Report 2008/05

Soil parameter estimates for Senegal and The Gambia derived from SOTER and WISE

(SOTWIS-Senegal, version 1.0)

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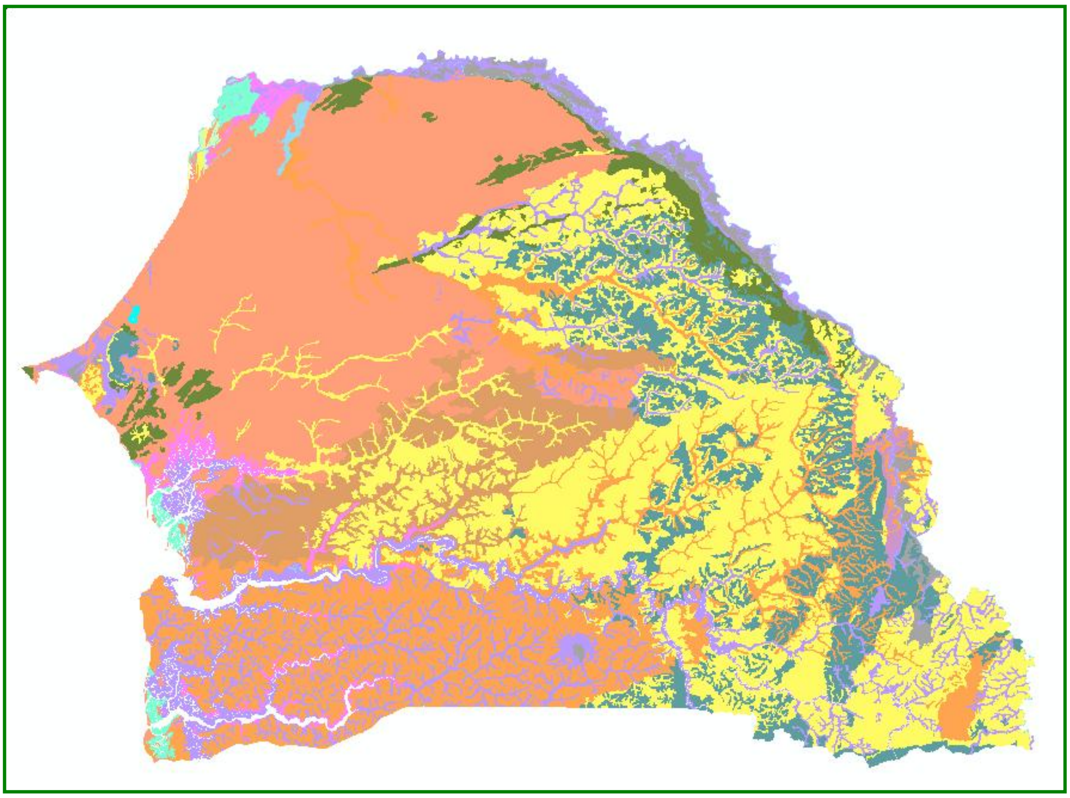
(November 2008)



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Front cover: Dominant major soil groups (FAO 1990) mapped for Senegal and The Gambia in SOTER.

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SUMMARY

This report describes a harmonized set of soil parameter estimates for Senegal and the Gambia. The data set was derived from the 1:1 million scale Soil and Terrain Database for the region (SENSOTER, ver. 1.0) and the ISRIC-WISE soil profile database, using standardized taxonomy-based pedotransfer (taxotransfer) procedures.

The land surface of Senegal and the Gambia, covering some 208 000 km^2, has been characterized using 149 unique SOTER units. Each SOTER unit consists of up to four different soil components. In so far as possible, each soil component has been characterized by a regionally representative profile, selected and classified by national soil experts. Conversely, in the absence of any measured legacy data, soil components were characterized using synthetic profiles for which only the FAO-Unesco (1988) classification is known.

Soil components in SENSOTER have been characterized using 90 profiles of which 34 are synthetic. The latter represent some 37 per cent of the territory. Comprehensive sets of measured attribute data are not available for most of the measured profiles (56) collated in SENSOTER. Consequently, to permit modelling, gaps in the soil analytical data have been filled using consistent taxotransfer procedures. Modal soil parameter estimates necessary to populate the taxotransfer procedure were derived from statistical analyses of soil profiles held in the ISRIC-WISE database — the current procedure only considers profiles in WISE that have FAO soil unit names identical to those mapped for the study area (41) and that originate from the Tropics (*n*= 4510).

Parameter estimates are presented for 18 soil variables by soil unit for fixed depth intervals of 0.2 m to 1 m depth: organic carbon, total nitrogen, pH(H_2O), CEC_{soil}, CEC_{clay}, base saturation, effective CEC, aluminium saturation, $CaCO_3$ content, gypsum content, exchangeable sodium percentage (ESP), electrical conductivity (ECe), bulk density, content of sand, silt and clay, content of coarse fragments (> 2 mm), and volumetric water content (-33 kPa to -1.5 MPa). 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 studies of global environmental change. Soil parameter estimates can be linked to the spatial data (map), using GIS, through the unique SOTER-unit code; database applications should consider the full map unit composition and depth range.

The derived data presented here can be used for exploratory assessments at national scale (1:1 000 000). They should be seen as best estimates based on the current selection of soil profiles in SENSOTER and data clustering procedure — the type of taxotransfer rules used to fill gaps in the measured data has been flagged to provide an indication of confidence in the derived data.

Keywords: legacy soil data, taxotransfer procedures, soil parameter estimates, secondary data set, Senegal, The Gambia, WISE database, SOTER database

1 INTRODUCTION [1]

ISRIC, FAO and UNEP, under the aegis of the International Union of Soil Sciences (IUSS), are updating the information on world soil resources in the World Soils and Terrain Digital Databases (SOTER) project. Once global coverage has been attained, a global SOTER is to supersede the 1:5 million scale Soil Map of the World (Nachtergaele and Oldeman 2002; Oldeman and van Engelen 1993).

SOTER databases are composed of two main elements: a geographic and an attribute data component. 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. Methodological details may be found in the SOTER Procedures Manual (van Engelen and Wen 1995).

Soil components of individual SOTER units are characterized by a representative soil profile (Figure 1). These legacy data are selected from available soil survey reports, as the SOTER program does not involve new ground surveys. As a result, there are often gaps in the measured (i.e. *primary*) analytical data, in particular the soil physical data. This precludes the direct use of *primary* SOTER data in models. ISRIC has therefore developed a uniform, consistent methodology for filling common gaps in *primary* SOTER databases to produce *secondary* (SOTWIS) data sets for general-purpose applications (Batjes 2003; Batjes *et al.* 2007). This taxotransfer rule-based procedure draws heavily on soil analytical held in the ISRIC-WISE soil profile database (see Batjes *et al.* 2007). So far, the consistent taxotransfer procedure has been applied to SOTER data for Latin America and the Caribbean, Central and Eastern Europe, Southern Africa, Central Africa and other areas with SOTER-like databases (see www.isric.org for details). The approach has also been used in support of the Harmonized World Soil Database (FAO *et al.* 2008).

