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Preparation of consistent soil data sets for modelling purposes: Secondary SOTER data for four case study areas

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Abstract

The common GIS-based approach to regional analyses of soil organic carbon (SOC) stocks and changes is to define geographic layers for which unique sets of driving variables are derived, which include land use, climate, and soils. These GIS layers, with their associated attribute data, can then be fed into a range of empirical and dynamic models. Common methodologies for collating and formatting regional data sets on land use, climate, and soils were adopted for the project *Assessment of Soil Organic Carbon Stocks and Changes at National Scale* (GEFSOC). This permitted the development of a uniform protocol for handling the various input for the dynamic GEFSOC Modelling System.

Consistent soil data sets for Amazon-Brazil, the Indo-Gangetic Plains (IGP) of India, Jordan and Kenya, the case study areas considered in the GEFSOC project, were prepared using methodologies developed for the World Soils and Terrain Database (SOTER). The approach involved three main stages: (1) compiling new soil geographic and attribute data in SOTER format; (2) using expert estimates and common sense to fill selected gaps in the measured or primary data; (3) using a scheme of taxonomy-based pedotransfer rules and expert-rules to derive soil parameter estimates for similar soil units with missing soil analytical data. The most appropriate approach varied from country to country, depending largely on the overall accessibility and quality of the primary soil data available in the case study areas.

The secondary SOTER data sets discussed here are appropriate for a wide range of environmental applications at national scale. These include agro-ecological zoning, land evaluation, modelling of soil C stocks and changes, and studies of soil vulnerability to pollution. Estimates of national-scale stocks of SOC, calculated using SOTER methods, are presented as a first example of database application. Independent estimates of SOC stocks are needed to evaluate the outcome of the GEFSOC Modelling System for current conditions of land use and climate.

Keywords: Organic carbon; SOTER database; Soil parameter estimates; Taxotransfer rules

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1. Introduction

Present and future needs for soil information include an up-to-date geographical coverage, access to secondary soil information obtained via pedotransfer functions or models from the primary (measured) data, and monitoring of changes in soil characteristics as associated, for example, with changes in land use systems and processes of global change (Batjes, 2002; Baumgardner, 1999; Bullock, 1999). The ordinary GIS-based approach to regional analysis is to develop geographic layers for which unique sets of driving

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variables are presented, such as land use, climate and soils (Batjes, 2004a; Falloon et al., 2002; Paustian et al., 1997). These GIS layers, and the underlying attribute data, can then be used as input for a range of empirical and dynamic models.

Common methodologies for collating and formatting regional data sets on land use, climate and soils were adopted for the Global Environmental Facility (GEF) co-financed project *Assessment of Soil Organic Carbon Stocks and Change at National Scale* (GEFSOC, 2003; Milne et al., 2007-a). This was essential to permit development of a uniform protocol for handling the inputs for the Global Environment Soil Organic Carbon Modelling System (hereafter referred to as the GEFSOC system) (Easter et al., 2007). This generic system couples two dynamic C models (Century and RothC) and an empirical model (IPCC, 2003) with GIS. It can be used to quantify the potential impact of land use/management and climate scenarios on sequestration of organic C in soils at national and sub-national scale.

This paper focuses on the collation, screening, and consolidation of soil and terrain data for the four GEFSOC case study areas: Amazon-Brazil, the Indo-Gangetic Plains (IGP) of India, Kenya, and Jordan. First, we discuss how the primary data have been collated using the methodology of the World Soils and Terrain Database (SOTER). SOTER is a collaborative activity of ISRIC, FAO, and UNEP, carried out under the aegis of the International Union of Soil Sciences (Oldeman and van Engelen, 1993; van Engelen and Wen, 1995). The methodology has been applied in various regions of the world at scales ranging to 1:100,000–1: 5,000,000 (van Engelen, 1999). Continental scale, SOTER databases are now available for Latin America and the Caribbean (FAO, 1998b), Central and Eastern Europe (FAO and ISRIC, 2000) and Southern Africa (FAO and ISRIC, 2003), while work for Europe (King et al., 2002) and Central Africa is in progress. Interim products, with only limited soil profile data included, are available for north-eastern Africa (FAO, 1998a) and North and Central Eurasia (FAO and IIASA, 1999). Ultimately, once global coverage has been achieved, SOTER is to replace the 1:5,000,000 Soil Map of the World (FAO, 1995; Nachtergaele and Oldeman, 2002).

