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Development of a 5 by 5 arc-minutes global data set of soil parameter estimates for use with the IMAGE model

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Contents

List of Tables

List of Figures

ABSTRACT

A harmonized global set of soil parameter estimates, at a resolution of 5 by 5 arc-minutes, for use with the IMAGE model (Alcamo *et al.* 1998), is described. The data set was derived from a combination of soil geographic data, derived from the 1:5M scale digital Soil Map of the World, and soil parameter estimates derived from the ISRIC-WISE soil profile database.

The land surface between longitudes -180°W and +180°E and latitudes +84°N and -56.50°S has been characterized using 4931 unique map units. Each grid cell can comprise from one to eight soil units, characterized according to the original FAO Legend. The suitability of each of these component soils for a broad land use type (LUT), "rainfed agriculture with moderate to high levels of inputs and technology", was assessed using physical land evaluation.

Fifteen soil parameters, identified as being useful for agro-ecological zoning, land evaluation, crop growth simulation, modelling of soil gaseous emissions and analyses of global environmental change, were considered in this study. Parameter estimates (medians) were presented by FAO soil unit for fixed depth intervals. For each grid cell, these soil parameter estimates were generated for: (1) the spatially dominant soil unit, (2) the soil unit with the highest (best) suitability rating for the considered LUT, (3) the soil unit with the lowest suitability rating, and (4) the remaining soil units.

Parameter estimates for organic carbon, pH(H_2O), CEC_{soil}, CEC_{clay}, base saturation, aluminium saturation, exchangeable sodium percentage (ESP), electrical conductivity of saturated paste (ECe), content of sand, silt and clay, and content of coarse fragments (> 2 mm) are given for the topsoil (0-0.3 m) and the subsoil (0.3-1 m). For soil drainage class, effective soil depth, and available water capacity (-10 to -1500 kPa) parameter estimates are presented on a profile basis (to 1 m or less when appropriate).

Results are presented as summary files that can be linked to the spatial data of the digital Soil Map of the World in a GIS, through the unique map unit code.

The current list of soil parameter estimates should be seen as best estimates based on the current selection of soil profiles and data clustering procedure, and the spatial data held on the digital Soil Map of the World.

Keywords: soil parameter estimates, environmental modelling, FAO Soil Map of the World, ISRIC-WISE database, secondary data set

1. INTRODUCTION

This report describes the procedures and data used to develop a global data set of soil parameter estimates, with a spatial resolution of 5 by 5 arc-minutes, for use with the IMAGE model (Alcamo *et al.* 1998).

Harmonized data sets of soil properties are needed for a wide range of environmental studies, including agro-ecological zoning, assessments of food productivity, soil gaseous emissions/sinks and environmental change (Batjes *et al.* 1997; Bouwman *et al.* 2002; Cramer and Fischer 1997; Fischer *et al.* 2002; Scholes *et al.* 1995; van Drecht *et al.* 2003). Until the global update on world soil resources in the Soil and Terrain Database project (SOTER, see Nachtergaele 1999; Oldeman and van Engelen 1993) has been completed, the combination of spatial data from the digital Soil Map of the World (DSMW, see FAO 1995a) and soil parameter estimates derived from the ISRIC-WISE database (Batjes 2002b) will probably remain the most-detailed source on world soils for global modelling. Various sources and types of uncertainty are associated with the spatial and attribute data, and the models themselves; these have been reviewed elsewhere (Batjes 1999, 2002a, b; Bouwman *et al.* 1999; Burrough 1986; Cramer and Fischer 1997; Fischer *et al.* 2002; Goodchild and Gopal 1989; Nachtergaele 1999).

The DSMW (FAO 1995b) was derived from the printed version of the Soil Map of the World (FAO-Unesco 1971-1981), with minor corrections and updates. The soil geographic information held on the printed SMW has been collated prior to the 1970s; the reliability thereof is known to vary considerably between different areas. Part of this information, for example that shown on the DSMW for South America (FAO-Unesco 1971), is outdated (Batjes 2000; FAO *et al.* 1998). In other regions, such as Denmark, intensive agriculture over the last decades has led to a significant change in soil properties and sometimes even in soil classification (Krogh and Greve 1999). Such changes, however, are not yet reflected in the spatial data of the DSMW.

The global selection of about 9600 profiles in WISE has been derived from field studies mainly carried out between 1960 and 2000. For several of the 106 soil units considered on the DSMW there are still relatively few measured data so that a number of soil parameter estimates had to be derived via taxotransfer rules – these rules have been documented in Batjes (2002a).

Each 5 by 5 arc-minutes grid cell of the DSMW may contain from 1 up to 8 component soils, characterized according to the original Legend (FAO-Unesco 1974). The suitability of each component soil for a broad land use type (LUT), "rainfed agriculture with moderate to high levels of inputs and technology", was assessed using physical land evaluation (FAO 1976). Subsequently, selected soil parameter estimates were generated for each grid cell for: (1) the spatially dominant soil unit, (2) the soil unit with the highest (best) suitability rating for the considered LUT, (3) the soil unit with the lowest suitability rating, and (4) the remaining soil units.

The data sources are described in Section 2.1 and the procedures developed for the physical land evaluation in Section 2.2. Results are discussed in Section 3 and conclusions drawn in Section 4. The structure of the various output tables are described in Appendices 1 and 2, and the installation procedure in Appendix 3.

2. MATERIALS AND METHODS

2.1 Soil data

2.1.1 Spatial data

The spatial distribution of soil units per 5 by 5 arc-minutes grid cell was taken from the 1:5M scale, digital Soil Map of the World (FAO 1995a). The base map of the DSMW is based on ETOPO5[1] (Earth Topography — 5 Minute), which was assembled from several uniformly gridded databases into a worldwide gridded data set with a cell size of 5 minutes of latitude by 5 minutes of longitude. Like for ETOPO5, cells in the DSMW are written row-wise from the West

[1] http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML

to the East starting at the Northwest corner. At the equator, the cell size corresponds with about 0.0833 decimal degrees.