[1] *All reports that describe secondary SOTER (SOTWIS) databases have similar structure and content, the main difference being the region-specific information presented in each document [NHB].*

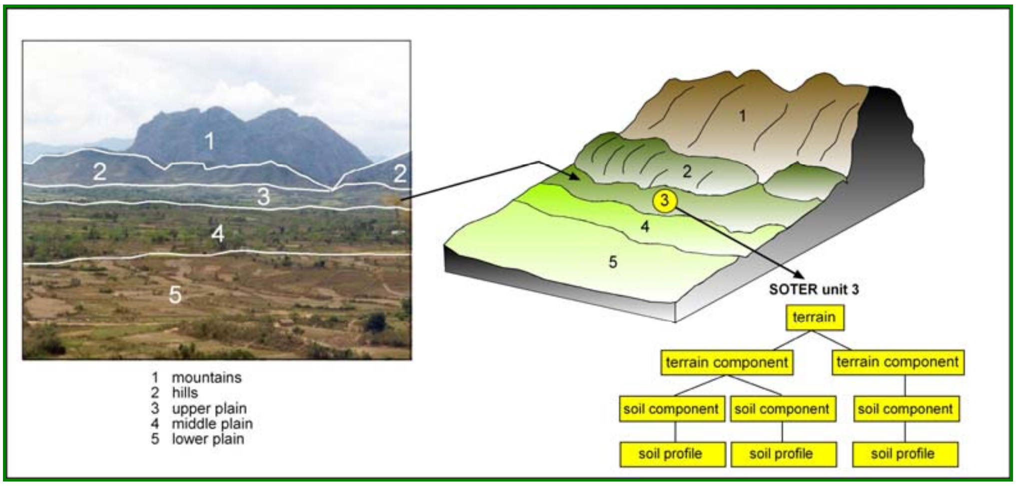

Figure 1. Representation of SOTER units and their conceptual structure

This report discusses the application of the taxotransfer procedure to the *primary* SOTER data for Senegal and the Gambia (hereafter referred to as SENSOTER). Chapter 2 describes the materials and methods with special focus on the procedure for preparing the *secondary* SOTER data. Results are discussed in Chapter 3, while concluding remarks are drawn in Chapter 4. The structure of the various output tables and installation procedure are documented in the Appendices.

2 MATERIALS AND METHODS

2.1 Source of primary SOTER data

Release 1.0 (Oct. 2008) of the SOTER database covering Senegal and The Gambia, compiled in the framework of the Global Assessment of Land Degradation and Improvement (GLADA), provided the basis for this study (see Dijkshoorn *et al.* 2008). The available soil geographical and attribute data were collated into SOTER format in close collaboration with the Institut National de Pédologie, Dakar. Although the map has a generalized scale of 1:1 million, the detail and quality of the primary information varies widely within the study area. Most soil profile data, for example, originated from surveys carried out in the western part of Senegal (Figure 1). Conversely, there are few profile observations for the eastern section of Senegal in the data set. Further, there are no profile data for The Gambia in SENSOTER.

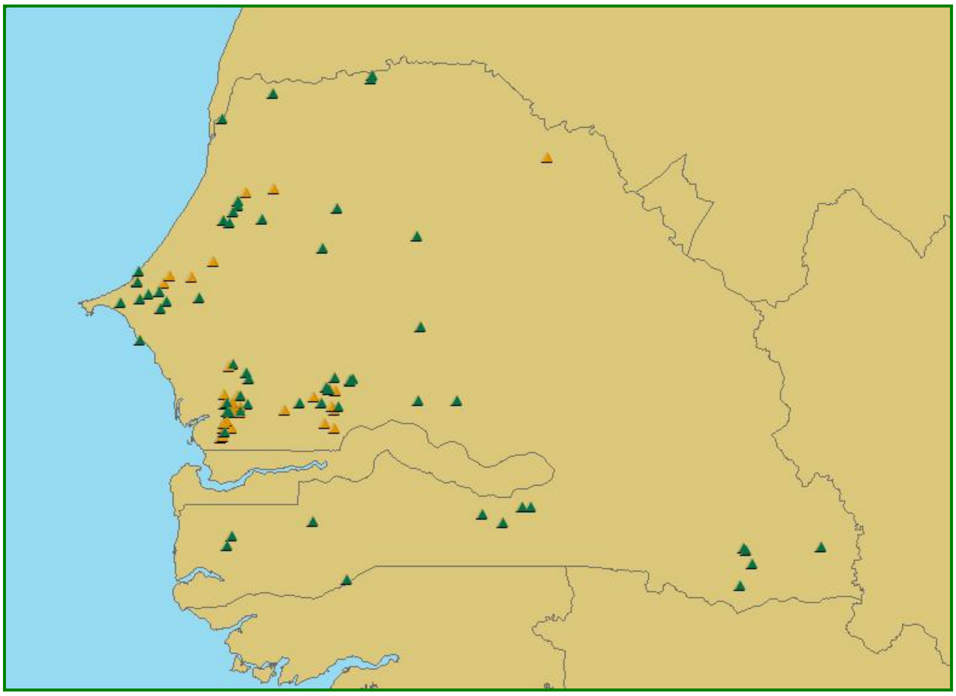

Figure 2. Distribution of measured soil profiles in SENSOTER[2]

[2] Soil profiles that are linked to SOTER units are coded in green; brown codes refer to auxilliary profiles stored in SENSOTER.

All profiles in SENSOTER were characterised according to the Revised Legend of FAO (1988) and World Reference Base for Soil Resources (FAO 2006). The Revised Legend, however, was used to display/map the soil units using GIS to ensure global consistency with earlier SOTER databases (e.g. FAO and ISRIC 2003; FAO *et al.* 1998).

2.2 Preparation of secondary SOTER data

2.2.1 Checking of primary data

A preliminary version of the *primary* SOTER database was first screened using automated integrity checks developed for WISE (Batjes 1995). These procedures revealed several inconsistencies which would preclude the application of the taxotransfer procedure. Consequently, staff at the Institut National de Pédologie (Dakar) were contacted to remedy these errors. The resulting SENSOTER database (Dijkshoorn *et al.* 2008) provided the basis for the current study. It should be noted, however, that identical ISO codes are used for adjoining map units from Senegal and The Gambia in SENSOTER — this inconsistency in SOTER coding, however, was maintained here as it would not affect the results of the pedotransfer procedure.

The screened dataset includes 90 profiles, consisting of 56 real profiles and 34 virtual profiles; all these profiles are physically linked to the spatial data in accord with SOTER standards. The average density of measured profiles is 0.28 per 1000 km^2; this may be termed low for exploratory surveys (see Landon 1991).

In accord with SOTER conventions (van Engelen and Wen 1995), so-called virtual profiles have been introduced when the FAO classification for a given soil unit was known from soil maps (e.g. Stancioff *et al.* 1984), but there are no real profiles (i.e. measured data) to characterize these units. For each virtual profile, the soil drainage class was inferred using expert judgement. Similarly, a default depth of 100 cm has been assumed for all virtual profiles, except for those representing Leptosols for it was set at 50 cm. Further, the content of organic carbon was arbitrarily set at 4 g OC kg^{-1} for 0-20 cm and at 1 g OC kg^{-1} below this depth for all for LPq and LPk units.

Figure 3 shows which proportion of the SENSOTER map has been characterized using synthetic profiles, corresponding with some 37% of the study area. The largest area represented by a single profile corresponds with some 12% of the area (profile *SNORSTOM/MKE53*). Conversely, 46 out of the 90 profiles each represent less than 0.5% of the study area (< 1000 km^2) each.

