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Soil data derived from SOTER for studies of carbon stocks and change in Kenya

(Version 1.0)

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SUMMARY

This report presents a harmonized set of soil parameter estimates for Kenya, developed to permit modelling of soil carbon stocks and change at the national scale. The Soil and Terrain Database for Kenya (KENSOTER), at scale 1:1M, compiled by the Kenya Soil Survey, formed the basis for the current work.

The land surface of the Republic of Kenya – excluding lakes and towns – has been characterized using 397 unique SOTER units corresponding with 623 soil components. The major soils have been described using 495 profiles, which include 178 synthetic profiles, selected by national soil experts as being representative for these units. The associated soil analytical data have been derived from soil survey reports and expert knowledge.

Gaps in the measured soil profile data have been filled using a step-wise procedure which includes three main stages (Batjes 2003): (1) collate additional measured soil analytical data where available; (2) fill gaps using expert knowledge and common sense; (3) fill the remaining gaps using a scheme of taxotransfer rules.

Parameter estimates are presented by soil unit for fixed depth intervals of 0.2 m to 1 m depth for: organic carbon, total nitrogen, pH(H_2O), CEC_{soil}, CEC_{clay}, base saturation, effective CEC, aluminum saturation, $CaCO_3$ content, gypsum content, exchangeable sodium percentage (ESP), electrical conductivity of saturated paste (ECe), bulk density, content of sand, silt and clay, content of coarse fragments, and available water capacity. These attributes have been identified as being useful for agro-ecological zoning, land evaluation, crop growth simulation, modelling of soil carbon stocks and change, and analyses of global environmental change.

The current parameter estimates should be seen as best estimates based on the current selection of soil profiles and data clustering procedure. Taxotransfer rules have been flagged to provide an indication of the possible confidence in the derived data.

Results are presented as summary files and can be linked to the 1:1M scale SOTER map for Kenya in a GIS, through the unique SOTER-unit code.

The secondary data set is appropriate for studies at the national scale. Correlation of soil analytical data, however, should be done more rigorously when more detailed scientific work is considered.

Keywords: soil parameter estimates, Kenya, environmental modelling, soil carbon, WISE database, SOTER database, secondary data set

1. INTRODUCTION

Three main sources of greenhouse gases generated or modified by human activities are: fossil fuel combustion, the chemical industry including cement production, and land use changes and system conversion (Watson *et al.* 2000; WBBGU 1998). On the other hand, agroecosystems can be adroitly managed to reduce carbon emissions and increase carbon sinks in vegetation and soil. It appears that this increased carbon uptake/storage can offset fossil fuel emissions temporarily (on a time scale from decades to a century) and partially, after which new steady state levels will be reached provided these systems remain undisturbed. Options for carbon sequestration must be chosen on the basis of knowledge of the nature and likely magnitude of C pools, whether organic or inorganic, in the soils of a given biome or agro-ecological region and the responses of these soils to different land use and management and anticipated changes in climate (Batjes 1999a; Lal *et al.* 1999; Sampson and Scholes 2000).

The current study[1] has been carried out in the framework of the GEF co-funded project, *Assessment of Soil Organic Carbon Stocks and Change at National Scale* (GFL-2740-02-4381). The project will develop and demonstrate generic tools, which quantify the potential impact of land management and climate scenarios on change in soil carbon stocks at national and sub-national level. It involves participation from national scientists in Brazil, India, Jordan and Kenya working closely with data management and modeller groups in Austria, France, the Netherlands, the United Kingdom and the USA.

The main research objectives, summarized on the project website[2], are:

1. To identify and use long-term, plot scale, experimental datasets to systematically evaluate and refine modelling techniques to quantify carbon sequestration potential in tropical soils;

[1] Having the same scope, the structure and body of the report for Kenya are similar to the one prepared for Jordan (Batjes *et al.*, 2003)
[2] http://www.reading.ac.uk/GEFSOC

2. To define, collate and format national-scale soils, climate and land-use datasets and to use them in the development of coupled modelling-GIS tools to estimate soil carbon stocks;

3. To demonstrate these tools by estimating current soil organic carbon stocks at country-scale – using the Gangetic Plains (India), Jordan, Kenya and Amazon-Brazil as case studies – and to compare these estimates with the existing techniques of combining soil mapping units and interpolating point data;

4. To quantify the impact of defined changes in land use and climate on carbon sequestration in soils with a view to assisting in the formulation of improved policies to optimise resource use in the four case-study countries.

This report presents parameter estimates for the major soils of Kenya, at scale 1: 1 000 000, for use in the modelling component of the GEF-SOC project. The materials and methods are described in Chapter 2, with special focus on the procedure for preparing the secondary SOTER sets. Results are discussed in Chapter 3, while concluding remarks are drawn in Chapter 4. The structure of the various output tables is documented in the Appendices, which also include a brief description of the contents of the secondary SOTER file for Kenya (Appendix 5).

The secondary SOTER data set annex GIS file for Kenya can be downloaded via www.isric.org[3].

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[3] After official termination of the GEFSOC project (July 2005).

2. MATERIALS AND METHODS

2.1 Biophysical setting

The Republic of Kenya lies along the equator in East Africa and is broadly bounded by 5^o 30' N and 4^o 30' S latitude and 34^o E and 42^o E longitude. It covers 582 646 km^2 (Times Atlas 2003) and has over 30 million inhabitants. Many areas in central and western Kenya, particularly in the Kisii region and near to Lake Victoria, are densely populated (500 -1200 inhabitants km^{-2}).

Details about the varied geology of Kenya may be found in Mathu and Davies (1996) and Schlueter (1997). There are four major relief zones within the country: the coastal and eastern plains, the central and western highlands, the Rift Valley Basin and the lake Victoria Basin. The country shows a wide range of natural regions, varying from hot arid lowlands to cool humid highlands, with soils of widely differing carrying capacity (Kassam *et al.* 1991; Sombroek *et al.* 1982).

Elevation increases gradually from 0 m above mean sea level near the Indian Ocean to between 2000 and 3400 m in the highlands. The central highlands are dissected by the Eastern Rift Valley, which is about 40 to 50 km wide and up to 1000 m lower than the flanking highlands. Kenya has various mountain ridges with elevations above 3000m, including Mount Elgon (4375 m) and Mount Kenya (5199 m).

Mean annual air temperature is strongly related to elevation. It decreases from about 27^o C near Mombasa along the coast, to 17^{o}C in Nairobi in the central highlands, to less than 10^o C above 3000 m.

Average annual rainfall ranges from 150 to 500 mm in the arid east and northeast of the country, from 500 to 1000 mm in the semi-arid regions and from 1000 to 2500 mm in the more humid areas in the central highlands and near Lake Victoria. Sombroek *et al.* (1982) subdivided Kenya into seven agro-climatic zones based on the ratio of average annual rainfall over average annual potential evaporation

(r/E_o). This ratio ranges from < 0.15 in the very arid zone (VII) up to > 0.8 in the humid zone (I).