The Arctic and Antarctica are not included on the DSMW. The spatial data set is bound by longitudes -180°W and +180°E and latitudes +84°N and -56.50°S. This corresponds to 4320 columns and 1686 rows or 7,283,520 grid cells in total. The original ERDAS files (WORLD.GIS and WORLD.TRL), prepared by FAO (1995a), were converted to ArcView® GRID format for use in this study.

The legend of the DSMW comprises 4931 different map units, which consist of soil units or associations of soil units. When a map unit is not homogeneous, it is composed of one dominant soil unit and up to eight component soils. According to FAO's composition rules, the latter include associated soils (>20% of the map unit) and inclusions (<20% of the map unit).

In 35 cases, however, the dominant soil unit as given in the DSMW expansion files proved to be incorrect. For example, in map unit number (SNUM) 1823, coded "Yh10-a", the fifth soil ($soil_5$; DS= dune sands) covers 50% of the map unit and the so-called dominant soil ($soil_1$, Yh) only 10%. In all instances, this related to miscellaneous soil units with more than 50% coverage and these were always listed as the last component soil for the given map unit. These errors have been corrected in this study. The original map unit codes, however, were maintained to preserve consistency with the original codes used on the DSMW.

In seven instances (SNUM 3075, 3076, 3663, 4205, 5018, 5101, and 5211), the same soil unit was listed twice in FAO's expansion files. In such cases, the area of identical soil units within the map unit was summed and the expansion files were updated accordingly.

Statistics for the proportion of the dominant and component soils — based on the updated expansion files — are given in Table 1. The median area of the dominant soil unit ($soil_1$) within a map unit is 60%, with lower and upper quartiles of 50 and 70% respectively. The median area for $soil_1$, $soil_2$ and $soil_3$ combined is 100% with lower quartile of 90% and a minimum of 60%. So, in most cases, the grid cells can be adequately characterised by their three main component soils.

Table 1. Relative proportion of dominant and component soils within the map units of the Soil Map of the World

Descriptive statistics	Relative proportion[a] of dominant and component soils (%)							
	Soil1[b]	Soil2	Soil3	Soil4	Soil5	Soil6	Soil7	Soil8
Minimum	24	0	0	0	0	0	0	0
1st Quartile	50	20	0	0	0	0	0	0
Median	60	20	10	0	0	0	0	0
3rd Quartile	70	30	20	10	0	0	0	0
Maximum	100	50	34	25	10	10	5	4

[a] The actual area within a 5 by 5 arc-minutes grid will vary with latitude — the grid cell size is about 9 x 9 km at the equator and will decrease gradually to the poles according to a cosine function of latitude. [b] $Soil_1$ is the dominant soil and $Soil_2$ to $Soil_8$ are the component soils.

In addition to the 106 soil units, coded from Af to Zt, clustered into 26 major soil groupings, the Legend (FAO-Unesco 1974) considers six miscellaneous units: DS= dunes or shifting sands; ST= salt flats; RK= rock outcrops; ND= no data; WR= inland waters or oceans; and GL= Glaciers. In this study, the original code for no data (ND) was changed to NA to avoid possible confusion with Nd, dystric Nitosols.

2.1.2. Soil parameter estimates

Median soil parameter estimates by soil unit (FAO-Unesco 1974) were derived from analyses of the ISRIC-WISE soil profile database (Batjes 2002a, b) with minor modifications, based on expert-judgement, for some soil units (i.e. Regosols, Podzols, Rendzinas and Rankers). Fifteen key attributes, commonly required in studies of environmental change were considered (Table 2) like for a preceding study at 30 by 30 arc-minutes resolution (Batjes 2002c). Information on median soil drainage classes per FAO soil unit was taken from Batjes (1997), again with minor refinements based on expert-judgement.

Table 2. List of soil parameters, their abbreviations and units of measurement

Abbreviation	Description	Units
- For topsoil and subsoil:		
ORGC	Organic carbon	% (mass)
PHH2O	Soil reaction in water	pH units
CECsoil	Cation exchange capacity	$cmol_c\ kg^{-1}$
CECclay	Cation exchange capacity of clay size fraction[a]	$cmol_c\ kg^{-1}$
BSAT	Base saturation (as % of CEC_{soil})	%
ALSAT	Aluminium saturation (as % of effective CEC)[c]	%
ESP	Exchangeable sodium percentage (% of CECsoil)	%
ECE	Electrical conductivity of saturated paste	$dS\ m^{-1}$
GRAVEL	Fragments >2 mm	% (volume)
SAND	Sand	% (mass)
SILT	Silt	% (mass)
CLAY	Clay	% (mass)
- For whole profile (to 1 m or less):		
TAWC2_cor	Available water capacity (from -10 to -1500 kPa) [b]	$mm\ m^{-1}$
DEPT	Depth to physically limiting layer	cm
DRAINY	Drainage class (FAO 1977)	classes

[a] 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). [b] The soil water potential limits for TAWC conform to FAO standards (i.e. pF2.0 to pF4.2, see Doorenbos and Kassam 1978). Values shown have been corrected for the presence of fragments >2 mm and median soil depth per FAO soil unit. [c] Effective CEC was defined as sum of exchangeable bases plus exchangeable ($H^+ + Al^{3+}$) (van Reeuwijk 1995).

There were no soil parameter estimates for the miscellaneous units considered on the DSMW. Therefore, the following assumptions were used:

- Dune sands (DS): soil parameter estimates for Arenosols (Q) were used as default, except for organic carbon content that was set to 0.2% for the topsoil and 0.1% for the subsoil.
- Rock outcrops (RK): as above, but using soil parameter estimates for Lithosols (I) as default. The content of organic carbon, however, was set at 0.1% and the depth of soil at 1 cm.
- Not Determined (NA): as above, but using soil parameter estimates for Arenosols (Q) as the default.
- Salt Flats (ST): as above, but using soil parameter estimates for Solonchaks (Z) as the default. The content of organic carbon was set at 0.2% for the topsoil and at and 0.1% for the subsoil.
- Oceans and Inland Waters (WT): all parameter estimates were set at -1 to permit visualisation using GIS.