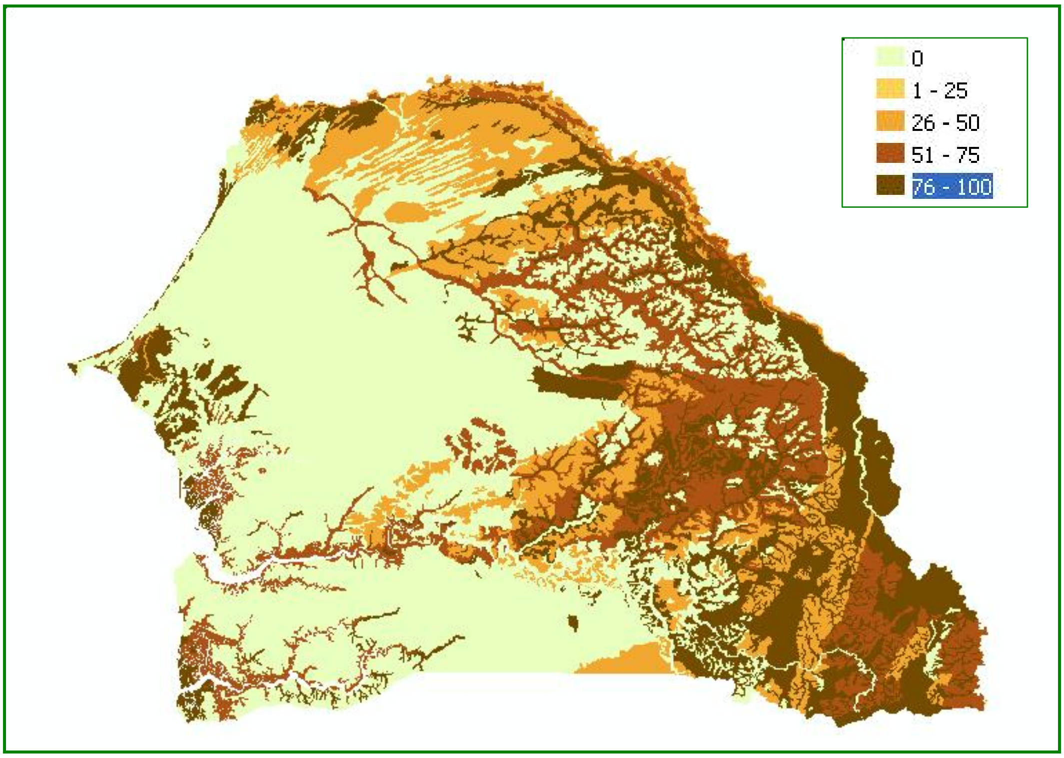

Figure 3. Relative area (%) of SOTER units in Senegal and The Gambia characterized by synthetic profiles

Fourteen units on the map correspond with miscellaneous units such as marshes (vasières) and quarries — these are only characterized in the GIS-file.

2.2.2 Filling gaps in the measured soil data

Being based on available soil survey reports, there are always gaps in the soil analytical data — the limited set of so-called "mandatory SOTER attributes" simply is not available for most profiles in SENSOTER.

Gaps in the attribute data were filled here using consistent taxotransfer procedures (Batjes 2003; Batjes *et al.* 2007). The soil variables considered in the procedure are detailed in Section 2.3.3. The soil parameter estimates required to run these procedures were derived from statistical analyses of 4510 profiles extracted from version 3.0 of the ISRIC-WISE database. This selection only included those profiles in WISE that: a) have similar FAO (1988) classification as mapped for SENSOTER (Table 1) and b) originate from the Tropics, broadly defined here as the region bounded by latitude 23.5° N and 23.5 ° S.

Table 1. FAO soil units mapped in SENSOTER and number of similar soil profiles in WISE used for taxotransfer rule development

FAO soil units	SENSOTER [a]	WISE [b]
Acf	4 (3/1)	265
Acg	1 (1/0)	43
Ach	3 (2/1)	392
Acp	2 (1/1)	89
Ara	1 (1/0)	31
Arb	2 (1/1)	57
Arc	1 (1/0)	49
Arg	1 (0/1)	54
ARh	8 (7/1)	239
ARl	2 (2/0)	163
ARo	3 (2/1)	145
CMc	1 (0/1)	134
CMd	1 (0/1)	86
Cme	1 (0/1)	206
CMg	1 (0/1)	94
CMo	1 (0/1)	156
CMv	1 (0/1)	61
CMx	1 (0/1)	56
FLe	3 (2/1)	161
FLs	1 (0/1)	6
FLt	4 (3/1)	43
FRh	1 (0/1)	213
GLd	2 (1/1)	87
GLe	9 (8/1)	201
GLk	1 (0/1)	8
GLu	1 (0/1)	45
LPd	1 (0/1)	66
LPe	2 (0/2)	70
LPk	1 (0/1)	12
LPq	1 (1/0)	13
LXf	8 (7/1)	185

FAO soil units	SENSOTER [a]	WISE [b]
LXg	1 (1/0)	35
LXh	1 (1/0)	216
RGd	4 (3/1)	61
Rge	5 (3/2)	167
SCg	2 (1/1)	24
SCh	1 (1/0)	24
SNg	1 (0/1)	43
SNh	1 (0/1)	79
Vre	2 (1/1)	312
VRk	2 (2/0)	119

[a] First number is for total number of soil profiles linked to the SENSOTER map units; the first number in brackets is for measured profiles, the second for virtual profiles (i.e. profiles for which there are no measured data; these have codes like Sn*syn*15 or SN*syn*LPe)

[b] Number of profiles from WISE considered in the taxotransfer scheme (n = 4510)

Measured values in WISE that underlie the taxotransfer scheme — like those held in SENSOTER — will reflect both variations inherent to the soil unit and those that can be ascribed to the methods of sampling and measurement. For reasons outlined earlier (Batjes 2002, p. 6-11), a pragmatic approach to the comparability of soil analytical data had to be adopted for use with small scale SOTER databases. A similar approach has been used with the Harmonized World Soil Database (FAO *et al.* 2008). This type of approach is considered appropriate for soil data applications at small scale, say 1 < 1:500 000 — correlation of soil analytical data, however, should be done more rigorously when more precise scientific research is considered.

The analytical data for each combination of soil unit, texture class and depth layer were screened using a robust outlier scheme, by attribute (see Batjes 2003). The output of the taxotransfer procedure has been stored in a *secondary* data set (known as SOTWIS database); for details see Appendix 1.

2.2.3 List of soil variables

Special attention has been paid to those key attributes (Table 2) that are commonly required in studies of agro-ecological zoning, food productivity, soil gaseous emissions/sinks and environmental change (see Batjes *et al.*

1997; Bouwman *et al.* 2002; Cramer and Fischer 1997; Easter *et al.* 2007; FAO *et al.* 2008; Fischer *et al.* 2002; Scholes *et al.* 1995).

Table 2. List of soil variables considered in secondary SOTER data sets

Organic carbon
Total nitrogen
Soil reaction (pH_{H2O})
Cation exchange capacity (CEC_{soil})
Cation exchange capacity of clay size fraction (CEC_{clay}) [a b]
Base saturation (as % of CEC_{soil}) [b]
Effective cation exchange capacity (ECEC) [b c]
Aluminium saturation (as % of ECEC) [b]
$CaCO_3$ content
Gypsum content
Exchangeable sodium percentage (ESP) [b]
Electrical conductivity (ECe)
Bulk density
Coarse fragments (> 2 mm, volume %)
Sand (mass %)
Silt (mass %)
Clay (mass %)
Available water capacity ($cm^3\ cm^{-3}\ 10^2$ or vol%; -33 kPa to -1.5 MPa) [b d]

[a] CEC_{clay} was calculated from CEC_{soil} by assuming a mean contribution of 350 $cmol_c$ per 100 g OC, the common range being from 150 to over 750 $cmol_c$ per 100 g (Klamt and Sombroek 1988). Similarly, as a rule of thumb, CEC_{OC} values of 300 to 400 $cmol_c$ per 100 g OC (NH_4OAc, pH 7.0), are used by USDA-NRCS (1995 p. 26).

[b] Calculated from other measured soil properties.

[c] ECEC is defined as exchangeable (Ca^{++}+ Mg^{++}+ K^++ Na^+) + exchangeable (H^++ Al^{+++}) (van Reeuwijk 2002).

[d] Limits for soil water potential for Available Water Capacity (AWC) conform to USDA standards (Soil Survey Staff 1983); these values are not corrected for volume percentage of coarse fragments.

Table 2 does not include soil hydraulic properties because measured data for the latter are generally lacking in the systematic soil survey reports that underlie SOTER and WISE.

3 RESULTS AND DISCUSSION

3.1 Map unit composition

The soil geographic and attribute data collated in SENSOTER represent a significant improvement on the information for the region on the 1:5 000 000 scale Soil Map of the World (FAO 1995), which only considers two profile descriptions for Senegal (FAO-Unesco 1977).