The climate is controlled by the inter-tropical convergence zone (ITCZ). Much of Kenya experiences the main rainfall from March through May and the short rains from October to November. The dry season extends from January to February and from June to September in most years. Natural climatic hazards include recurring drought and flooding during the rainy seasons.

Agriculture and tourism form the backbone of Kenya's economy. A large fraction of the population makes their living from subsistence agriculture: the predominant food crops include maize, rice, wheat, beans, banana and cassava. The main export crops are coffee, tea and sisal. Cattle rearing, mainly for beef, is practiced particularly in the semi-arid areas together with wildlife conservation. Over 75 per cent of the country is non-arable and arable land occurs mainly in the central, western and coastal regions.

Mathu and Davies (1996) discuss the main environmental issues in Kenya. These include land degradation by water erosion, increased cultivation in marginal areas, overgrazing, deforestation, pollution of rivers and lakes, and loss of bio-diversity. Increased population density has also resulted in increased intensity of crop production and depletion of soil fertility. One of the main biophysical causes of lower food production is decreasing soil fertility, particularly low availability of phosphorus and nitrogen, coupled with decreasing levels of soil organic matter (Gichuru *et al.* 2003; Mulongoy and Merckx 1993; Woomer *et al.* 1998).

Mantel *et al.* (1999) studied the impact of water erosion on productivity of maize in Kenya. Fischer *et al*. (1996) modelled the impact of climate change and increases in atmospheric CO_2 concentrations on agricultural production. At the subnational level, these effects may vary substantially both in terms of magnitude and direction. Land use change, the main driving factors of which have been described by Lambin *et al.* (2003), in combination with climate change will have a varying impact on net primary production, and thus soil carbon stocks, in the various natural regions of Kenya. A selection of these aspects will be studied during the modelling phase of the GEFSOC project.

2.2 Source of data

The Exploratory Soil Map of Kenya (Sombroek *et al.* 1982), complemented by soil inventories carried out between 1980-1993, formed the basis for compiling the 1:1M SOTER database for the country (KSS 1995). The soil geographical and attribute data have been collated in SOTER format by staff of the Kenya Soil Survey (KSS) between 1993 and 1995, with technical back stopping by ISRIC.

2.3 SOTER methodology

The SOTER methodology allows mapping and characterization of areas of land with a distinctive, often repetitive, pattern of landform, lithology, surface form, slope, parent material, and soils (Van Engelen and Wen 1995). The approach resembles physiographic or land systems mapping. The collated materials are stored in a SOTER database linked to GIS, permitting a wide range of applications (e.g., Falloon *et al.* 1998; Graef 1999; Mantel and Van Engelen 1999). The SOTER methodology is mainly applied at scales ranging from 1:250 000 to 1:5M.

Each SOTER database is comprised of two main elements, a geographical component and an attribute data component (Figure 1). The *geographical database* holds information on the location, extent and topology of each SOTER unit. The *attribute database* describes the characteristics of the spatial unit and includes both area data and point data. A geographical information system (GIS) is used to manage the geographic data, while the attribute data are handled in a relational database management system (RDBMS).

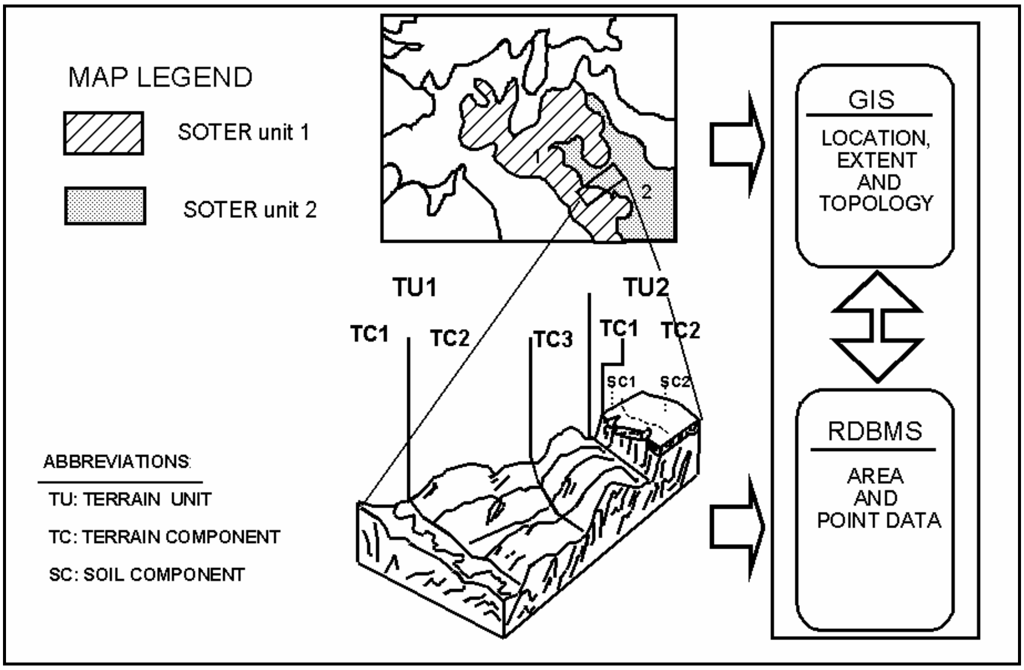

Figure 1. Schematic representation of two SOTER units and their terrain and soil components

Each SOTER unit in the geographic database has a unique identifier, called SOTER unit-ID (SUID). This primary key provides a link to the attribute data for its constituent terrain, terrain component(s) (TCID) and soil component(s) (SCID) (see Appendix 4).

Each soil component within a SOTER unit is described by a profile (PRID), identified by the national soil experts as being regionally representative. Profiles are characterised according to the Revised Legend of FAO (1988). Representative profiles are selected from available soil survey reports, as the SOTER program does not involve new ground surveys. Batjes (1999b) reviewed issues of data acquisition, quality control and sharing in the context of SOTER projects.

A comprehensive description of the methodology and coding conventions is given by Van Engelen and Wen (1995). The SOTER attribute data are managed with an automated data entry facility (Tempel 2002). In addition, SOTER uses commercially available Access® and ArcView® software.

2.4 Preparation of secondary SOTER data sets

2.4.1 List of soil parameters

Special attention has been paid to the key attributes required for the spatial runs of the two organic carbon models considered in the GEF-SOC project: RothC and Century. These are: the extent and type of soil, soil drainage status, content of clay, content of organic carbon, and bulk density per depth layer (Falloon *et al.* 1998; Paustian *et al.* 1997). This limited set has been expanded to include 18 soil parameters (Table 1) commonly required in studies of agro-ecological zoning, food productivity, soil gaseous emissions/sinks and environmental change (see Batjes 2004; Bouwman *et al.* 2002; Cramer and Fischer 1997; Fischer *et al.* 2002; Scholes *et al.* 1995).