- Glaciers and land ice (GL): all parameter estimates were set at -2.

In case of shallow soils, such as Lithosols, parameter estimates for the topsoil were also assigned to the "subsoil" to avoid having blanks in the input files for the subsoil.

2.2 Physical land evaluation

Land evaluation is concerned with the assessment of the performance of land when it is used for specified purposes (FAO 1976). It can provide a rational basis for taking land use decisions based on analysis of relations between land use and land, taking into account both physical and socio-economic considerations and the need to preserve the environmental resources for future use. The degree of detail of conclusions which can be derived from a land evaluation is strongly determined by the level of spatial aggregation of the climatic and soil data, as well as the possible level of integration of the bio-physical and socio-economic information (Bouma and Bregt 1989; Fischer *et al.* 2002). At the present scale of scale of 1:5M, "micro-variations" in the environmental features will be de-emphasized so as to highlight regional trends (Batjes 1990). Whereas the physical factors of the environment are of a relatively stable nature, assuming the use of sound management and conservation practices, the socio-economic features are not. Macro-scale land evaluation, therefore, should in first instance deal with the relatively stable aspects of the physical environment, while social and economic considerations may be introduced at a later stage, for example using models such as IMAGE (Alcamo *et al.* 1998). This kind of approach has been termed two-stage land evaluation by FAO (1976).

The physical land evaluation considered one broadly defined agricultural land use type (LUT). The LUT comprised a modal, rainfed annual crop and it was assumed that "moderate to high levels of input and technology" could be used. The rating procedure is according to the Framework for Land Evaluation (FAO 1976), which allows mapping of land as highly suitable (S_1), moderately (S_2), marginally suitable (S_3), and not-suitable (N) for a given LUT.

On Suitable (S) lands, sustained use of the kind under consideration is expected to yield benefits which justify the inputs, without unacceptable risk of damage to land resources. Land rated as highly suitable (S_1) has no significant or only minor limitations to sustained application of the LUT under consideration, which will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level. Marginally suitable (S_3) land, however, will have limitations which in aggregate are considered severe for sustained application of a given LUT. This will reduce productivity or benefits, or increase required inputs to the extent that this expenditure will be only marginally justified (FAO 1976). Land considered Not-suitable (N) has qualities (or limitations) that appear to preclude sustained use of the LUT under consideration. Boundaries between suitability classes may need to be reviewed and revised with time in light of technical developments and economic and social changes (FAO 1976, 1983). Possible limitations of length of growing period (i.e. climate) are not considered in the current rating scheme, and these should be derived from auxiliary sources.

Land use requirements, expressed as factor ratings for the modal crop — assumed to be comparable to maize in its biophysical requirements — were derived from various sources (Anon. 1984; FAO 1983; Landon 1991; Sys *et al.* 1993). Each soil unit was assessed according to its limitations for the considered LUT, according to the criteria in Table 3. Individual factor ratings (FR_i) or reduction factors by soil parameter were as follows: FR_1= 1.0 for no to slight limitations, FR_2= 0.8 for moderate limitations, FR_3 = 0.6 for severe limitations, and FR_4= 0.2 for very strong limitations.

The rating system for nutrient availability, nutrient retention, and ease of cultivation only considered the top 30 cm. For soil toxicities and excess of salts, however, the most limiting ratings for the topsoil (0-30 cm) or subsoil (30-100 cm) were used. When more than one diagnostic factor was considered to rate a land quality, for example nutrient availability, the most limiting factor was used to determine the factor rating (FR_i) for that land quality.

Extra correction factors (cf) were introduced to better differentiate between possible adverse effects of a shallow groundwater table and/or the occurrence of impervious and compact layers when rating the effective soil depth for so-called "physically deep" soils — chemical limitations for root development were considered under the headings of "excess of salts" and "soil toxicities".

The factor rating for rooting conditions (FR_d) was set at $FR_i - 2\times cf$ for all members of Planosols (W) and Histosols (O), all plinthic soil units (Ap, Lp and Fp), Podzols with a thin iron pan (Pp) and all gelic subunits. For all gleyic subunits, the factor rating was set to $FR_i - cf$.

When none of the above conditions were met, the factor rating for the remaining soil units was set at $FR_i - 2\times cf$ for very poorly (V) and imperfectly drained (P) soil units, and at FR_i - cf for imperfectly drained soils (I). The value for the correction factor (cf) was set at 0.19 based on repeated trials runs and model evaluation.

When the factor rating (FR_i) for a given land quality for the LUT was smaller than 0.62 this has been flagged in the overall suitability code, using the coding conventions shown in Table 4. Inherently, such flags were only used for soil units that were assessed as being S_2 (moderately suitable) or S_3 (marginally suitable) for the given LUT. When applicable, the flags for main limitations were listed starting with those for physical conditions followed by chemical conditions. This ranking was done under the assumption that, for the present LUT, it should generally be more difficult and thus costly to remedy limitations associated with physical than with chemical properties of the soil. For example, a soil unit assessed as S_{3dmf} has as main limitations its unfavourable rooting conditions (d), soil moisture retention capacity (m), and nutrient availability (f).