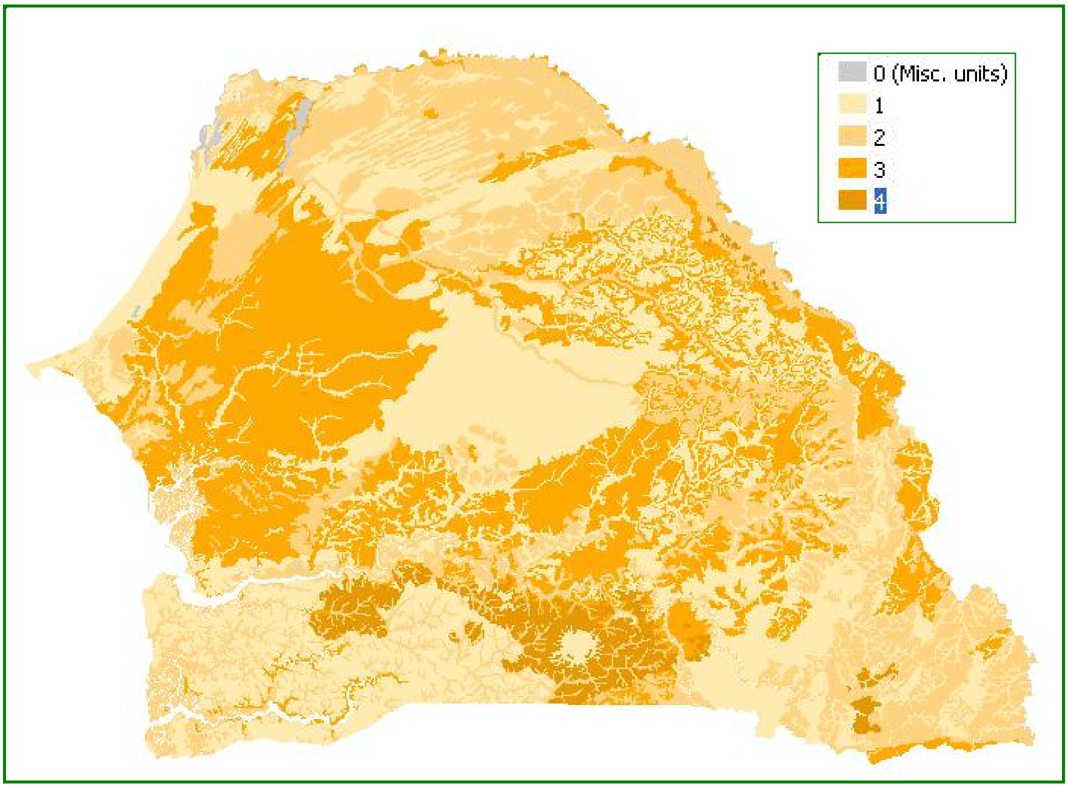

Figure 4. Number of soil components per SOTER unit

Senegal and The Gambia has been described using 274 unique map units or SOTER units in SENSOTER. These comprise 154 terrain components and 274 soil components. There are 2242 polygons on the map. At the small scale under consideration, most mapping units should be compound. About 56% of the map units have been mapped as single units, 32% as having 2 soil components, 11% as consisting of 3 soil components, and 1% as comprising 4 different soil units (i.e. soil components, see Figure 4). This map unit complexity must be considered when using the data; typically, this will have to be done using software, specifically written for a particular application (e.g. Batjes *et al.* 2007; Easter *et al.* 2007).

The full composition of each SOTER unit has been summarized in table *SOTERunitComposition* (Appendix 1). This table lists the name and relative area of the main major FAO soil group for each map unit, as well as the type and relative area of all the component soil units (Figure 5).

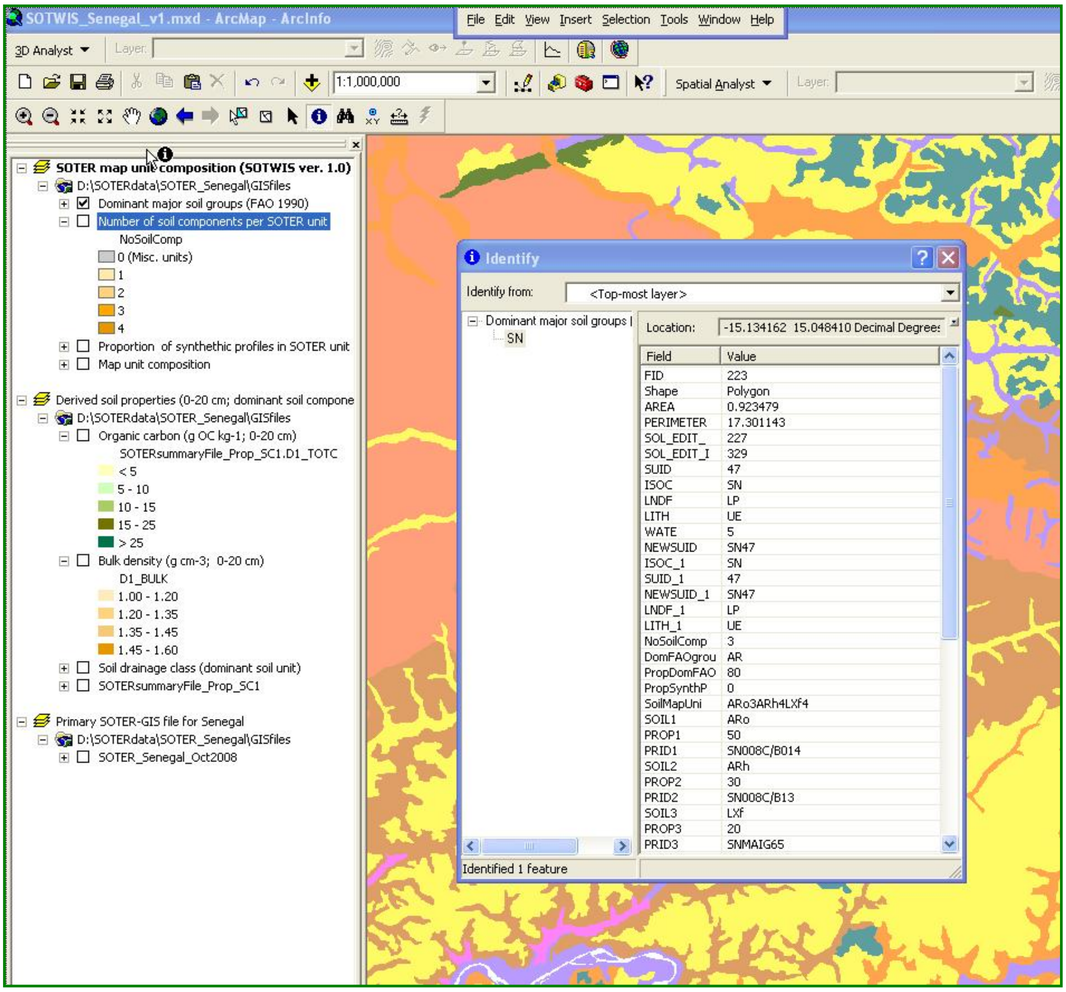

Figure 5. Complexity of SOTER mapping units

3.2 Soil Parameter estimates

The taxotransfer procedure generates soil parameter estimates for five standardized depth ranges of 20 cm each to 1 m, and 2 standardized depth ranges of 50 cm (100-150 cm and 150-200 cm) (see Batjes 2008). Inherently, parameter estimates for the deeper layers are considered less reliable than those for the upper layers of soil as they are based on less extensive data sets. Therefore, the current data set only holds derived data up to 1 m depth, or less when applicable (e.g. for shallow Leptosols).