Table 1. List of soil parameters

Organic carbon
Total nitrogen
Soil reaction (pH_{H2O})
Cation exchange capacity (CEC_{soil})
Cation exchange capacity of clay size fraction (CEC_{clay}) • ‡
Base saturation (as % of CEC_{soil}) ‡
Effective cation exchange capacity (ECEC) † ‡
Aluminum saturation (as % of ECEC) ‡
$CaCO_3$ content
Gypsum content
Exchangeable sodium percentage (ESP) ‡
Electrical conductivity of saturated paste (ECe)
Bulk density
Coarse fragments (volume %)
Sand (mass %)
Silt (mass %)
Clay (mass %)
Available water capacity (AWC; from -33 to -1500 kPa; % w/v) ‡ □

‡ Calculated from other measured soil properties.

† ECEC is defined as exchangeable (Ca^{++}+Mg^{++}+K^{+}+Na^{+}) + exchangeable (H^{+}+Al^{+++}) (Van Reeuwijk 1995).

• CEC_{clay} was calculated from CEC_{soil} by assuming a mean contribution of 350 $cmol_c$ kg^{-1} OC, the common range being from 150 to over 750 $cmol_c$ kg^{-1} (Klamt and Sombroek 1988).

□ The soil water potential limits for AWC conform to USDA standards (Soil Survey Staff 1983). Values shown have not been corrected for the presence of coarse fragments.

Table 1 does not consider soil hydraulic properties. Although these are essential for many simulation studies, these are seldom measured during soil surveys. As a result, the corresponding records are lacking in databases such as SOTER and WISE. Information on soil hydraulic properties and pedotransfer functions for Western Europe and the USA may be found in auxiliary databases (see Nemes *et al.* 2003; Wösten *et al.* 1998) but similar work for tropical soils has just begun (Tomasella and Hodnett 1997, 1998; Van den Berg *et al.* 1997).

2.4.2 Consistency and integrity checks of the primary data

Data consolidation started with the conversion of the initial SOTER database for Kenya (KSS 1995) from dBaseIV® into Access 2000®. This exercise included a check on data consistency and integrity. Various errors and gaps have been corrected at this stage using expert knowledge and common sense. All alphanumeric and selected numeric data, such as pH, sum of (sand + silt + clay) and available water capacity, were subjected to a rigorous scheme of data checks (see p. 52 in Batjes 1995).

2.4.3 Soil characterization according to FAO Revised Legend

Soil characterization in Kenya is according to the Revised Legend of FAO (1988). Soil names in KENSOTER have largely been taken at face value, unless errors occurred in the codes provided for the FAO Revised Legend. In the latter cases, the classification has been checked using the available soil morphological and analytical data.

2.4.4 Procedure for filling gaps in the measured data

The SOTER work for Kenya (1993-1995) drew on materials resulting from an exploratory survey at scale 1:1M. Therefore complete soil analytical data sets are not available for all profiles. The occurrence of such gaps precludes the direct use of primary SOTER data in models. Therefore, a standardized procedure has been developed to fill gaps in key measured data in three main stages (Batjes 2003):

a) Collate additional measured soil data where these exist, in the uniform SOTER format;

b) Use national expert estimates and common sense to fill selected gaps in a secondary data set;

c) Use taxotransfer rule (TTR) derived soil parameter estimates for similar FAO soil units, as derived from the global WISE profile database.

The desirability of the above stages decreases from highest (a) to lowest (c). Step (c) is detailed by Batjes (2003). Steps (a) and (b), being specific to the Kenyan case and, thus, strongly dependent on national inputs, are discussed in detail below.

a) Collating additional measured data

This stage is self-explanatory and depends upon the availability of suitable materials and their accessibility to the national project scientists working with the relevant soil survey organisations. KSS staff have provided ISRIC with data for 52 new soil profiles from so far under-represented areas of the country. The spatial information for the corresponding soil components in SOTER has also been updated by KSS. After having performed the routine checks on data consistency and integrity, this new information has been incorporated into a revised version of the primary SOTER database for Kenya at ISRIC. During the subsequent screening of the revised database, it appeared that information was still lacking regarding the composition of various soil components.

b) Using expert-based estimates

The second stage depends upon the expertise of soil scientists, well versed with the national soil conditions, and pedological common sense.

Synthetic profiles can be introduced in SOTER when there are no measured data for a given soil unit, provided the soil classification is known at the level of the Soil Component. While most synthetic profiles have been provided by KSS (1995), it has been necessary for ISRIC to create an additional 47 synthetic profiles to fill the remaining gaps in the spatial component of the primary SOTER set. For the latter, the necessary information on soil classification has been distilled from the legend of the 1:1M Exploratory Soil Map (Sombroek *et al.* 1982). All synthetic profiles were flagged to avoid confusion with real profiles, for example KESYN015 or KE117/1-19syn.

The updated primary SOTER database for Kenya contains 495 representative soil profiles, including 178 (35 %) synthetic profiles. This corresponds with an average density of 0.06 representative profiles per 100 km^2. Overall density, including the synthetic profiles, is 0.08 per 100 km^2.

c) Application of taxotransfer rules

The taxotransfer (TTR) approach was developed initially for application with the Soil Map of the World, in collaborative studies with FAO and IIASA, using soil analytical data held in ISRIC's WISE database (Batjes 2002; Batjes *et al.* 1997). The methodology has been modified in the framework of the GEFSOC project for use with national scale SOTER databases. The approach is detailed by Batjes (2003).

3. RESULTS AND DISCUSSION

3.1 General

Three hundred ninety seven (397) unique SOTER units — excluding lakes and towns — have been mapped for Kenya corresponding with 623 soil components. In total, this corresponds with 3261 mapped polygons.

At the small scale under consideration, most SOTER units will be compound units. Some of the spatially minor soil units, however, may be of particular relevance. For example, organic soils of inland basins in the highlands can be of great importance for national inventories of carbon stocks and change in Kenya. It is therefore recommended that end-users consider all component soil units of a SOTER unit in their assessments or model runs.

Ultimately, the type of research purpose will determine which parameter estimates or single value maps are of importance. Therefore, the full map unit composition can best be addressed with tailor made programs designed to meet the scope of the application.

3.2 SOTER unit composition

A table – *sensu* Access® databases – has been generated showing the full composition of each SOTER unit in terms of its dominant soils – each one characterized by a regionally representative profile – and their relative extent.

The relative extent of each soil unit has been expressed in 5 classes to arrive at a compact map unit code: 1 – from 80 to 100 per cent; 2 – from 60 to 80 per cent; 3 – from 40 to 60 percent; 4 – from 20 to 40 per cent, and 5 – less than 20 percent.

Figure 2 shows an excerpt of the corresponding table for Kenya, and Appendix 1 its structure. Based on current knowledge, the SOTER or map unit with NEWSUID number KE253 is coded as CMc1FRr5. The 253th map unit for the country is comprised of 85 per cent calcaric Cambisols (CMc) and 15 per cent rhodic Ferralsols (FRr).