Table 3. Factor ratings for modal crop and land use type (LUT) [h]

Crop requirements			Diagnostic factor			
Land quality	Diagnostic factor	Units	Degree of limitation[a]			
			Nil to Slight	Moderate	Severe	Very severe
Oxygen availability	Drainage class[b]	class	E, S, W	M	I	V,P
Nutrient availability	Organic carbon	%	≥1.0	0.5-1.0	0.25-0.5	<0.25
	Base saturation	%	50-100	35-50	15-35	<15
	Soil reaction	pH	5.5-7.5	5.0-5.5 or 7.5-8.0	4.5-5.0 or 8.0-8.4	≤4.5 or ≥8.4
Nutrient retention capacity	CEC_{soil}	$cmol_c\ kg^{-1}$	≥20	10-20	5-10	<5
Rooting conditions	Effective soil depth[c]	cm	≥100	50-100	25-50	<25
Excess of salts[d]	Salinity (ECe)	$dS\ m^{-1}$	0-2	2-6	6-15	>15
	Sodicity (ESP)	% of CECs	0-8	8-15	15-25	>25
Soil toxicities[d]	Al-saturation	% of ECEC	0-10	10-20	20-30	>30 (or topsoil or subsoil pH≤4.5)
Ease of cultivation/ Mechanization	Texture [ef]	class	C,M, MF, F (clay<35%, irresp. clay type)	C,M, MF, F (35<clay%<=50 if 2:1 clays; else 35<clay%<60)	F, VF (50<clay%<75 if 2:1 clays, else 60<clay%<75)	VF (clay>75%)
	Gravel content[e]	vol. %	0-10	10-20	20-30	>30
	Slope class[g]	%	0-8	8-30	>30	>30
Soil moisture Holding capacity	Profile available to given depth	mm	>120	80-120	40-80	0-40

[a] Numeric values assigned to factor ratings (FR_i) are according to the degree of limitations: 1.0 for Nil to Slight; 0.8 for moderate; 0.6 for Severe, and 0.2 for Very Severe. [b] Soil drainage class according to FAO (1977): E= excessively , S= somewhat excessively, W= well, M= moderately well , I= imperfectly, P= poorly, and V= very poorly drained. [c] For additional corrections, for example for plinthic, gelic and gleyic soil units see text. [d] Based on most limiting value for 0-30 or 30-100 cm depth range. [e] Limit for sticky and swelling (2:1 type) clays tentatively set at CEC_{clay} >45 $cmol_c\ kg^{-1}$ clay, corrected for contribution of organic carbon. [f] For topsoil (0-30 cm). Abbreviations for soil textural classes are: C= Coarse; M= Medium; MF= Medium Fine; F= Fine; and, VF= Very fine (CEC 1985). [g] Slope classes according to FAO Composition Rules (FAO 1995b, p. 7). [h] The LUT was defined as "rainfed annual crops grown under moderate to high levels of input and technology".

Table 4. Conventions for coding the main types of limitations

Code[a]	Description
c	ease of cultivation/mechanization
d	rooting conditions
f	nutrient availability
m	soil moisture retention capacity
n	nutrient retention
o	availability of oxygen (limitation)
s	excess of salts (ESP and/or ECE)
t	soil toxicities (AL)

[a] Only shown when soil units were rated S_2 or S_3 for the considered land use type.

The most limiting value for the factor ratings under consideration (i.e., FR_1 to FR_8) was used to determine the final suitability rating (SR) of a soil unit for the given LUT (Batjes and Bouwman 1989):

$$SR = (\text{most limiting } FR_i) * (\text{SUM of 7 other } FR_i\text{'s})/7 \qquad (1)$$

Conversion of the final suitability ratings (SR) into an overall suitability class always remains arbitrary (FAO 1983; Fischer *et al.* 2002) — ideally, matching of land qualities with land use requirements should be based on "fuzzy sets" rather than an "exact Boolean" approach (Burrough 1989; McBratney and Odeh 1997). The rating scheme in Table 5 was selected as being most appropriate, based on expert-judgement, subsequent to repeated test runs and sensitivity analyses.

Table 5. Scheme for rating the overall land suitability for the given land utilization type

Suitability class	Final rating (SR)	Number strong limitations[a b]
S_1: highly suitable	≥ 0.64	0
S_2: moderately suitable	0.40 – 0.64	0
S_3: marginally suitable	0.16 – 0.40	≤1
N : not suitable	< 0.16	≥2

[a] Factor rating ≤0.2 (see Table 4, excluding nutrient availability, which, in principle, when strongly limiting can still be remedied for the considered LUT, albeit at an increasing cost). [b] If the above conditions for S_2 were met and ≥3 factor ratings were flagged as limiting then the overall suitability rating was downgraded to S_3 while maintaining all the flags (Table 4). Similarly, if the conditions for S_3 were met and ≥4 factor ratings were flagged as limiting then the overall suitability rating was downgraded to N.

3. RESULTS

According to the above criteria and assumptions, 16 of the 110 soil units considered on DSMW — including the miscellaneous units DS, NA, RK, and ST — were considered highly suitable, 26 moderately suitable, 43 marginally suitable, and 25 not-suitable for the considered LUT. Detailed results of the land evaluation procedure, and soil parameter estimates, for each soil unit and grid cell can be found in the attached data sets (Appendix 3).

Output is presented in MS Access® and ArcView3.3® format. The associated information can be off-loaded to a wide range of data formats, using the in-built export facility of the various software packages, depending on the user's specific needs. The structures of the various output tables are described in Appendices 1 and 2.

The output includes tabular data for:

a) The spatially **d**ominant soil unit (i.e. soil1; see table *SoilPar_**D***), irrespective of its suitability rating.

b) The main, or most extensive, soil unit considered **s**uitable for the given LUT (table *SoilPar_**S***).

c) The main soil unit considered **n**ot-suitable for the LUT under consideration (table *SoilPar_**N***).

d) The remaining soil units of a map unit (table *SoilPar_**Ow***), that is those not considered in tables *SoilPar_S* and *SoilPar_N*. Contrary to the preceding cases, however, table *SoilPar_Ow* presents area-weighted, soil parameter estimates for the "remaining" soil units in a map unit and gives the total number of so-called "other" soil units. If there was one "other" soil, the FAO_74 classification was also given. Otherwise, the FAO-code was replaced by "xx" and the number of "**o**ther" soil units considered during the area-**w**eighting was listed (i.e. ≥ 2). When the number of "other" soil units under consideration was zero, all the corresponding soil parameters estimates plus the relative area were recoded to -3 while the FAO_74 code was flagged as "--". The corresponding soil units have been characterised in Table *SoilPar_O****source*****.** The relative area of the "other" soil units is larger than the combined areas of the main suitable (a) and not-suitable soil units (b) in less than 6% of the mapping units.