In case of missing measured values in SOTER, the cut-off point for applying any taxotransfer rule is $n_{WISE} < 5$; that is there should be at least 5 cases in the WISE subset for the corresponding combination of soil unit, soil variable, soil layer, and soil textural class in order to apply the substitution procedure. Soil textural classes were defined in accordance with current SOTER standards – coarse, medium, fine, very fine and medium fine (see Fig. 8, Appendix 6). The taxotransfer procedure is summarized in Figure 6; see also Appendix 3.

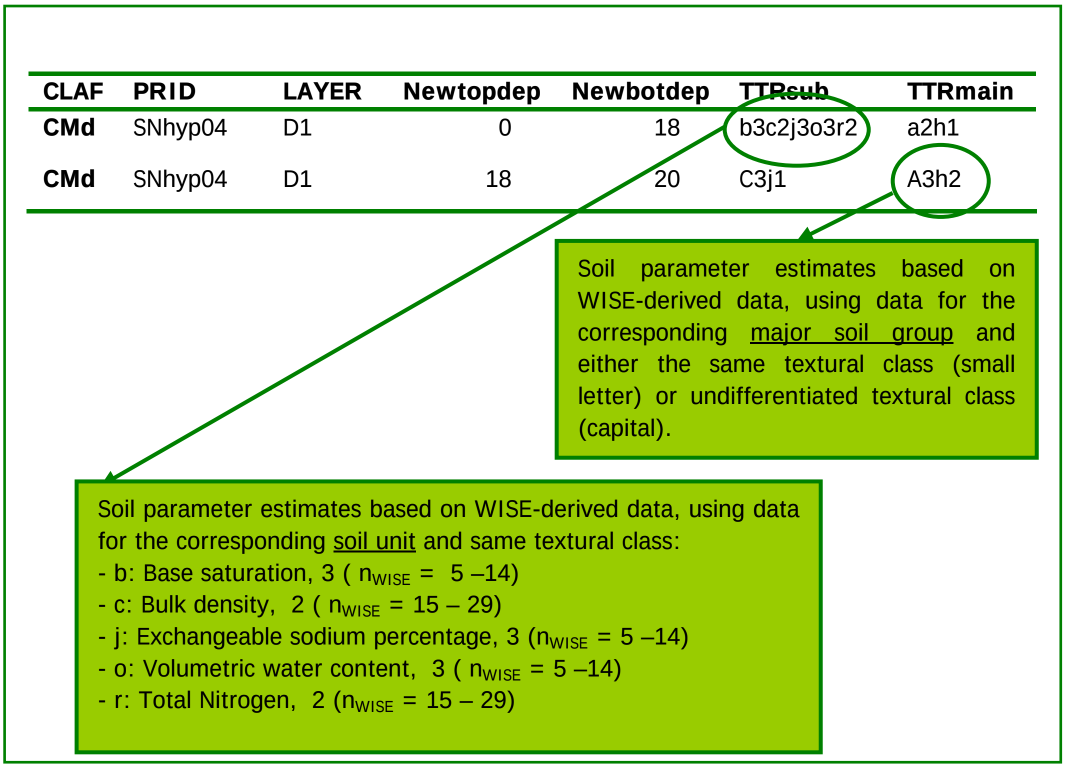

Figure 6. Schematic representation of taxotransfer procedure for filling gaps in SOTER

Each flag listed under *TTRsub* (where *sub* stands for FAO soil unit) and *TTRmain* (where *main* stands for major soil group) consists of a sequence of letters followed by a numeral, for example *A3h2*. The letters indicate soil attributes for which a taxotransfer rule has been applied; coding conventions are explained in Appendix 3. The number code reflects the size of the sample population in WISE, after outlier rejection, on which the statistical analyses that underlie taxotransfer scheme were based (Table 3).

Table 3. Criteria for defining confidence in the derived data

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

[a] n_{WISE} is the sample size after the screening or outlier rejection procedure
[b] The cut-off point in the TTR-approach is $n_{WISE} < 5$

When a *small letter* is used for *TTRsub*, the substitution was based on median data for the corresponding soil unit, depth layer and textural class (for example, Rhodic Ferralsols (FRr), 0-20 cm (D1), Fine and $n_{WISE} > 5$). Otherwise, when a *capital* is used, this indicates that the substitution for the given soil attribute was based on the whole set for the corresponding soil unit and depth layer, irrespective of soil texture (i.e. undifferentiated or *u*). The same coding conventions apply for TTRmain, but substitutions then consider derived soil data for the corresponding major FAO soil group.

Expert rules are applied after the taxotransfer rules to remedy possible pedological inconsistencies (or artefacts) thay may have arisen in the TTR-derived data. Such a check is necessary because individual TTR-rules do not consider possible co-relations between different soil variables. For example, one expert rule (XR-TCEQ) checks whether there are indeed no carbonates in acid soil layers (pH <5.5). Similarly, another expert rule (XR-BSAT) checks whether base saturation is low in acid soils and so on. In view of the diversity of soils worldwide, however, it remains difficult to account for all possible situations.

Derived soil data, resulting from the taxotransfer procedure, are presented in table *SOTERparameterEstimates*; see Appendix 2 for details.

3.3 Type and number or taxotransfer rules used

There are numerous gaps in the *primary* soil analytical data in SENSOTER (see 2.2.1). Table 4 lists how often each *taxotransfer* respective or *expert*-rule has been applied for each attribute as a percentage of the total number of "horizon/layer/depth" combinations in the *secondary* SOTER or SOTWIS set; details may be found in table *SOTERflagTTRrules* (Appendix 3).

Table 4. Type and frequency of taxotransfer rules (TTR) and expert rules (XR) applied

TTR code (SOTNAM)	Frequency of occurrence (%)			
	TTRsub	TTRmain	TTRtotal	Expert rules
TTR-ALSA	55	23	78	-
TTR-BSAT	55	2	57	-
TTR-BULK	95	5	100	-
TTR-TCEQ	71	1	72	-
TTR-CECS	48	1	49	-
TTR-CFRAG	76	20	96	-
TTR-CLAY	39	0	39	-
TTR-ECEC	85	2	87	-
TTR-ELCO	31	12	43	-
TTR-ESP	57	3	60	-
TTR-GYPS	27	23	50	-
TTR-PHAQ	37	0	37	-
TTR-SAND	39	0	39	-
TTR-SILT	39	0	39	-
TTR-AWC	51	42	93	-
TTR-TCEQ	38	15	53	-
TTR-TOTC	56	0	56	-
TTR-TOTN	57	2	59	-
XR-Alsa	-	-	-	22
XR-Bsat	-	-	-	4
XR-Elco	-	-	-	71
XR-Gyps	-	-	-	27
XR-Tceq	-	-	-	44
XR-CECc	-	-	-	18
XR-ESP	-	-	-	0
XR-Cfrag	-	-	-	0
XR-Bulk	-	-	-	0
XR-AWC	-	-	-	7

Note: For definitions of abbreviations see text and Table 4, see also Appendix 3; '-' stands for not applicable.

Table 4 shows, for example, that available water capacity (AWC) has been estimated in 93% of the cases using data for similar soil units (51% of cases, see under TTRsub) resp. similar major soil groups (42%). Further, expert rules for available (XR-AWC) have been applied in 7% of the cases. Similarly, all bulk density data had to be derived using taxotransfer rules in view of the absence of any measured bulk density data in SENSOTER.

3.4 Assumptions and limitations

Soil unit classifications (FAO 1988), as presented in the *primary* SENSOTER database, were taken at face value. Soil experts, however, may classify the same soil profile differently when the available soil morphological and soil analytical data are 'limited' and subjective assumptions have to be made (e.g., Goyens *et al.* 2007; Kauffman 1987; Spaargaren and Batjes 1995). The soil classification code, however, is the primary driver of the taxotransfer procedure (see 2.2.2).