SOTERunitComposition : Table

NEWSUID	SoilMapUnit	SOIL1	PROP1	Profile-ID1	SOIL2	PROP2	Profile-ID2	SOIL3	PROP3	Profile-ID3
KE251	FRr1 [251]	FRr	100	KE190/3-4						
KE252	LXh2FRr4FRh5 [252]	LXh	70	KE175/2-21	FRr	20	KE173/2-1	FRh	10	KESYN-252-1-2
KE253	CMc1FRr5 [253]	CMc	85	KE182/3-12	FRr	15	KE173/2-1			
KE254	NTr2FRr3 [254]	NTr	60	KE173/2-199	FRr	40	KE173/2-2			
KE255	VRe1FRr5 [255]	VRe	85	KE173/3-3	FRr	15	KE173/2-2			
KE256	LXh1VRk4 [256]	LXh	80	KE173/2-153	VRk	20	KE172/4-33			
KE257	LVv3ACh4CMc4 [257]	LVv	55	KE9.2	ACh	20	KE115/2-35	CMc	25	KE192/3-64
KE258	CMc1 [258]	CMc	100	KE190/2-212						
KE259	LVk1 [259]	LVk	100	KE170-10						

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Figure 2. Characterization of SOTER units in terms of their main component soils – with their representative profile – and their relative extent

3.3 Soil Parameter estimates

The depth-weighted primary and TTR-derived data, by layer, for the 18 soil properties under consideration (Table 1) have been stored in a secondary SOTER data set (Figure 3); the cut-off point for applying any TTR is $n_{WISE} < 5$. The structure of the corresponding file is described in Appendix 2.

SOTERparameterEstimates : Table

CLAF	PRID	Drain	Layer	Topl	Botl	CFRAG	SDTO	STPC	CLPC	PSCL	BULK	TAWC	CECS	BSAT	CECc	PHAQ	TOTC	ECEC	ALSA
FRr	KE101/3-224	W	D1	0	20	0	38	12	50	F	1.23	8	10	55	15	4.9	8.5	14	9
FRr	KE101/3-224	W	D2	20	40	0	34	10	56	F	1.30	7	10	56	14	5.0	7.0	10	12
FRr	KE101/3-224	W	D3	40	60	0	38	10	52	F	1.30	7	9	48	13	5.1	6.5	7	25
FRr	KE101/3-224	W	D4	60	70	0	42	10	48	F	1.30	7	8	42	12	5.1	6.0	9	22
ACh	KE101/3-225	W	D1	0	20	1	34	22	44	F	1.20	8	8	50	13	5.0	7.0	15	8
ACh	KE101/3-225	W	D2	20	40	1	34	15	51	F	1.25	9	8	36	13	5.1	5.5	8	10
ACh	KE101/3-225	W	D3	40	60	1	34	8	58	F	1.30	7	8	32	12	5.1	4.0	8	9
ACh	KE101/3-225	W	D4	60	80	1	34	8	58	F	1.30	8	8	32	12	5.1	4.0	8	7
ACh	KE101/3-225	W	D5	80	100	1	22	14	64	V	1.30	8	8	21	10	5.1	4.0	8	6
CMo	KE101/3-234	W	D1	0	20	0	30	18	52	F	1.22	8	14	45	18	5.2	13.2	4	10
CMo	KE101/3-234	W	D2	20	40	0	38	12	50	F	1.30	7	11	65	18	5.2	6.0	8	7
CMo	KE101/3-234	W	D3	40	55	0	38	12	50	F	1.30	6	11	51	18	5.2	6.0	4	26
VRd	KE101/3-235	P	D1	0	20	1	16	10	74	V	1.25	14	41	51	55	5.7	1.2	53	0
VRd	KE101/3-235	P	D2	20	40	1	15	9	76	V	1.20	14	40	50	50	5.4	5.4	58	4
VRd	KE101/3-235	P	D3	40	60	1	14	8	78	V	1.21	14	31	48	37	5.3	6.0	58	5
VRd	KE101/3-235	P	D4	60	80	1	19	9	72	V	1.29	15	34	68	47	5.3	2.3	38	5
VRd	KE101/3-235	P	D5	80	100	1	24	10	66	V	1.50	15	34	100	52	5.3	0.3	55	6

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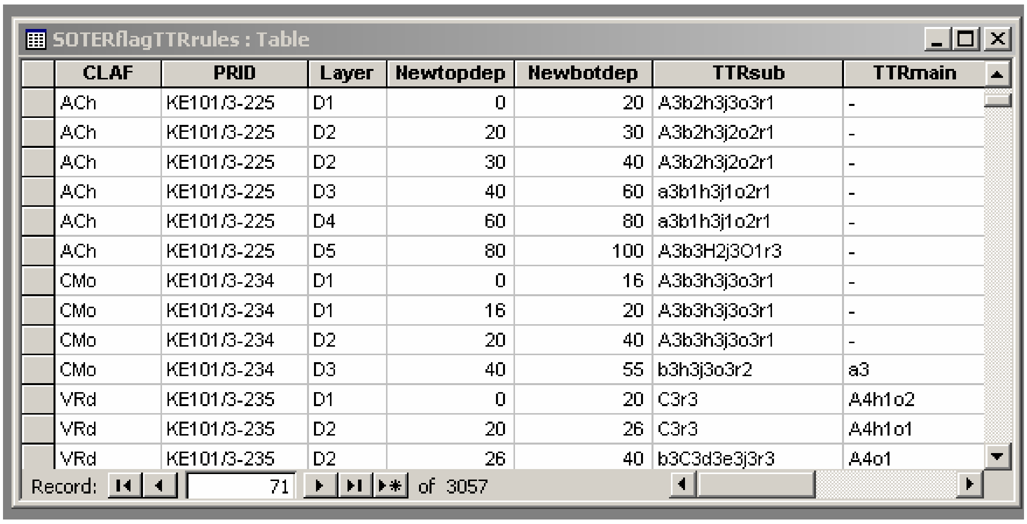
Figure 3. Example of ultimate result of the application of the TTR-scheme and depth-weighing for four profiles

The type of TTR used, if any, has been flagged by profile and depth layer in a separate table (Figure 4, Appendix 3). The field TTRsub indicates that the data substitution for a given attribute, in the secondary SOTER set, is based on WISE-derived parameter estimates for similar soil units. Otherwise, should the corresponding population in WISE be too small (n_{WISE} < 5) for a meaningful substitution, the rules used are flagged under TTRmain (see Batjes 2003).



SOTERflagTTRrules : Table

CLAF	PRID	Layer	Newtopdep	Newbotdep	TTRsub	TTRmain
ACh	KE101/3-225	D1	0	20	A3b2h3j3o3r1	-
ACh	KE101/3-225	D2	20	30	A3b2h3j2o2r1	-
ACh	KE101/3-225	D2	30	40	A3b2h3j2o2r1	-
ACh	KE101/3-225	D3	40	60	a3b1h3j1o2r1	-
ACh	KE101/3-225	D4	60	80	a3b1h3j1o2r1	-
ACh	KE101/3-225	D5	80	100	A3b3H2j3O1r3	-
CMo	KE101/3-234	D1	0	16	A3b3h3j3o3r1	-
CMo	KE101/3-234	D1	16	20	A3b3h3j3o3r1	-
CMo	KE101/3-234	D2	20	40	A3b3h3j3o3r1	-
CMo	KE101/3-234	D3	40	55	b3h3j3o3r2	a3
VRd	KE101/3-235	D1	0	20	C3r3	A4h1o2
VRd	KE101/3-235	D2	20	26	C3r3	A4h1o1
VRd	KE101/3-235	D2	26	40	b3C3d3e3j3r3	A4o1

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Figure 4. Flagging of taxotransfer rules by profile, depth zone and attribute

Each flag consists of a sequence of letters followed by a numeral (see under TTRsub and TTRmain in Figure 4). The letters indicate soil attributes for which a TTR has been applied (Figure 5). The number code reflects the size of the sample population in WISE, after outlier rejection, on which the statistical analyses was based (Table 2).