For Oceans (WT) and Glaciers (GL), the "suitability ratings" have been coded *wt* and *gl*, respectively, to permit visualization in GIS. As has been indicated earlier, the corresponding "soil parameter estimates" were set at -1 and -2, respectively. Similarly, the relative area for units WT and GL has been recoded to -1 and -2, always being 100% of a grid cell at the considered resolution.

The information resulting from the physical land evaluation has been summarized in table *LEV_RAT* (see Appendix 2), an excerpt of which is shown in Figure 1. For example, the dominant soil unit (FAO74_D) of the map unit with the unique identifier 50 (SNUM) consists of rhodic Ferralsols (Fr), which cover 50% of map unit (FAOSOIL) *Fr2-2/3b*. The dominant soil unit (Fr) was considered moderately suitable (S_{2n}) for the considered LUT, in view of its limitations for nutrient retention (n, see Table 4). In total, this map unit also comprises of 10% of marginally suitable (see under S_3) soils and 40% of soil units considered not-suitable (see under N) for the given LUT. Lithosols (I) are the predominant soil unit considered not-suitable for the given LUT. For this map unit, the spatially dominant soil unit (FAO74_D) and the main suitable soil unit (FAO74_S) are the same. For each map unit, and hence 5 by 5 arc-minutes grid cell, the total area of soil units rated as S_1, S_2, S_3 and N will always be 100% since the full soil unit composition has been taken into account.

LEV_RAT : Table

SNUM	FAOSOIL	Phase1	FAO74_D	AREA_D	SUIT_D	S1	S2	S3	S	FAO74_	AREA_S	SUIT_S	SoilNum_S	N	FAO74_N	AREA_N	SUIT_N	SoilNum_N	WR	GL
45	Fp7-2ab	03	Fp	60.0	N	0.0	40.0	0.0	40.0	Af	20.0	S2n	2	60.0	Fp	60.0	N	1	0.0	0.0
47	Fp8-2ab	03	Fp	30.0	N	0.0	20.0	0.0	20.0	Af	20.0	S2n	2	80.0	Fp	30.0	N	1	0.0	0.0
48	Fp9-3a	--	Fp	50.0	N	10.0	10.0	0.0	20.0	Ne	10.0	S1	3	80.0	Fp	50.0	N	1	0.0	0.0
50	Fr2-2/3b	06	Fr	50.0	S2n	0.0	50.0	10.0	60.0	Fr	50.0	S2n	1	40.0	I	20.0	N	2	0.0	0.0
51	Fr8-2/3b	06	Fr	50.0	S2n	20.0	50.0	0.0	70.0	Fr	50.0	S2n	1	30.0	Rd	20.0	N	3	0.0	0.0
52	Gd6-2a	--	Gd	50.0	N	0.0	10.0	20.0	30.0	Fo	20.0	S3tnf	2	70.0	Gd	50.0	N	1	0.0	0.0
53	Gd5-2a	--	Gd	70.0	N	0.0	0.0	0.0	0.0	--	0.0	-	-9	100.0	Gd	70.0	N	1	0.0	0.0
55	Ge22-a	--	Ge	40.0	S3do	20.0	10.0	70.0	100.0	Ge	40.0	S3do	1	0.0	--	0.0	-	-9	0.0	0.0
56	Ge23-2/3a	--	Ge	60.0	S3do	0.0	20.0	80.0	100.0	Ge	60.0	S3do	1	0.0	--	0.0	-	-9	0.0	0.0
57	Gh7-2a	--	Gh	60.0	S3dof	10.0	0.0	60.0	70.0	Gh	60.0	S3dof	1	30.0	Od	30.0	N	2	0.0	0.0
58	Gm15-2a	--	Gm	40.0	S3do	20.0	10.0	70.0	100.0	Gm	40.0	S3do	1	0.0	--	0.0	-	-9	0.0	0.0
60	I	--	I	100.0	N	0.0	0.0	0.0	0.0	--	0.0	-	-9	100.0	I	100.0	N	1	0.0	0.0
61	I	04	I	50.0	N	0.0	0.0	0.0	0.0	--	0.0	-	-9	100.0	I	50.0	N	1	0.0	0.0

Record: 1 of 4932

Figure 1. Example of suitability ratings for selected map units

Combined use of the information held in tables *SoilPar_S*, *SoilPar_Ow* and *SoilPar_N* will permit modellers to access soil parameter estimates covering 100% of each grid cell. To facilitate this process, so-called summary tables have also been generated on a soil parameter basis. Table *xORGC*, for example, will contain all the necessary information on organic carbon content (see Appendix 2).

Figure 2 shows parameter estimates for the dominant soil unit for the map units considered in Figure 1, as an example. The soil parameter estimate for soil organic carbon (ORGC) of plinthic Ferralsols (Fp) is 1.36 % for the topsoil (*ORGC_TM*) and 0.48% for the subsoil (*ORGC_BM*).