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

A high confidence rating for a given parameter estimate, however, does not necessarily imply that this estimate will be representative for the soil unit under consideration. Profile selection for SOTER and WISE, as for many other small-scale soil databases, is not probabilistic, but based on available data and expert knowledge. Several of the soil attributes under consideration in Table 2 are not diagnostic in the Revised Legend (FAO 1988). In addition, some soil properties are readily modified by changes in land use or management, for example soil pH, aluminium saturation, soil salinity, and organic matter content. Information on land use/management history by profile, however, is not available in SOTER and, as such, this aspect could not be considered explicitly in the taxotransfer procedure.

Finally, it should be noted that adoption of different criteria for clustering data would inherently lead to varying parameter estimates. For example, selecting a different soil classification system (e.g., FAO 1974, FAO 1988 or WRB 2006), limits for depth layers (e.g., 0-20 cm intervals up to 100 cm *versus* 0-30 cm and 30-100 cm), criteria for defining soil textural classes (e.g., 5 classes in SOTER *versus* 3 classes for the FAO Soil Map of the World), choice of critical limits for applying taxotransfer rules (i.e. reject when $n_{WISE} < 5$ or $n_{WISE} < 15$), as well as the type of outlier-rejection and statistical procedures used, and the number of WISE profiles under consideration. Most importantly, however, the outcome will primarily be determined by the number and quality of the legacy profile data collated in the underpinning, *primary* SOTER database. In particular their geographic distribution over the region respectively various SOTER units, the degree to which the various data-fields have been filled, and the overall comparability of analytical methods used.

3.5 Linkage to GIS

SOTER units mapped for the region comprise up to four soil components. The full map unit composition has been summarized in one single table (*SOTERunitComposition*, see Appendix 1). Results of the taxotransfer procedure for each soil component, as typified by the representative profile, are stored in table *SOTERparameterEstimates* (Appendix 2). Results in this table have been linked to the corresponding SOTER units in two tables having the same content, but different data structures: a) *SOTERsummaryFile*, in which data by layer (D_i) are presented vertically by *NEWSUID*, *TCID* and *SCID* (Appendix 4), and b) *SOTERsummaryFile_Prop* in which derived data for layer D_1 to D_5 are data presented horizontally by *NEWSUID*, TCID and SCID (Appendix 5).

Data in the later tables can be linked to GIS through *NEWSUID*, the unique SOTER map unit code. It should be noted, however, that GIS can only be used to display one "set of attributes" at a time per polygon or SOTER map unit. For example, derived topsoil properties for the dominant soil component in a SOTER unit (i.e. TCID=1, SCID=1 and Layer= D1) — the overall procedure is visualized in Figure 7 for a hypothetical database.

Typically, specific data selections that consider the full soil unit composition of individual SOTER units will have to be made before 'aggregated' model output can be coupled back to the GIS. Details of such an approach may be found in Easter et al. (2007).

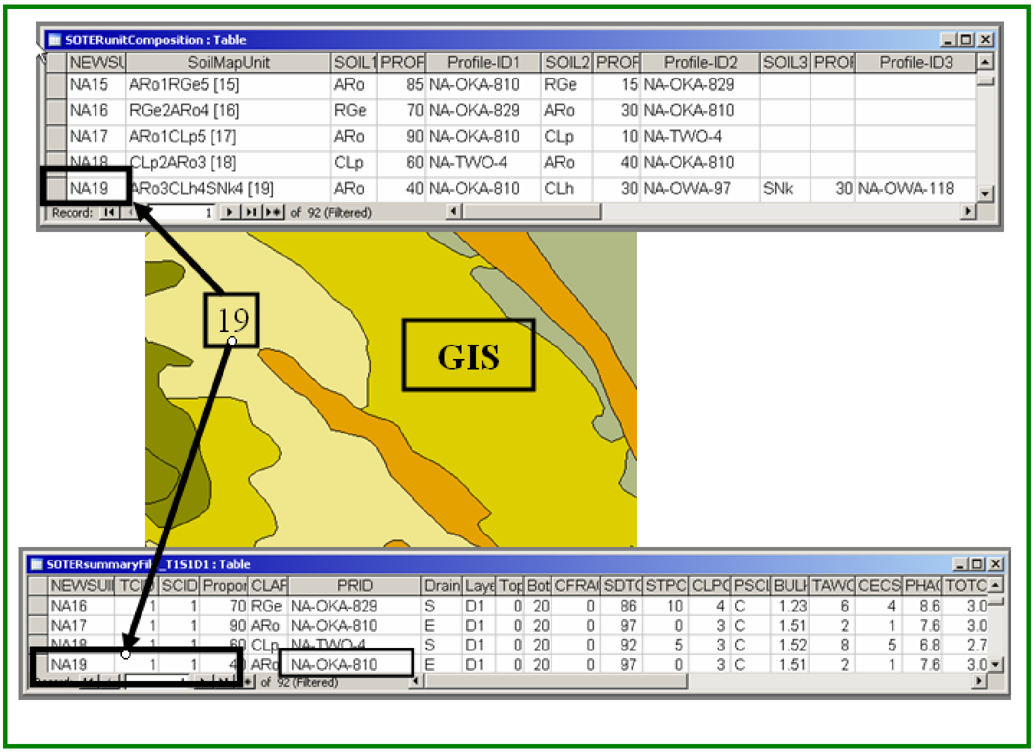

Figure 7. Schematized procedure for linking soil parameter estimates for the upper layer (D1) of the main soil unit (TCID=1; SCID=1) of a SOTER map unit with the geographical data

4 CONCLUSIONS

- The soil geographic and profile data collated in SENSOTER represent a substantial improvement of the information for Senegal and The Gambia as presented on the 1:5M scale FAO-Unesco Soil Map of the World.
- The detail and quality of primary soil and terrain data underpinning SENSOTER resulted in a variable resolution of the secondary product presented here.
- Linkage between the soil profile data and the spatial component of SENSOTER required generalisation of measured soil (profile) data by soil unit and depth zone. This involved the transformation of variables that show a marked spatial and temporal variation and that 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 when developing the taxotransfer procedure. Although this is considered appropriate at the present scale (1:1 000 000), such a comparison must be done more rigorously when more detailed scientific work is considered.
- The derived soil data presented here can be used for exploratory assessments at national scale — they should be seen as best estimates based on the current selection of soil profiles in SENSOTER and data clustering procedure.
- End-users should familiarize themselves with the procedures and assumptions that have been used to derive the soil parameter estimates prior to using them in models — possible uncertainties are documented in the data set.

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APPENDICES

Appendix 1. Structure of table SOTERunitComposition

Table *SOTERunitComposition*, in MS-Access® format, gives the full composition of each SOTER unit in terms of its: landform, lithology (parent material), dominant major FAO soil group and its relative extent, then component in soil units with their relative extent, and the identifier for the corresponding representative profile. The relevant information was distilled from three primary SOTER tables, *viz. Terrain*, *SoilComponent*, and *Profile*, to facilitate data processing. The content of this table can be linked to the geographical data in a GIS through the unique SOTER unit code or NEWSUID, a combination of the fields for ISO and SUID.