Table 2. Criteria for defining confidence in the derived data

Code	Confidence level	n_{WISE}
1	Very high	> 30
2	High	15-29
3	Moderate[†]	5-14
4	Low	1-4
-	No data	0

* n_{WISE} is the sample size after the screening procedure (see Figure 5)
[†] The cut-off point in the TTR-approach is n_{WISE} < 5

When a small letter is used, the substitution considered median data for the corresponding textural class (for example, Fine and n_{WISE} > 5). Otherwise, when a capital is used, this indicates that the substitution is based on the whole set for the corresponding soil unit and depth layer, irrespective of soil texture (i.e. undifferentiated or #). The same coding conventions apply for TTRmain. This is depicted schematically for the upper 0 to 20 cm of a hypothetical profile (KEhyp04):

CLAF	PRID	LAYER	Newtopdep	Newbotdep	TTRsub	TTRmain
CMx	KEhyp04	D1	0	18	b3c2j3o3r2	a2h1
CMx	KEhyp04	D1	18	20	C3j1	A3h2

Soil parameter estimates based on WISE-derived data, using data for the corresponding major grouping and either the same textural class (small letter) or undifferentiated textural class (capital).

Soil parameter estimates based on WISE-derived data, using data for the corresponding soil unit and same textural class:
- b: Base saturation, 3 (n_{WISE} = 5 –14)
- c: Bulk density, 2 (n_{WISE} = 15 – 29)
- j: Exchangeable sodium percentage, 3 (n_{WISE} = 5 –14)
- o: Volumetric water content, 3 (n_{WISE} = 5 –14)
- r: Total Nitrogen, 2 (n_{WISE} = 15 – 29)

For some profiles, all 18 parameter estimates have been derived via taxotransfer or using expert estimates. This is already reflected by the abbreviation *syn* in the profile identifier.

The overall assumption is that the confidence in a TTR-based parameter estimate should increase with the size of the sample populations present in WISE, after outlier rejection. In addition, the confidence in soil parameter estimates listed under TTRsub, will be higher than for those listed under TTRmain.

SWcodes : Table

SOTnam	WISnam	SoilVariable	TTRflag	Comments
---	---	---	y	PSCL estimated from PTR-derived sand, silt and clay
ALSA	ALSA	ALSAT	a	exchangeable Aluminum percentage (% of ECEC)
BSAT	BSAT	BSAT	b	base saturation (% of CECs)
BULK	BULK	BULKDENS	c	bulk density
CECC	CECC	CECCLAY	d	cation exchange capacity of clay fraction (corr. for org. C)
CECS	CECS	CECSOIL	e	cation exchange capacity
CFRAG	GRAV	GRAVEL	f	coarse fragments
CLPC	CLAY	CLAY	g	clay % (see also Y for texture (g, m & n))
ECEC	ECEC	ECEC	h	effective CEC
ELCO	ECE	ECE	i	electrical conductivity
ESP	ESP	ESP	j	exchangeable Na percentage (% of CECs)
GYPS	GYPS	GYPSUM	k	gypsum content
PHAQ	PHH2	PHH2O	l	pH in water
SDTO	SAND	SAND	m	sand %
STPC	SILT	SILT	n	silt %
TAWC	TAWC	TAWC	o	volumetric water content (-33 to - 1500 kPa)
TCEQ	CACO	CACO3	p	carbonate content
TOTC	ORGC	ORGC	q	organic carbon content
TOTN	TOTN	TOTN	r	total nitogen content

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Figure 5. Conventions for coding the various attributes used in the taxotransfer scheme.

A high confidence rating does not necessarily imply that the soil parameter estimates shown will be representative for the soil unit under consideration. Profile selection for SOTER, as for any other soil database, is not probabilistic but based on available data and expert knowledge. Several of the soil attributes under consideration in Table 1 are not diagnostic in the Revised Legend (FAO 1988). In addition, some properties are readily modified by changes in land use or management, for example the organic and inorganic carbon content upon irrigation.

Table 3 lists how often a given TTR has been applied as a percentage of the total number of horizons (up to a depth of 100 cm) in the SOTER profile database; details may be found in table SOTERflagTTRrules (see Appendix 3). For example, the aluminum saturation percentage (ALSA) has been estimated using TTRs in 87 % of the cases, mainly using data for similar major soil groupings (see under TTRmain). For bulk density (BULK) this is 36 %, which indicates that either measured or expert-estimates of bulk density are available for 64 % of the horizons under consideration. TTRs have been used in 91 per cent of the cases for total nitrogen (TOTN), reflecting that this variable has seldom been measured during the national soil survey program.

Table 3. Type and frequency of taxotransfer rules applied

Parameter	Code	Frequency of occurrence (%)		
		TTRsub	TTRmain	Total
ALSA	A	12	76	87
BSAT	B	45	1	46
BULK	C	34	1	35
CECC	D	35	1	36
CECS	E	18	0	19
CFRAG	F	34	0	34
CLPC	G	17	0	17
ECEC	H	90	9	99
ELCO	I	14	4	17
ESP	J	44	1	44
GYPS	K	10	8	18
PHAQ	L	17	0	17
SDTO	M	17	0	17
STPC	N	17	0	17
TAWC	O	86	7	93
TCEQ	P	41	7	48
TOTC	Q	29	0	29
TOTN	R	90	1	91

Note: For definitions of abbreviations see text and Figure 5.

3.4 Linkage to GIS

Aggregated information about the SOTER unit composition and results of the TTR-work can be linked to the SOTER map using GIS. At the national scale, this can be done via the unique SOTER unit identifier (SUID, see Appendix 4). In transnational databases, however, linkage will be through the NEWSUID, which is a combination of the country's ISO code plus the SUID code.

Most SOTER units in Kenya comprise at least two soil components. In the primary database, the associated information is stored in a range of relational databases to enhance data storage and management efficiency. To assist end-users, a new table has been created that incorporates data held in the primary SOTER database and the present information on soil parameter estimates (Figure 6, Appendix 4). Clearly, this wealth of information, although needed for the modelling work, complicates linkage to GIS.