SoilPar_D : Table

SNUM	FAOSOIL	FAO_74	SUIT	SUIT_ml	AREA	SOILNUm	ORGC_TM	ORGC_BM	PHH2O_	PHH2O_E	CECSOIL_TM	CECSOIL_BM	CECCLAY_TM	CECCLAY_E	BSAT_TM	BS
45	Fp7-2ab	Fp	N	N	60	1	1.36	0.48	4.90	5.20	6	4	6	6	36	
47	Fp8-2ab	Fp	N	N	30	1	1.36	0.48	4.90	5.20	6	4	6	6	36	
48	Fp9-3a	Fp	N	N	50	1	1.36	0.48	4.90	5.20	6	4	6	6	36	
50	Fr2-2/3b	Fr	S2n	S2n	50	1	1.22	0.48	5.40	5.30	8	6	10	9	62	
51	Fr8-2/3b	Fr	S2n	S2n	50	1	1.22	0.48	5.40	5.30	8	6	10	9	62	
52	Gd6-2a	Gd	N	N	50	1	1.39	0.40	4.90	5.00	12	10	27	30	49	
53	Gd5-2a	Gd	N	N	70	1	1.39	0.40	4.90	5.00	12	10	27	30	49	
55	Ge22-a	Ge	S3do	S3do	40	1	1.00	0.38	6.20	6.40	13	14	39	40	80	
56	Ge23-2/3a	Ge	S3do	S3do	60	1	1.00	0.38	6.20	6.40	13	14	39	40	80	
57	Gh7-2a	Gh	S3dof	S3do	60	1	4.05	0.71	5.10	5.10	20	14	35	25	28	
58	Gm15-2a	Gm	S3do	S3do	40	1	1.76	0.68	6.40	6.70	21	18	42	39	86	
60	I	I	N	N	100	1	1.41	1.41	7.60	7.60	16	16	50	50	100	
61	I	I	N	N	50	1	1.41	1.41	7.60	7.60	16	16	50	50	100	

Record: 1 of 4932

Figure 2. Soil parameter estimates for the dominant soil unit for selected map units

The information held in the various output tables can be linked (joined) to the soil geographical information through the unique map unit code (SNUM) of each grid cell, using a Geographical Information System (GIS). At the present scale of 1:5 M, results can best be presented as classes. Figure 3 shows an example of the type of views that can be displayed and handled using GIS software. The underlying soil parameter estimates, in un-binned format, can be found in the corresponding attribute tables (see Appendix 2).

Ultimately, the type of research purpose will determine which parameter estimates or single value maps will be required for a specific application. The corresponding data selections can best be made with tailor-made programs designed to meet the scope of these applications.

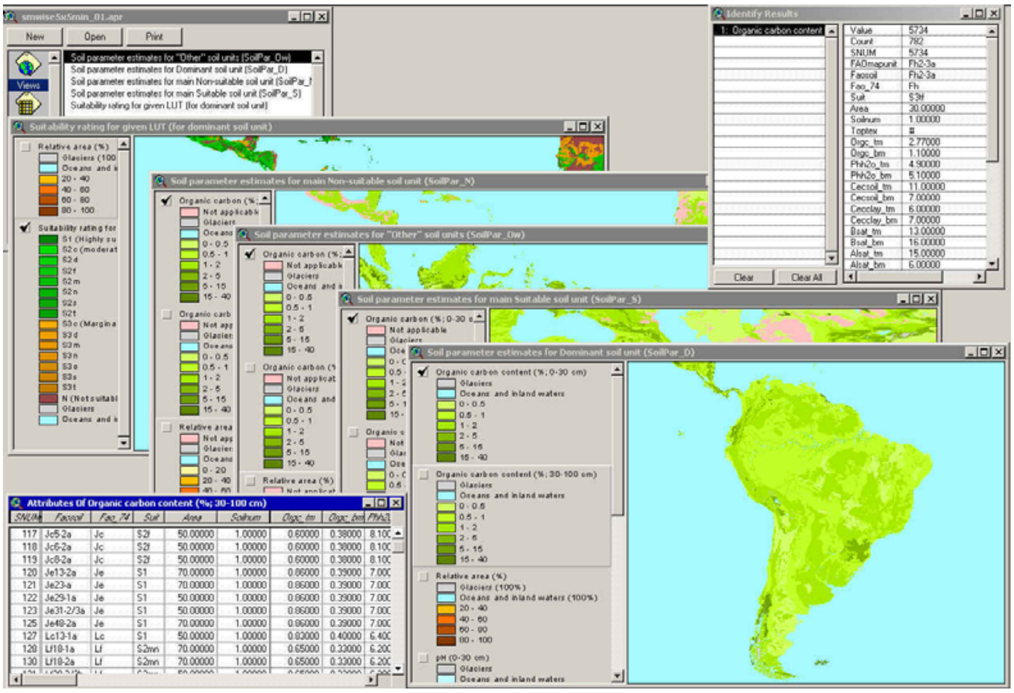

Figure 3. Example of GIS ouput

4. CONCLUSIONS

Linkage of the WISE-derived soil parameter estimates with the spatial component of the DSMW map required generalisation of measured soil (profile) data by FAO 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. Other sources of uncertainty are associated with the spatial data and assumptions used in the land evaluation procedure.

The present, geo-referenced sets of soil parameter estimates should be seen as best estimates based on analyses of the currently available selection of profile data held in WISE and the soil geographic information of the DSMW.

The information held in this derived data set is considered appropriate for environmental studies at global scale, pending the update of the information on world soil resources at scale 1:5M in a global soil and terrain (SOTER) database product.

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APPENDICES

Appendix 1: Structure of main output tables

All output files like *SoilPar_**D***, *SoilPar_**S***, *SoilPar_**N***, and *SoilPar_**Ow*** have a similar structure. However, unlike for *SoilPar_D*, *SoilPar_S*, *SoilPar_N*, table *SoilPar_Ow* also lists the number of "other" soil units that have been considered in the area-weighting procedure (field *NUMofSOILs*, see Section 2).