SOTER involves no new ground surveys, being based upon available data. The spatial data are compiled using a method that resembles physiographic soil mapping or land systems mapping, increasingly using digital elevation models and computer algorithms to generalize the available soil geographic information (Dobos et al., 2002; King et al., 2002; van Engelen and Huting, 2004). The scale of mapping determines the level of soil information that can be shown – ideally, it should coincide with the spatial and temporal scales of the processes that are going to be modelled and the questions to be answered (Middelburg et al., 1999; Paustian et al., 1997; Wessman, 1992). Possible sources of uncertainty in spatial soil data, *vis a vis* those found in observational (measured) data, have been discussed elsewhere (Bregt and Beemster, 1989; Burrough, 1986; Goodchild, 1994; Landon, 1991).

Inherently, national scale SOTER databases encompass a marked degree of data integration, the aim being to simplify the geographical distribution of soil types to a regionally representative pattern. These soil types are then characterized using a suite of representative profiles (van Engelen and Wen, 1995), selected by national experts. The necessary measured (i.e. *primary*) soil profile data are mainly compiled from soil survey reports; typically, they have been sampled and characterized over a number of years (e.g., 1970–2000). These reports seldom contain all the mandatory attributes required for SOTER, resulting in gaps in the databases. The latter often preclude the direct use of the *primary* data in environmental assessments and modelling—until the present time, gaps had to be filled using tailor-made solutions (Batjes and Dijkshoorn, 1999; Mantel and van Engelen, 1999). Therefore, a standardized procedure was developed to fill gaps in the *primary* data (Batjes, 2003). Subsequently, the resulting *secondary* SOTER data were used to estimate stocks of SOC, using so-called mapping approaches. At a later stage in the project, these estimates were used to evaluate the output of the GEFSOC system for the Kyoto baseline year (1990); results of the latter work have been detailed elsewhere (Al-Adamat et al., 2007; Bhattacharyya et al., 2007; Cerri et al., 2007; Kamoni et al., 2007). Findings of the subsequent scenario work (2000–2030) can support land-use policy formulation and may be used to take actions to mitigate climate change and take advantage of the emerging C market, as described by Milne et al. (2007-b).

2. Compilation of primary SOTER databases

2.1. 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 (Fig. 1).

Each SOTER database comprises a geographic and an attribute-data component. The *geographic database* holds information on the location, extent, and topology of each SOTER unit—this information is managed using a geographic information system (GIS). The *attribute database* describes the characteristics of the spatial unit; it comprises both area data and point data—this information is handled using a relational database management system (RDBMS).

Each soil component within a SOTER unit is characterized by a typical profile (Fig. 1), identified as being regionally representative by national soil experts. Being derived from soil survey reports, complete and uniform sets of soil analytical data were seldom available for all these profiles. Therefore, gaps in the measured data were filled