SOTERsummaryFile : Table

NEWSUID	TCID	SCID	Propc	CLAF	PRID	Layer	TopDe	BotDe	CFRA	SDTO	STPC	CLPC	BULK	TAWC	CECS	BSAT	PHAQ	TOTC	TOTN	ECEC	ALSA
KE34	1	1	85	CMe	KESYN4	D1	0	20	36	25	27	48	1.34	9	19	89	6.0	8.8	1.26	26	0
KE34	1	1	85	CMe	KESYN4	D2	20	40	60	25	20	55	1.28	10	15	88	6.0	5.0	0.80	23	0
KE34	1	2	15	CMd	KE117/1-17	D1	0	20	0	29	22	49	1.23	14	18	31	5.9	10.3	1.80	15	0
KE34	1	2	15	CMd	KE117/1-17	D2	20	30	0	56	16	28	1.30	13	18	27	5.6	8.0	0.74	7	0
KE35	1	1	100	ACh	KE116/1-23	D1	0	20	0	36	12	52	1.25	8	16	39	5.1	12.0	1.20	15	8
KE35	1	1	100	ACh	KE116/1-23	D2	20	40	0	28	12	60	1.20	8	15	45	4.7	10.0	0.92	6	10
KE35	1	1	100	ACh	KE116/1-23	D3	40	60	0	26	14	60	1.15	8	15	30	4.7	9.5	0.75	8	8
KE35	1	1	100	ACh	KE116/1-23	D4	60	80	0	24	16	60	1.10	8	15	15	4.7	9.0	0.60	8	7
KE35	1	1	100	ACh	KE116/1-23	D5	80	100	0	24	16	60	1.10	8	15	15	4.7	9.0	0.60	8	6
KE36	1	1	100	NTh	KESYN5	D1	0	20	0	25	30	45	1.30	6	30	64	5.0	15.0	1.88	10	6
KE36	1	1	100	NTh	KESYN5	D2	20	40	0	21	26	53	1.38	6	26	36	5.4	11.3	1.12	12	8
KE36	1	1	100	NTh	KESYN5	D3	40	60	0	20	25	55	1.40	7	25	49	5.5	10.0	0.43	11	13
KE36	1	1	100	NTh	KESYN5	D4	60	80	0	20	24	56	1.40	6	25	66	5.5	9.5	0.46	10	19
KE36	1	1	100	NTh	KESYN5	D5	80	100	0	20	20	60	1.40	6	25	54	5.5	8.0	0.30	9	22

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Figure 6. Excerpt of a SOTER summary file for units KE34, KE35 and KE36

For visualization and analysis in GIS, it will often be necessary to make an extra selection. For example, in the case of the RothC and Century models, information may be required about the properties of the topsoil – that is layer D1: 0-20 cm – for the dominant soil. In this case, the necessary selection will be for the first Terrain Component (TCID=1), first Soil Component (SCID= 1) and the upper most layer (D1= 1). The corresponding selection is included as a separate table in the secondary database for Kenya. The database structure is detailed in Appendix 4.

Figure 7 schematically shows the procedure for linking the various secondary attribute data to the geographical SOTER data held in the GIS. For ease of visualization, it considers only the upper layer (D1) of the spatially dominant (first) soil component of SOTER unit KE19.

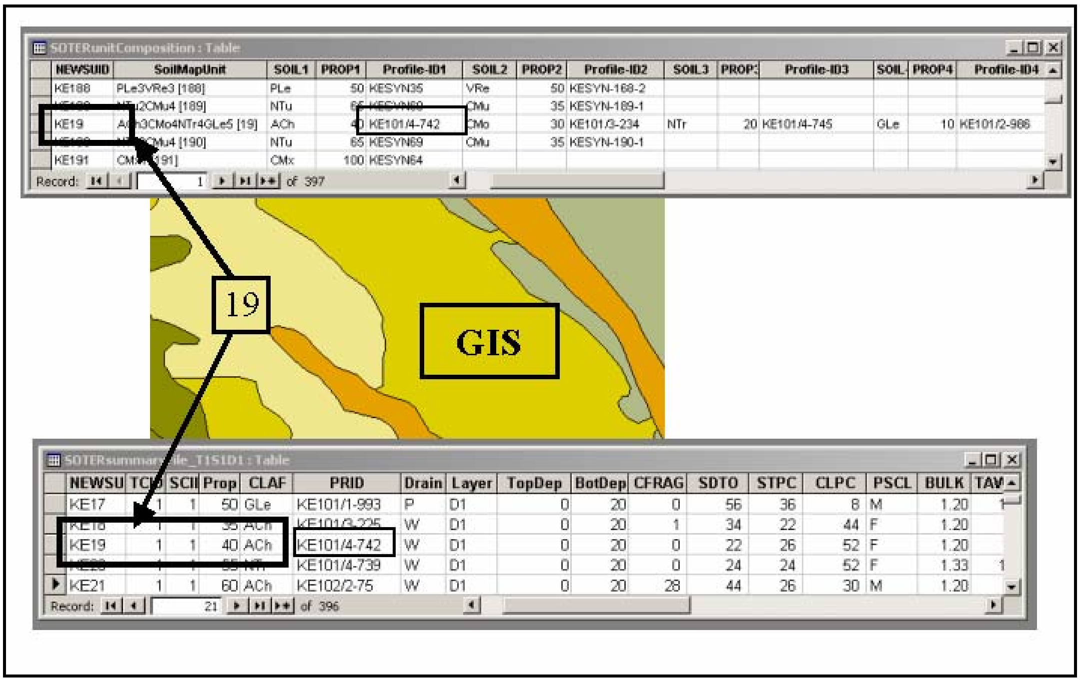

Figure 7. Linking soil parameter estimates for the top 20 cm of the dominant soil (KE101/4-472) of SOTER unit KE19 with the geographical component of SOTER

All geographic data in SOTER are presented in vector format. However, should grid-based soil layers be required, these can be generated using the convert-to-grid module of the spatial analyst extension to ArcView (ESRI 1996). The minimum legible delineation implied by the mapping scale of 1:1 million is about 25 km^2. Gridding should be based on the SUID field to permit subsequent linkage with the various attribute tables discussed in this report. The procedure will be same as depicted earlier in Figure 7.

4. CONCLUSIONS

- Linkage between soil profile data and the spatial component of a SOTER map, for environmental applications, requires generalisation of measured soil (profile) data by soil unit and depth zone. This involves the transformation of variables that show a marked spatial and temporal variation and that may have been determined in a range of laboratories according to various analytical methods.

- A pragmatic approach to the comparability of soil analytical data has been adopted. This is considered appropriate at the present scale of 1:1M but must be done more rigorously when more detailed scientific work is considered.
- The present set of soil parameter estimates for Kenya should be seen as best estimates, based on the currently available selection of profile data held in KENSOTER and WISE.
- Modellers should familiarize themselves with the assumptions and taxotransfer rules used to develop the set of soil parameter estimates, before using these in their models.
- Assessments and model simulation of soil organic carbon stocks and change – like any other environmental study – should consider the full SOTER unit composition, not only the dominant soil component.
- The detail and quality of primary information available within the country results in a variable resolution of the products presented.
- The secondary data set is appropriate for studies at national scale, including agro-ecological zoning, land evaluation, and modelling of carbon stocks and changes.