Structure of table SOTERunitComposition[a]

Name	Type	Description
ISOC	Text	ISO-3166 country code (1994) or WD for World
SUID	Integer	The identification code of a SOTER unit on the map and in the database
NEWSUID	Text	Globally unique code for SOTER unit, comprising fields ISOC plus SUID (e.g. SN15 or GM03)
LNDF	Text	Code for SOTER landforms (see SOTWIS_codes)
LITH	Text	Code for SOTER lithology (See SOTWIS_codes)
NoOfSoilComp	Text	Number of soil components in given SOTER unit
DomFAOgroup	Text	Dominant FAO major soil group in SOTER (Note: This need not always be SOIL1)
PropDomFAOGroup		Proportion of dominant major soil group in SOTER unit (%)
PropSynthProf		Proportion of SOTER unit characterized by a synthethic profile (%)
SoilMapunit	Text	Aggregated code for map unit summarizing the overall composition [b]
SOIL1	Text	Characterization of the first (main) soil unit according to the Revised FAO-Unesco Legend
PROP1	Integer	Proportion, as a percentage, that the main soil unit occupies within the SOTER unit
PRID1	Text	Unique code for the corresponding measured resp. virtual soil profile (e.g. SNsynRGd)
SOIL2	Text	As above but for the next soil unit
PROP2	Integer	As above
PRID2	Text	As above
SOIL3	Text	As above but for the next soil unit
PROP3	Integer	As above
PRID3	Text	As above

Name	Type	Description
SOIL4	Text	As above but for the next soil unit
PROP4	Integer	As above
PRID4	Text	As above
SOIL5	Text	As above but for the next soil unit
PROP5	Integer	As above
PRID5	Text	As above
SOIL6	Text	As above but for the next soil unit
PROP6	Integer	As above
PRID6	Text	As above
SOIL7	Text	As above but for the next soil unit
PROP7	Integer	As above
PRID7	Text	As above
SOIL8	Text	As above but for the next soil unit
PROP8	Integer	As above
PRID8	Text	As above
SOIL9	Text	As above but for the next soil component
PROP9	Integer	As above
PRID9	Text	As above
SOIL10	Text	As above but for the next soil component
PROP10	Integer	As above
PRID10	Text	As above

[a] Generally, not all 10 available fields for $SOIL_i$ will be filled in SOTER. In the case of Senegal, up to 4 different soil components have beend defined for each map unit.

[b] These codes have the following format: VRe2GLe4. The relative extent of each soil unit (e.g., VRe) 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.

Appendix 2. Structure of table SOTERparameterEstimates

Table SOTER*parameterEstimates* lists parameter estimates — depth-weighted by layer — for all soil units (represented by their PRID) that have been mapped for the study region. This information can be linked to the soil geographical data – in a GIS – through the unique profile code (PRID).

Structure of table SOTER*parameterEstimates*

Name	Type	Description
CLAF	Text	FAO-Unesco (1988) Revised Legend code
PRID	Text	profile ID (as listed in *SOTERmapunitComposition*)
Drain	Text	FAO soil drainage class
Layer	Text	code for depth layer (from D1 to D5; e.g. D1 is from 0 to 20 cm etc.)
TopDep	Integer	depth of top of layer (cm)
BotDep	Integer	depth of bottom of layer (cm)
CFRAG	Integer	coarse fragments (vol.% > 2 mm)
SDTO	Integer	sand (mass %)
STPC	Integer	silt (mass %)
CLPC	Integer	clay (mass %)
PSCL	Text	SOTER texture class (see Appendix 6)
BULK	Single	bulk density (kg dm^{-3})
TAWC	Integer	available water capacity (cm^3 cm^{-3} 10^2, -33 kPa to -1.5 MPa conform to USDA standards)
CECs	Single	cation exchange capacity ($cmol_c$ kg^{-1}) for fine earth fraction
BSAT	Integer	base saturation as percentage of CEC_{soil}
ESP	Integer	exchangeable Na as percentage of CEC_{soil}
CECc	Single	CECclay, corrected for contribution of organic matter ($cmol_c$ kg^{-1}) [a]
PHAQ	Single	pH measured in water
TCEQ	Single	total carbonate equivalent (g C kg^{-1})
GYPS	Single	gypsum content (g kg^{-1})
ELCO	Single	electrical conductivity (dS m^{-1})
TOTC	Single	organic carbon content (g C kg^{-1})
TOTN	Single	total nitrogen (g N kg^{-1})
ECEC	Single	effective CEC ($cmol_c$ kg^{-1})
ALSA	Integer	exchangeable AL as percentage of ECEC

[a] CECclay is only calculated for layers where clay content >5%; else CEC_{clay} is set at -9 (see Appendix 3).

Contents of table SOTER*parameterEstimates* should be consulted in conjunction with table *SOTERflagTTRrules.* The later lists the taxotransfer rules that have been applied for each profile, by depth layer and soil attribute. Details are given in Appendix 3.

Appendix 3. Structure of table SOTERflagRules

Table SOTER*flagTTRrules* documents the type of taxotransfer rules that have been used to create table *SOTERparameterEstimates* (Appendix 2). Coding conventions are detailed in Table 5.

Structure of table *SOTERflagTTRrules*

Name	Type	Description
CLAF	Text	FAO Legend code
PRID	Text	Unique identifier for representative profile
Layer	Text	code for depth layer (from D1 to D5; e.g. D1 is from 0 to 20 cm)
Newtopdep	Integer	Depth of top of layer (cm)
Newbotdep	Integer	Depth of bottom of layer (cm)
TTRsub	Text	Code showing the type of taxotransfer rule used (based on derived data for *soil units*; see text)
TTRmain	Text	Code showing the type of taxotransfer rule used (based on derived data for *major units*; see text)
TTRexpert	Text	Additional flags (based on expert-rules)

Note: Expert rules (TTRexpert) are run after the TTR-procedures (see text). For example, exchangeable aluminium percentage (ALSA) has been set at zero when pH_{water} is higher than 5.5. Similarly, the 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 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, the common range being from 150 to over 750 $cmol_c$ per 100 g (Klamt and Sombroek 1988) — CEC_{clay} values presented here thus are only rough estimates.

Table 5. Conventions used for coding soil attributes in the taxotransfer scheme

TTRflag	SOTnam	WISnam	SoilVariable	Comments
A	ALSA	ALSA	ALSAT	Exch. Aluminum percentage (% of ECEC)
B	BSAT	BSAT	BSAT	base saturation (% of CECs)
C	BULK	BULK	BULKDENS	Bulk density
D	CECC	CECC	CECCLAY	cation exchange capacity of clay fraction
E	CECS	CECS	CECSOIL	cation exchange capacity
F	CFRAG	GRAV	GRAVEL	coarse fragments
G	CLPC	CLAY	CLAY	clay %
H	ECEC	ECEC	ECEC	Effective CEC
I	ELCO	ECE	ECE	electrical conductivity

TTRflag	SOTnam	WISnam	SoilVariable	Comments
J	ESP	ESP	ESP	exchangeable Na percentage (% of CECs)
K	GYPS	GYPS	GYPSUM	gypsum content (g C kg^{-1})
L	PHAQ	PHH2	PHH2O	pH in water
M	SDTO	SAND	SAND	sand %
N	STPC	SILT	SILT	silt %
O	TAWC	TAWC	TAWC	Vol. water content (-33 kPa to -1.5 MPa)
P	TCEQ	CACO	CACO3	carbonate content (g kg^{-1})
Q	TOTC	ORGC	ORGC	organic carbon content (g C kg^{-1})
R	TOTN	TOTN	TOTN	total nitrogen content (g N kg^{-1})
Y	---	---	---	PSCL estimated from TTR-derived sand, silt and clay content (where applicable)

Abbreviations: TTRflag = code for TTR-rule; SOTnam = codes used in SOTER; WISnam= codes used in WISE; SoilVariable= soil variables as described in Table 2 (page 8).

Appendix 4. Structure of table SOTERsummaryFile

Table *SOTERsummaryFile* has been created to facilitate access to the derived data. For each SOTER unit (NEWSUID) on the map, it lists the soil parameter estimates by component soil unit and depth layer.

Layer data are presented in one single column, i.e. vertically(see also Appendix 5).