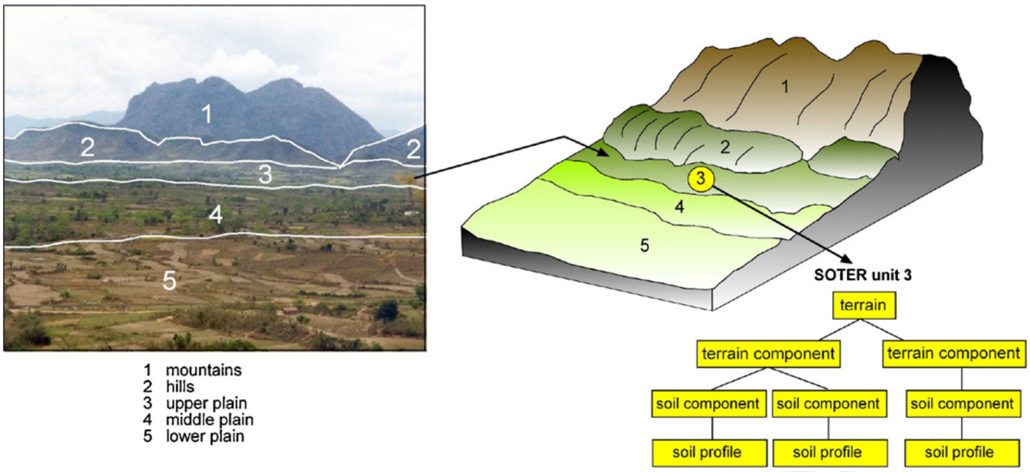

Fig. 1. Representation of SOTER units and conceptual structure of a SOTER unit.

using a system of taxotransfer rules, that is taxonomy-based pedotransfer rules and expert-rules (see Section 3.3).

2.2. Data compilation

The scale at which data were compiled for the national SOTER databases was determined by the different needs of each host country. Consequently, the SOTER databases considered here have different scales: 1:500,000 for Jordan, 1:1,000,000 for Kenya and IGP-India, and 1:5,000,000 for Amazon-Brazil. The level of detail, both in terms of soil geographical and attribute data presented, can also vary depending on the base materials available in each case study area.

Jordan, Kenya and Brazil already had a national scale SOTER database (ACSAD, 1996; FAO, 1998b; KSS, 1995; NSMLUP, 1996), but this was not so for IGP-India. Following a SOTER training session, the National Bureau for Soil Survey and Land Use Planning compiled a compatible data set for IGP-India (Chandran et al., 2005). All four *primary* SOTER/GIS sets were screened, consolidated and re-formatted during the GEFSOC project.

3. Preparation of secondary SOTER data sets

3.1. Selection of soil variables

Special attention was paid to the inputs required by the process-based C-models (RothC and Century) embodied in the GEFSOC system, i.e. location and relative extent of soil type, soil drainage status (hydricity), content of clay, sand and silt, content of organic C and bulk density per depth layer (Falloon et al., 1998; Paustian et al., 1997). This limited set was expanded to include 18 soil variables (Table 1) to permit a wider range of assessments such as land evaluation, agro-ecological zoning, modelling of food productivity and studies of soil gaseous fluxes.

3.2. Procedures for filling gaps in the measured data

The gap-filling procedure involved three stages (Batjes, 2003), the desirability of which decreases from highest (Stage 1) to lowest (Stage 3):

- Stage 1: Collate additional soil geographic and attribute data where these exist, in the uniform SOTER format.
- Stage 2: Use expert estimates and common sense to fill selected gaps in the measured data in a secondary data set.
- Stage 3: Use taxotransfer rules to derive soil parameter estimates for similar FAO soil units, clustered by textural class and depth range, complemented with a system of expert rules.

Table 1
Soil variables considered in *secondary* SOTER databases (Batjes, 2003)

Organic carbon
Total nitrogen
Soil reaction (pH_{H_2O})
Cation exchange capacity (CEC_{soil})
Cation exchange capacity of clay size fraction (CEC_{clay})[a]
Base saturation (as % of CEC_{soil})
Effective cation exchange capacity (ECEC)[b]
Aluminium saturation (as % of ECEC)
$CaCO_3$ content
Gypsum content
Exchangeable sodium percentage (ESP)
Electrical conductivity of saturated paste (ECe)
Bulk density
Coarse fragments (vol.%)
Sand (mass%)
Silt (mass%)
Clay (mass%)
Available water capacity (AWC; cm to specified depth, from −33 to −1500 kPa; % v/v)

[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] ECEC was defined as exchangeable ($Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$) + exchangeable ($H^{+} + Al^{3+}$) (van Reeuwijk, 2002).

Table 2
Overview of SOTER-activities undertaken for each case study area

Stage[a]	Case study area			
	Amazon-Brazil	IGP-India	Jordan	Kenya
1	–	X[a]	–	X
2	–	–	X	X
3	X	X	X	X

[a] Stages 1–3 are detailed in the text; the Xs indicate which of these activities have been undertaken in each country.