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APPENDICES

Appendix 1: SOTER unit composition file

This summary table gives the full composition of each SOTER unit in terms of its main soil units (FAO, 1988), their relative extent, and the identifier for the corresponding representative profile. It contains information aggregated from a number of primary SOTER tables, *viz.* SoilComponent and Profile. It can be easily linked to the SOTER geographical data in a GIS through the unique SOTER unit code – NEWSUID, a combination of the fields for ISO and SUID – and linked to the table holding the soil parameter estimates through the unique profile identifier (PRID, see Appendix 2 and Figure 7).

Structure of table SOTERunitComposition

Name	Type	Size	Description
ISOC	Text	2	ISO-3166 country code (1994)
SUID	Integer	2	The identification code of a SOTER unit on the map and in the database
NEWSUID	Text	10	Globally unique SOTER code, comprising fields ISOC plus SUID
SOIL1	Text	3	Characterization of the first (main) according to the Revised Legend (FAO, 1988)
PROP1	Integer	2	Proportion, as a percentage, that the main soil occupies Within the SOTER unit
PRID1	Text	15	Unique code for the corresponding representative soil profile (as selected by the national soil experts)
SOIL2	Text	3	As above but for the next soil component
PROP2	Integer	2	As above
PRID2	Text	15	As above
SOIL3	Text	3	As above but for the next soil component
PROP3	Integer	2	As above
PRID3	Text	15	As above
SOIL4	Text	3	As above but for the next soil component
PROP4	Integer	2	As above
PRID4	Text	15	As above
SOIL5	Text	3	As above but for the next soil component
PROP5	Integer	2	As above
PRID5	Text	15	As above
SOIL6	Text	3	As above but for the next soil component
PROP6	Integer	2	As above
PRID6	Text	15	As above
SOIL7	Text	3	As above but for the next soil component

(cont.)

PROP7	Integer	2	As above
PRID7	Text	15	As above
SOIL8	Text	3	As above but for the next soil component
PROP8	Integer	2	As above
PRID8	Text	15	As above
SOIL9	Text	3	As above but for the next soil component
PROP9	Integer	2	As above
PRID9	Text	15	As above
SOIL10	Text	3	As above but for the next soil component
PROP10	Integer	2	As above
PRID10	Text	15	As above

Note: Generally, not all 10 available fields for $SOIL_i$ will be filled in SOTER.

Appendix 2: Taxotransfer rule-based soil parameter estimates

This table lists soil parameters estimates for all representative profiles considered in a given SOTER database. This information can be linked to the geographical component of the SOTER database – in a GIS – through the unique profile code (PRID, see Appendix 1).

Structure of table SOTERparameterEstimates

Name	Type	Size	Description
CLAF	Text	3	Revised Legend FAO (1988) code
PRID	Text	15	profile ID (as documented in table SOTERunitComposition)
Drain	Text	2	FAO soil drainage class
Layer	Text	8	code for depth layer (from D1 to D5; e.g. D1 is from 0 to 20 cm)
TopDep	Integer	4	depth of top of layer (cm)
BotDep	Integer	4	depth of bottom of (cm)
CFRAG	Integer	2	coarse fragments (> 2mm)
SDTO	Integer	2	sand (mass %)
STPC	Integer	2	silt (mass %)
CLPC	Integer	2	clay (mass %)
PSCL	Text	1	FAO texture class (see note at end of this report for codes)
BULK	Single	4	bulk density (kg dm^{-3})
TAWC	Integer	2	available water capacity (vol. % , -33 to -1500 kPa conform to USDA standards)
CECS	Single	4	cation exchange capacity ($cmol_c$ kg^{-1}) for fine earth fraction
BSAT	Integer	2	base saturation as percentage of CECsoil

(cont.)

CECc	Single	4	CECclay, corrected for contribution of organic matter ($cmol_c\ kg^{-1}$)
PHAQ	Single	4	pH measured in water
TCEQ	Single	4	total carbonate equivalent ($g\ kg^{-1}$)
GYPS	Single	4	gypsum content ($g\ kg^{-1}$)
ELCO	Single	4	electrical conductivity ($dS\ m^{-1}$)
TOTC	Single	4	organic carbon content ($g\ kg^{-1}$)
TOTN	Single	4	total nitrogen ($g\ kg^{-1}$)
ECEC	Single	4	effective CEC ($cmol_c\ kg^{-1}$)

Note: These are depth-weighted values. In view of the TTR-rules applied and depth weighting, the parameters listed for TOTC and TOTN should not be used to compute C/N ratios!

The above table should be consulted in conjunction with table SOTERflagTTRrules that documents the taxotransfer rules that have been applied (see Appendix 3).

Appendix 3. Flagging taxotransfer rules

The type of taxotransfer that has been used when creating the table SOTERparameterEstimates (Appendix 2) is documented in table SOTERflagTTRrules. Further details on coding conventions may be found in the text (Section 3.3).

Structure of table SOTERflagTTRrules

Name	Type	Size	Description
CLAF	Text	3	Revised Legend (FAO, 1988) code
PRID	Text	15	Unique identifier for representative profile
Newtopdep	Integer	2	Depth of top of layer (cm)
Newbotdep	Integer	2	Depth of bottom of layer (cm)
TTRsub	Text	50	Codes showing the type of taxotransfer rule used (based on data for soil *units*; see text)
TTRmain	Text	50	Codes showing the type of taxotransfer rule used (based on data for *major units*; see text)
TTRfinal	Text	25	Additional flags (based on expert knowledge)

Note: The exchangeable aluminum percentage (ALSA) has been set at zero when pH_{water} is higher than 5.5. Similarly, the electrical conductivity (ELCO), content of gypsum (GYPS) and content of carbonates (TCEQ) have been set at zero when pH_{water} is less than 6.5. Finally, the CEC of the clay fraction (CEC_{clay}) has always been re-calculated from the depth-weighted measured and TTR-derived data for

CEC_{soil} and content of organic carbon, assuming a mean contribution of 350 $cmol_c$ kg^{-1} OC [Klamt, 1988 #1567]. When applicable, this has been flagged in the field TTRfinal; the coding conventions are given in Figure 5.

Appendix 4: SOTER summary file

Interpretations of a SOTER database, in combination with the current set of soil parameter estimates requires a good knowledge of relational database handling systems and a sound understanding of the SOTER database structure. This may be an obstacle to end-users with limited programming expertise. Therefore, to facilitate access to the data and its ultimate linkage to GIS, a SOTER summary file has been created. The structure of the corresponding table is shown below.

Information on landform, lithology and slope has been derived from the KENSOTER database (KSS 1995).

Structure of table SOTERsummaryFile

Name	Type	Size	Description
ISOC	Text	2	ISO-3166 country code (1994)
SUID	Integer	2	The identification code of a SOTER unit on the map and in the database
NEWSUID	Text	10	Globally unique SOTER code, comprising fields ISOC Plus SUID
TCID	Integer	1	Number of terrain component in given SOTER unit
SCID	Integer	1	Number of soil component within given terrain component and SOTER unit
PROP	Integer	3	Relative proportion of above in given SOTER unit
CLAF	Text	3	Revised Legend FAO (1988) code
PRID	Text	15	Profile ID (as documented in table SOTER-unitComposition)
Drain	Text	2	FAO soil drainage class
Layer	Text	8	Code for depth layer (from D1 to D5; e.g. D1 is from 0 to 20 cm)
TopDep	Integer	4	Upper depth of layer (cm)
BotDep	Integer	4	Lower dept of layer (cm)
CFRAG	Integer	2	Coarse fragments (> 2mm)
SDTO	Integer	2	Sand (mass %)
STPC	Integer	2	Silt (mass %)
CLPC	Integer	2	Clay (mass %)

(cont.)