Structure of table *SOILPAR_x*:

Name	Data Type[a]	Description
SNUM	Number	The identification code for a map unit on the DSMW and in the database tables
FAOSOIL	Text	Globally unique DSMW map unit code
FAO_74[d]	Text	Characterization of the soil unit according to the FAO-UNESCO (1974) Legend (i.e., FAO74_**D**, FAO74_**S**, or FAO74_**N** as indicated in the table name)
NUMofSoils	*Number*	*No. of soils considered (only in table SoilPar_Ow)[e]*
SUIT	Text	Suitability rating of dominant soil unit for specified land use type (LUT) with codes for all limitations (see Table 4)
SUIT_ml	TEXT	As above, but showing only the main limitation (for a more compact GIS display)
SOILnum	Number	Sequential number of $Soil_i$ in map unit *(not in SoilPar_Ow)*
TopTex	Number	Code (flag) for topsoil textural class ("#" by default)
ORGC_TM	Number	Soil parameter estimate (median) for ORGC for topsoil[b]
ORGC_BM	Number	Soil parameter estimate[c] (median) for ORGC for subsoil
PHH20_TM	Number	Soil parameter estimate (median) for PHH20 for topsoil[b]
PHH20_BM	Number	Soil parameter estimate (median) for PHH20 for subsoil
CEC_{soil}_TM	Number	Soil parameter estimate (median) for CEC_{soil} for topsoil[b]
CEC_{soil}_BM	Number	Soil parameter estimate (median) for CEC_{soil} for subsoil
CEC_{clay}_TM	Number	Soil parameter estimate (median) for CEC_{clay} for topsoil[b]
CEC_{clay}_BM	Number	Soil parameter estimate (median) for CEC_{clay} for subsoil
BSAT_TM	Number	Soil parameter estimate (median) for BSAT for topsoil[b]
BSAT_BM	Number	Soil parameter estimate (median) for BSAT for subsoil
ALSAT_TM	Number	Soil parameter estimate (median) for ALSAT for topsoil[b]
ALSAT_BM	Number	Soil parameter estimate (median) for ALSAT for subsoil
ESP_TM	Number	Soil parameter estimate (median) for ESP for topsoil[b]
ESP_BM	Number	Soil parameter estimate (median) for ESP for subsoil
$TAWC_2$_COR	Number	Soil parameter estimate (median) for $TAWC_2$ for profile[b]

(cont.)

SAND_TM	Number	Soil parameter estimate (median) for SAND for topsoil[b]
SAND_BM	Number	Soil parameter estimate (median) for SAND for subsoil
SILT_TM	Number	Soil parameter estimate (median) for SILT for topsoil[b]
SILT_BM	Number	Soil parameter estimate (median) for SILT for subsoil
CLAY_TM	Number	Soil parameter estimate (median) for CLAY for topsoil[b]
CLAY _BM	Number	Soil parameter estimate (median) for CLAY for subsoil
GRAVEL_TM	Number	Soil parameter estimate (median) for GRAVEL for topsoil[b]
GRAVEL_BM	Number	Soil parameter estimate (median) for GRAVEL for subsoil
DEPT	Number	Soil parameter estimate (median) for DEPT for profile[b]
DRAINY	Number	Soil parameter estimate (modal) for DRAINY for profile[b]

[a] Details about Field Size, Format, Decimal places and a brief description of the attributes can be found in the corresponding MS Access® tables, using the "Design View" mode. [b] See Table 2 for abbreviations. [c] Soil parameter (medians) estimates were derived from the ISRIC-WISE database (Batjes 2002b), see Section 2. [d]Depending on the name of the file under consideration, the field FAO_74 either refers to the spatially dominant soil unit (_D) or to the spatially dominant soil unit considered most suitable (S_i) or not-suitable (N) for the LUT under consideration, or to the remaining soil units (suitable ratings variable and undefined) for the LUT under consideration (see text, Section 2). [e] In case of *SoilPar_Ow*, the names of the various soil units considered in the area-weighting have been specified in a separate table called *SoilPar_**Osource*** (see below).

Structure of table *SoilPAr_**Osource***:

Name	Data Type[a]	Description
SNUM	Number	The identification code for a map unit on the DSMW and in the database tables
FAOSOIL	Text	Globally unique DSMW map unit code
FAO_74	Text	Code for the soil unit ($Soil_j$) under consideration according to the FAO-UNESCO (1974) Legend
SUIT	Text	Suitability rating of $Soil_j$ for specified Land Use type (LUT)
SOILnum	Number	Sequential number of $Soil_j$ in map unit
TopTex	Text	Flag for topsoil texture (#)

NOTE: When FAOSOIL is WT or GL the suitability ratings have been set at *wt* and *gl*, and the corresponding area at -1 and -2, respectively, to permit visualization using GIS (i.e., to differentiate them from the class "not applicable" or "--" when a certain soil suitability rating does not occur in a given map unit; coded as -3).

Appendix 2: Structure of summary files

For each of the soil parameters under consideration (Table 2), so-called summary tables have also been generated. The name of these tables is *xNAME*, where NAME is the abbreviation for the soil parameters listed in Table 2. The structure for tables *xORGC* and *xDEPT* are given below, as examples.

In a Geographical Information System (GIS), data from the above tables can be linked (joined) to the geographical data of the digital Soil Map of the World (see *...\SMWISE5x5min\worldgrd_5x5*.**) through the unique map unit code (SNUM), for example using the "SQL connect" option of ArcView®. However, to speed up data loading when running the GIS-project file (*.apr) all MS Access® tables have also been converted to dBaseIV® format (e.g., *xBSAT.dbf*). These files are stored in subfolder *...\SMWISE5x5min \DBF*. All file names in this folder were truncated to the leftmost 4 characters of the MS Access® table name in view of the maximum length of 8 characters permitted under dBaseIV®. Similarly, field names were truncated to their 4 leftmost characters. For example, TAWC2_cor became TAWC in the dbf-files.