By their nature, stages 1 and 2 were the primary responsibility of the in-country case study partners while ISRIC's work was focussed on methodology development and the actual preparation of the *secondary* SOTER data. The most appropriate option(s) varied from country to country, depending largely on the overall accessibility to and quality of the available data (Table 2) as well as the time-schedule and objectives of the project (Milne et al., 2007-a).

During stage 1, for example, there was no direct need to collate additional profile data for the Brazilian SOTER (see Batjes et al., 2004a, pp. 8–9)—even though a wider range of profiles was available (Bernoux et al., 2003; Cooper et al., 2005). The opposite was true for Jordan; however, soil/GIS data from a preceding country-wide soil and land use mapping project (see Al-Qudah, 2001) were found to have been corrupted, thus precluding their use in the GEFSOC project. Conversely, Kenya Soil Survey provided some 50 new profiles for their country. The National Bureau for Soil Survey and Land Use Planning, Nagpur, compiled completely new soil and terrain data for IGP-India (Chandran et al., 2005).

During stage 2, a number of synthetic and virtual soil profiles had to be created for Jordan (9) and Kenya (47), while this was not necessary for Amazon-Brazil and IGP-India. Synthetic profiles can be introduced in SOTER when no measured data are available for a given soil component, provided the classification of the corresponding FAO soil unit is known. The required SOTER attributes are then estimated by national experts, based on their knowledge of local soil conditions. Alternatively, when this is not feasible, so-called virtual profiles can be defined—estimates for the corresponding soil parameters will then have to be derived using taxotransfer- and expert-rules. All synthetic and virtual profiles were flagged to avoid confusion with real (measured) profiles in the data sets. Finally, during Stage 3, the scheme of taxotransfer- and expert-rules was applied resulting in four new, consistent, *secondary* SOTER data sets; the procedure is detailed in Section 3.3.

The status of data sets, screened and consolidated during the GEFSOC project, is summarized in Table 3. Generally, at the small scales under consideration, most SOTER units were mapped as complexes comprising several soil components, except for IGP-India (Chandran et al., 2005). Details may be found in the technical reports for Brazil (Batjes et al., 2004a), IGP-India (Batjes et al., 2004b), Jordan (Batjes et al., 2003), and Kenya (Batjes and Gicheru, 2004).

3.3. *Development and application of taxotransfer- and expert-rules*

3.3.1. *Definition and procedures*

Gaps in the measured data were filled using a scheme of taxotransfer and expert-rules. A *taxotransfer* function is a means of estimating soil parameters based on modal soil characteristics of soil units from a combination of their classification name, which by definition implies a certain range for various soil attributes, expert knowledge and empirical rules, and statistical analysis of a large number of soil profiles belonging to the same taxon (Batjes et al., 1997). The elaboration of taxotransfer rules thus requires the availability of large soil profile databases such as WISE (Batjes and Bridges, 1994).

The work reported here expanded on ISRIC's taxotransfer-related work with FAO and IIASA (Batjes et al., 1997) and a follow up study for IFPRI (Batjes, 2002), which focussed on applications of the 1:5 M scale Soil Map of the World (FAO, 1995). During the GEFSOC project, however, an updated procedure was developed for use with *primary* SOTER databases. The procedure considers the Revised Legend (FAO, 1988) and uses a more detailed procedure for aggregating the soil profile data; data for each soil unit are now clustered according to five textural classes (CEC, 1985) and five depth ranges (0–20, 20–40, 40–60, 60–80 and 80–100 cm). Conversely, only two depth classes (0–30 and 30–100 cm) and three *topsoil* textural classes were used in the preceding taxotransfer-work for use with the Soil Map of the World, which considered the original legend (FAO-Unesco, 1974).

Table 3
Main characteristics of SOTER databases consolidated for the GEFSOC project

Case study area	Scale	Area ($\times$1000 km^2)	Number of				Profile density (per 1000 km^2)
			Polygons	Unique SUs	SCs per SU[a]	Profiles	
Brazil-Amazon	1:5 M	5100	571	299	1–5	331	0.06
Kenya	1:1 M	583	3261	397	1–4	495[b]	0.8
IGP-India	1:1 M	480	497	36	1	36	0.08
Jordan	1:0.5 M	89	47	27	1–4	48[b]	0.5

[a] SU: SOTER unit; SC: soil component (see Fig. 1).
[b] Includes a number of synthetic and virtual profiles as detailed in the country reports.