PSCL	Text	1	FAO texture class (see Figure 8)
BULK	Single	4	Bulk density (kg dm^{-3})
TAWC	Integer	2	Available water capacity (vol. %, -33 to -1500 kPa, USDA standards)
CECS	Single	4	Cation exchange capacity ($cmol_c$ kg^{-1}) of fine earth fraction
BSAT	Integer	2	Base saturation as percentage of CECsoil
CECc	Single	4	CECclay, corrected for contribution of organic Matter ($cmol_c$ kg^{-1})
PHAQ	Single	4	pH measured in water
TCEQ	Single	4	Total carbonate equivalent (g kg^{-1})
GYPS	Single	4	Gypsum content (g kg^{-1})
ELCO	Single	4	Electrical conductivity (dS m^{-1})
TOTC	Single	4	Organic carbon content (g kg^{-1})
TOTN	Single	4	Total nitrogen (g kg^{-1})
ECEC	Single	4	Effective CEC ($cmol_c$ kg^{-1})

Notes:
1) These are depth-weighted values, per 20 cm layer.
2) Terrain Components, and their constituent Soil Components, within a given SOTER unit are numbered starting with the spatially dominant one (see Figure 6). The sum of the relative proportions of all Soil Components within a SOTER unit is always 100 per cent.
3) A condensed file showing only soil parameter estimates for the main Terrain Component (TCID= 1) and Soil Component (SCID =1) for the upper layer (D1) is attached as table SoterSummaryFile_T1S1D1 (see Figure7). This type of tables can be created directly in the GIS, in the table mode, using the SQL-connect option.

Appendix 5: Contents of GIS-folder

The primary SOTER-GIS coverage for Kenya, as taken from KSS (1995), and the soil parameter estimates are provided in one single zip file called: SOTWIS_Kenya_ver1.zip.

By default, the compressed file will be unzipped to folder X:\SOTWIS_Kenya_ver1.0. This folder contains:

1) The project's apr-file, called SOTWIS_Kenya_01.apr. This file can best be accessed from within ArcView.
2) The SOTER shape, legend and documentation files for Kenya, in three separate subfolders.

3) The access database containing the soil parameter estimates (SOTWIS_Kenya_1.mdb; see Appendices 1 to 4 in ISRIC Report 2004/01).

The first time the project is loaded on a new system, the new folder settings will be automatically updated in the apr-file.

Different SQL queries will be needed depending on the applications or models. The current project file only shows a limited number of selections for the upper soil layer (D1= 0 to 20 cm or less for shallow soils) of the dominant soil of a SOTER unit, as required by the RothC and Century models. These are: content of organic carbon; content of inorganic carbon; bulk density; content of clay; content of coarse fragments, and soil drainage class.

Should other selections be needed, the underlying Access database can be easily queried via the SQL-connect option of ArcView.

If grid-based soil layers are required, these can be generated using the convert-to-grid module of the spatial analyst extension to ArcView (ESRI 1996). Gridding should be based on the NEWSUID field to permit subsequent linkage with the various attribute tables discussed in this report.

The project file was developed for a 17 inch screen.

Appendix 6: Limits for soil textural classes

The textural classes (PSCL, see Appendix 2 and 4) used in this study follow the criteria of FAO (1988) and CEC (1985). The following abbreviations are used: C–coarse, M–medium, Z–medium fine, F–fine and V–very fine. The symbol # is used for undifferentiated (i.e. C + M + F + Z + V). The class limits are shown in Appendix 6.

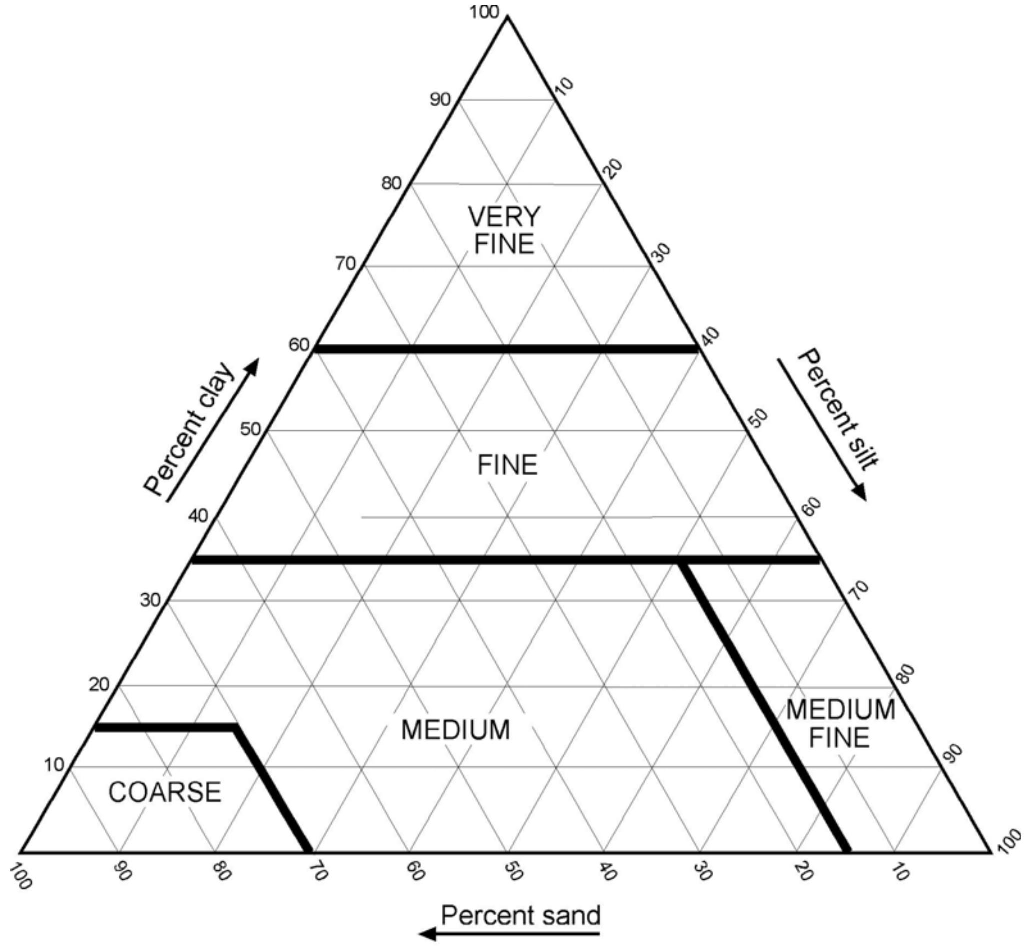

Figure 8. Soil texture classes