Structure of table *xOrgC*[a]:

Name	Data Type	Description
SNUM	Number	Unique number for DSMW map unit
FAOSOIL	Text	DSMW map unit (for details see,FAO 1995a)
FAO_74D	Text	FAO-UNESCO (1974) code for main (**D**ominant) soil unit
AREA_D	Number	Relative area of FAO_74D in map unit (%)
ORGC_Dt	Number	Median organic carbon content (%) in **t**opsoil (0-30 cm)
ORGC_Ds	Number	Median organic carbon content (%) in **s**ubsoil (0-100 cm)
FAO_74S	Text	FAO-UNESCO (1974) code for main **S**uitable soil unit
AREA_S	Number	Relative area of FAO_74D in map unit (%)
ORGC_St	Number	Median organic carbon content (%) in **t**opsoil (0-30 cm)
ORGC_Ss	Number	Median organic carbon content (%) in **s**ubsoil (0-100 cm)

(cont.)

FAO_74O	Text	Code or " - -" for "**o**ther" soil units (see text)
AREA_O	Number	Relative area of FAO_74D in map unit (%)
NofOther	Number	Number of so-called other soils (not belonging to _S or _N)
ORGC_Ot	Number	Area-weighted organic carbon content (%) in **t**opsoil
ORGC_Os	Number	Area-weighted organic carbon content (%) in **s**ubsoil
FAO_74N	Text	FAO-UNESCO (1974) code for main **Not**-suitable soil unit
AREA_N	Number	Relative area of FAO_74D in map unit (%)
ORGC_Nt	Number	Median organic carbon content (%) in **t**opsoil (0-30 cm)
ORGC_Nt	Number	Median organic carbon content (%) in **s**ubsoil (0-100 cm)

[a] This type of files presents soil parameter estimates for the topsoil (0-30 cm) and subsoil (0-100 cm or less when applicable); see Table 2.

Structure of table *xDEPT*[a]:

Name	Data Type	Description
SNUM	Number	Unique number for DSMW map unit
FAOSOIL	Text	DSMW map unit (for details see,FAO 1995a)
FAO_74D	Text	FAO-UNESCO (1974) code for main (**D**ominant) soil unit
AREA_D	Number	Relative area of FAO_74D in map unit (%)
DEPT_D	Number	Median soil depth (0-100 cm or less when applicable)
FAO_74S	Text	FAO-UNESCO (1974) code for main **S**uitable soil unit
AREA_S	Number	Relative area of FAO_74D in map unit (%)
DEPT_S	Number	Median soil depth (0-100 cm or less when applicable)
FAO_74O	Text	Code or "—" for "**o**ther" soil units (see text)
AREA_O	Number	Relative area of FAO_74D in map unit (%)
NofOther	Number	Number of so-called other soils (not belonging to _S or _N)
DEPT_O	Number	Median soil depth (0-100 cm or less when applicable)
FAO_74N	Text	FAO-UNESCO (1974) code for main **Not**-suitable soil unit
AREA_N	Number	Relative area of FAO_74D in map unit (%)
DEPT_N	Number	Median soil depth (0-100 cm or less when applicable)

[a] These files present soil parameter estimates for the whole profile (0-100 cm or less when applicable), that is for drainage class, soil depth, and moisture holding capacity (see Table 2).

The information resulting from the physical land evaluation has been summarized in table LEV_RAT.

Structure of table *LEV_RAT*:

Name	Data Type	Description
SNUM	Number	Unique number for DSMW map unit
FAOSOIL	Text	DSMW map unit (for details see FAO 1995a)
Phase1	Text	Code for phase (see FAO 1995a)
FAO_74D	Text	FAO-UNESCO (1974) code for **d**ominant soil
AREA_D	Number	Relative area of FAO_74**D** in map unit (%)
SUIT_D	Text	Suitability rating for above soil unit and specific LUT
S1	Number	Relative area of S_1-rated soil units (%)
S2	Number	Relative area of S_2-rated soil units (%)
S3	Number	Relative area of S_3-rated soil units (%)
S	Number	Relative area of S_1 + S_2 + S_3-rated soil units (%)
FAO_74S	Text	FAO-UNESCO (1974) code for main **S**uitable soil unit
AREA_S	Number	Relative area of FAO_74**S** in map unit (%)
SUIT_S	Text	Suitability rating for above soil unit and LUT
SoilNUM_S	Number	Sequential number of soil unit in map unit
FAO_74N	Text	FAO-UNESCO (1974) code for main **N**ot-suitable soil unit
AREA_N	Number	Relative area of FAO_74**N** in map unit (%)
SUIT_N	Text	Suitability rating for above soil unit and LUT
SoilNUM_N	Number	Sequential number of soil unit in map unit
WT	Number	Relative area of Oceans and Inland Waters (%)
GL	Number	Relative area of Glaciers in map unit (%)

Appendix 3: Installation procedure

The soil parameter estimates and GIS image files are provided in one single zip file called *SMWISE5x5min_ver1.zip*. The file size is about 7.5Mb zipped and about 57 Mb when unzipped.

The compressed file can be unzipped to any folder (X), in which all files will be decompressed to subfolder *X:\SMWISE5x5min_ver1.0*. This subfolder will contain:

1) The project's apr-file: *smwise5x5min_01.apr*. This file can best be accessed from within ArcView®.
2) Five subfolders: *worldgrd_5x5*, *LegendFiles*, *DBF*, *Info* and *Readme1st*.
3) The MS Access® database containing all the soil parameter estimates (*SMWISE5x5min_v1.mdb*; for details see Appendices 1 to 2).

The first time the project is opened on a new system, the path statements will be automatically updated to the new folder-settings in the new project or apr-file.

Only a limited selection of possible outputs has been shown in the GIS project file. Other selections can be generated by joining the relevant attribute tables (see folder *X:\SMWISE5x5min\DBF*) to the gridded DSMW data (see folder *X:\SMWISE5x5min\worldgrd_5x5*) though field *SNUM.*

Commercially available ArcView® GIS software, inclusive of the Spatial Analist® extension, is needed to manage the GIS files (ESRI 1996).

The project file was developed for use on a 17 inch screen.

———