The present scheme was based on statistical analyses of some 9600 profiles held in the ISRIC-WISE database, corresponding with over 43,000 horizons. Analyses of these data, so far, have permitted definition of 38,683 rules in total. The cut-off point for defining and applying any taxotransfer rule was that there were at least five observations for the soil unit, depth zone, soil textural class and attribute under consideration (i.e., $n_{\mathrm{WISE}} < 5$) (see Batjes, 2003 for a detailed discussion of the procedure).

In spite of the rather large number of taxotransfer-rules presently available, it has been necessary to introduce a number of expert-based rules. These rules take into consideration whether certain combinations of soil parameter estimates are considered pedo-chemically feasible or relevant for a specific soil unit. For example, the aluminium saturation percentage cannot be more than zero in soils with a high pH or, alternatively, calcium carbonate will not be present at low pH values. So far, 28 expert-rules have been defined (Batjes, 2003).

3.3.2. Flagging rules

All taxotransfer- and expert-rules have been flagged in the *secondary* databases to provide an indication of the inferred confidence in the soil parameter estimates presented (see Batjes and Gicheru, 2004; Batjes et al., 2003, 2004a, 2004b). The overall assumption has been that the confidence in a taxotransfer-based parameter estimate should increase with the size of the sample populations present in WISE. In addition, the confidence in soil parameter estimates derived from similar soil units should be higher than for those that had to be derived from similar major groups. However, a high inferred-confidence rating does not necessarily imply that the soil parameter estimates shown will be representative of the soil component under consideration. Profile selection for SOTER and WISE, like for any other regional soil database, is not probabilistic but based on available data and expert judgement. In addition, several of the soil properties under consideration here are readily modified by changes in land use, for example soil pH, soil salinity, aluminium saturation and organic matter content, and information on land use/management history was seldom available.

3.4. Linkage to GIS

The soil parameter estimates for the constituent soil components of a given SOTER unit – as characterized by the typical profiles (see Fig. 1) – were linked to the SOTER/GIS files, using the unique SOTER unit identifiers. The resulting, harmonized data sets can be used for a wide range of applications, including agro-ecological zoning, land evaluation, modelling of soil C stocks and changes, and studies of soil vulnerability to pollution. The following section shows how the *secondary* SOTER data have been used in the GEFSOC project concerned with estimating current and future changes under the influence of land use change.

4. Applications of the SOTER-GIS sets

4.1. Estimates of current SOC stocks

The project included a comparison of estimates of national SOC stocks computed with the GEFSOC system with independent estimates obtained using conventional mapping approaches. The latter generally involve combining soil or soil/vegetation map units with soil point data.

Map-based estimates of base line SOC stocks were available for Amazon-Brazil (Bernoux et al., 2002; Cerri et al., 2000; de Moraes et al., 1995) and India (Bhattacharyya et al., 2000a, 2000b, 2004; Velayutham et al., 2000). This was not the case for Kenya and Jordan therefore, new methods were developed to compute SOC stocks using the *secondary* SOTER data discussed here.

Kenya was used for methodology development; four different methods were compared (Batjes, 2004b):

(a) The SOC content (0–30 and 0–100 cm) computed for each representative profile was linked to the spatial information held on the GIS map annexe database.
(b) As above, but using the *average* SOC content for each FAO soil unit.
(c) As above, but using the *median* SOC content.
(d) Through simulation of *phenoforms.* For each soil *genoform* – here assumed to correspond with a given representative or typical profile (see Fig. 1) – different *phenoforms* were defined as resulting from differences or changes in soil management (Bouma et al., 1998b; Droogers and Bouma, 1997). Thereby, this practical approach permits the computation of variability in measured soil values within each soil component – the latter reflects both variations in the soil and those associated with the methods of sampling and measurement (Batjes, 2004b). Possible effects of mapped variation in soil conditions – i.e., the spatial data – on estimates of soil C stocks are also important, and these have been studied in an earlier paper (Batjes, 2000).