Structure of table SOTER*summaryFile*

Name	Type	Description
ISOC	Text	ISO-3166 country code (1994)
SUID	Integer	The identification code of a SOTER on the map and in the database
NEWSUID	Text	Globally unique map unit code, comprising fields ISOC plus SUID
TCID	Integer	Number of terrain component in given map unit
SCID	Integer	Number of soil unit within the given SOTER unit
Layer	Text	Code for depth layer (from D1 to D7; e.g., D1 is from 0 to 20 cm and D7 from 150 to 200 cm)
PROP	Integer	Relative proportion of SCID in given SOTER unit
CLAF	Text	FAO-Unesco Revised Legend code
PRID	Text	Profile ID (see table *SOTERunitComposition*)
Drain	Text	FAO soil drainage class
TopDep	Integer	Upper depth of layer (cm)
BotDep	Integer	Lower dept of layer (cm)
CFRAG	Integer	Coarse fragments (vol. % > 2 mm)
SDTO	Integer	Sand (mass %)
STPC	Integer	Silt (mass %)
CLPC	Integer	Clay (mass %)
PSCL	Text	FAO texture class (see Appendix 6)
BULK	Single	Bulk density (kg dm^{-3})
TAWC	Integer	Available water capacity (cm^3 cm^{-3} 10^2 or vol%, -33 kPa to -1.5 MPa)
CECS	Single	Cation exchange capacity ($cmol_c$ kg^{-1}) of fine earth fraction
BSAT	Integer	Base saturation as percentage of CECsoil
ESP	Integer	Exchangeable Na as percentage of CECsoil
CECc	Single	CEC_{clay}, corrected for contribution of organic matter ($cmol_c$ kg^{-1})
PHAQ	Single	pH measured in water
TCEQ	Single	Total carbonate equivalent (g C kg^{-1})
GYPS	Single	Gypsum content (g kg^{-1})

Name	Type	Description
ELCO	Single	Electrical conductivity (dS m^{-1})
TOTC	Single	Organic carbon content (g kg^{-1})
TOTN	Single	Total nitrogen (g kg^{-1})
ECEC	Single	Effective CEC ($cmol_c$ kg^{-1})
ALSA	Integer	Exchangeable Al as percentage of ECEC

Notes:

1) The soil components that occur within a SOTER unit are numbered sequentially, starting with the spatially dominant one. The sum of the relative proportions of all component soil units is always 100 per cent. This total will also include a number of unnamed 'impurities', commonly in excess of 15 to 30 percent of the map unit (Landon 1991 p. 16-17; Marsman and de Gruijter 1986).
2) Each map unit in the geographic database has a unique identifier (NEWSUID) consisting of the country ISO code (ISOC) and the SOTER unit-ID (SUID); this primary key provides a link to the attribute data for the constituent terrain, terrain component(s) (TCID) and soil components (SCID) (see Figure 1).
3) Tables with the same structure have been prepared for the DOMINANT soil unit only, by depth layer (i.e., for layer D1, see for example table *SOTERsummaryFile_T1S1D1*) to facilitate visualization using GIS, as example only. Comprehensive studies should consider the full map unit composition and depth range.
4) A limited number of records may contain a negative value (-9); this indicates that it has not yet been possible to plug the corresponding gaps using the current taxotransfer scheme due to a lack of measured data in WISE. Whenever possible, virtual profiles in SOTER should be replaced with real, measured profiles after which new secondary data may be generated.
5) Parameter estimates are depth-weighted values, per 20 cm layer up to 1m depth and per 50 cm from 1 to 2 m (derived soil properties for 100 to 200 cm, however, are not included in the present secondary database, see text).

Appendix 5. Structure of table SOTERsummaryFile_Prop

The field definitions in this table are identical to those used in *SOTERsummaryFile.* The main difference is that derived data for each soil component of a given SOTER unit are now listed in a single row (horizontally); data for a given layer are preceded by a flag for this layer. For example, field *D1_BULK* presents derived values for bulk density for layer D1 (0-20 cm), whereas *D2-BULK* holds data for layer D2 (20-40 cm) and so on. Using this file format, it is easier to query properties of the individual component soil units of a SOTER units using GIS. However, results can only be shown for one soil component, by SOTER unit, at a time (e.g. for TCID=1 and SCID=1).

Structure of table SOTER*summaryFile_Prop*

Name	Type	Description
ISOC	Text	ISO-3166 country code (1994)
SUID	Integer	The identification code of a SOTER on the map and in the database
NEWSUID	Text	Globally unique map unit code, comprising fields ISOC plus SUID
TCID	Integer	Number of terrain component in given map unit
SCID	Integer	Number of soil unit within the given SOTER unit
PROP	Integer	Relative proportion of SCID in given SOTER unit
CLAF	Text	FAO-Unesco Revised Legend code
PRID	Text	Profile ID (see table *SOTERunitComposition*)
Drain	Text	FAO soil drainage class
D1_TopDep	Integer	Upper depth of layer D1 (0-20 cm)
D1_BotDep	Integer	Lower dept of layer D1
D1_varx	Variable	Values (e.g., varx is ORGC, BULK, Clay) for layer D1
D2_TopDep	Integer	Upper depth of layer D2 (20-40 cm)
D2_BotDep	Integer	Lower dept of layer D2
D2_varx	Variable	Values (e.g, varx is ORGC, BULK, Clay) for layer D2
…	…	…
D5_TopDep	Integer	Upper depth of layer D5 (80-100 cm)
D5_BotDep	Integer	Lower dept of layer D5 (0-20 cm)
D5_varx	Variable	Values (e.g, varx is ORGC, BULK, Clay) for layer D5

Note: A table with the same structure has also been prepared for the DOMINANT soil unit only (i.e., TCID= 1 and SCID=1) to facilitate visualization using GIS, as example only (see table *SOTERsummaryFile_PROP_SC1*). Comprehensive studies, however, should always consider the full map unit composition and depth range.

Appendix 6. Soil textural classes

Soil textural classes (PSCL) are in accordance with revised SOTER criteria (Figure 8). The following abbreviations are used: C–coarse, M–medium, Z–medium fine, F–fine and V–very fine. Further, the symbol *u* is used for undifferentiated (i.e., C + M + F + Z + V). In addition, all Histosols data have been flagged as consisting of organic materials (O) even though this may not always be the case for all horizons/layers, in a strict taxonomic sense (see FAO 1988 , p. 39)

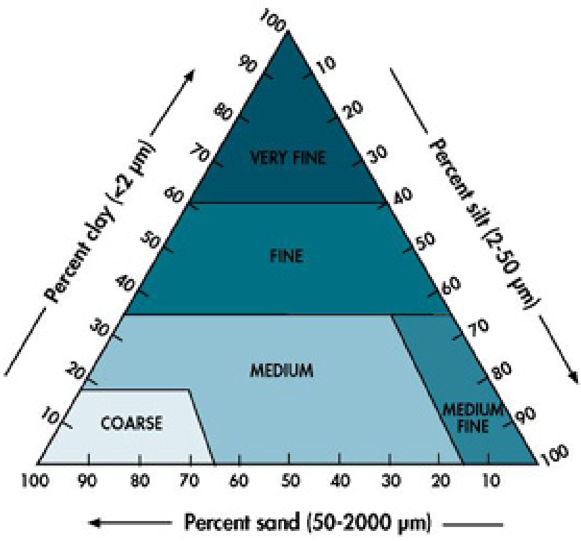

Figure 8. SOTER soil texture classes (Source: CEC 1985)

Appendix 7. Installation

The derived soil data and GIS-files are presented in one single zip file: *SOTWIS_Senegal_v1.zip*.

By default, this compressed file will be unzipped to folder *X:\SOTWIS_Senegal*, where *X* is the actual location (i.e. folder).

This new folder will contain:
- A *Readme1st* file and the documentation (ISRIC Report 2008/05)
- The project file (*SOTWIS_Senegal_v1.mxd*) with metadata (*.*mxd.xml)*
- Two subfolders:
  - *GISfiles* with the shape and selected layer files files, with associated metadata.
  - S*OTWIS* with the derived soil data in MSAccess® format (*SOTWIS_Senegal_v1.mdb*).

The GIS project file (*.mxd) includes several derived data sets for the top layer (0-20 cm) of the dominant soil unit of each SOTER unit (TCID=1, SCID=1), as examples.

Actual data applications should consider the full map unit composition, in terms of component soil units, and depth range; see text for details.

The dataset has been created using MS-Access® and ArcGIS9/ArcMap9.2®; the shapefiles may also be accessed using ArcView3.3®.

World Soil Information

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