis of Existing Soil and Water Conservation Practices in the Upper Tana, Kenya* | Muriuki JP and Macharia PN 2011 |
| GWC K13 | *Estimating Changes in Soil Organic Carbon in the Upper Tana, Kenya* | Batjes NH 2011 |
| GWC K14 | *Costs and Benefits of Land Management Options in the Upper Tana, Kenya: Using the Water Evaluation And Planning system - WEAP* | Droogers P, Hunink JE, Kauffman JH and van Lynden GWJ 2011 |
| GWC K15 | *Cost-Benefit Analysis of Land Management Options in the Upper Tana, Kenya* | Onduru DD and Muchena FN 2011 |
| GWC K16 | *Institutes for Implementation of Green Water Credits in the Upper Tana, Kenya* | Muchena FN and Onduru DD 2011 |
| GWC K17 | *Analysis of Financial Mechanisms for Green Water Credits in the Upper Tana, Kenya* | Muchena FN, Onduru DD and Kauffman JH 2011 |

ISRIC - World Soil Information

Ministry of Agriculture

Water Resources Management Authority

Kenya Agricultural Research Institute

Ministry of Water and Irrigation

International Fund for Agricultural Development

Future Water

ISRIC – World Soil Information has a mandate to serve the international community as custodian of global soil information and to increase awareness and understanding of soils in major global issues.

More information: www.isric.org

WAGENINGEN UR
For quality of life

ISRIC – World soil Information has a strategic association with Wageningen UR (University & Research centre)