Method (d) was found to be the most useful, because it can be used to define 95% confidence intervals for median soil C stocks at national scale, as opposed to the *single* estimates obtained with methods (a)–(c) (Batjes, 2004b). So it was selected for use with *secondary* SOTER data sets (Table 4).

For Amazon-Brazil, estimates of total SOC obtained by other researchers, using different methods, were in close agreement to the value obtained in the current work despite the different spatial patterns mapped by these methods. This comparison provides a validation of method (d) (Batjes, 2005). By contrast our SOC estimates for IGP-India differed by 8% (0–30 cm) and 25% (0–100 cm) from earlier estimates (Bhattacharyya et al., 2004): 630 Tg C for 0–30 cm and 1560 Tg C for 0–100 cm. Possible reasons for

Table 4
Estimates of baseline SOC stocks

Study area	Area ($\times 1000$ km^2)	Depth (cm)	Organic carbon (Tg C)[a]
Amazon-Brazil	5100	0–30	23,943–24,151
		0–100	42,343–43,814
IGP-India	480	0–30	572–587
		0–100	1163–1184
Jordan	89	0–30	76–78
		0–100	136–139
Kenya	582	0–30	1892–1911
		0–100	3669–3715

[a] Data shown are 95% confidence intervals for the median; for methodological details see Batjes (2004b). 1 Tg C = 10^{12} g C.

these differences are: (a) all soil components were characterized by a single soil unit/profile in IGP-SOTER (Table 3), whereas the underlying soil associations have been described by 2–3 soil types on the source maps (Chandran et al., 2005, p. 42–44); (b) somewhat different boundaries have been used for the Indo-Gangetic Plains, India, in various studies (see Chandran et al., 2005); (c) missing bulk density data have been estimated using different procedures; (d) the SOTER-based estimates are 95% confidence intervals for median SOC stocks as opposed to average stocks (Bhattacharyya et al., 2004). Typically, the median is more robust than the mean and more resistant to erratic extreme observations (Snedecor and Cochran, 1980).

4.2. Projected changes in SOC stocks

The secondary SOTER-GIS data were also used to assess SOC stocks and changes for defined scenarios of land use and climate change with the GEFSOC system (Easter et al., 2005). This modelling tool can compute SOC stocks using three procedures: two process-based C-models (RothC and Century) and the empirical IPCC-method (IPCC, 2003). The output of the GEFSOC system for 1990, the Kyoto baseline year, has been evaluated using the independent SOC estimates presented in Table 4; results have been detailed elsewhere (Al-Adamat et al., 2007; Bhattacharyya et al., 2007; Cerri et al., 2007; Kamoni et al., 2007). Falloon et al. (2007) discussed possible impacts of modelled climate change on soil and vegetation C storage in the case study areas.

4.3. Other uses

Complementary to the direct project goals (Milne et al., 2007-a), the *secondary* SOTER datasets for Kenya and Jordan were also used to: (1) calculate the stocks of organic (SOC) and inorganic (SIC) or carbonate C per agro-ecological region, and (2) to project changes in SOC stocks – for defined changes in land use and management – using an empirical model (Batjes, 2004b, 2006). The latter procedure included a physical land evaluation (FAO, 1976; Rossiter, 1996; Sys et al., 1993) which, similar to Global Agro-Ecological Zoning (GAEZ) procedures (FAO, 1996; Fischer et al., 2002), allows filtering-out of areas that are considered biophysically (un)suited for the proposed land use/management types (scenarios). For example, a particular soil unit may be too saline for growing a specific crop under the specified conditions of land management and inputs.

Caution is required when assessing the effects of land use change on SOC stocks without explicitly considering differences in soil types (Lettens et al., 2005). Considering such differences is also important when assessing possible effects of water erosion on crop production (Mantel and van Engelen, 1999), proposing alternative approaches to intensively managed land (Bouma, 2001; Bouma et al., 1998a), and assessing soil gaseous emissions (Bouwman et al., 2002; van Bodegom et al., 2002). Future releases of the GEFSOC system, therefore, should also consider soil properties other than clay content and wetness. In principle, this could be done using the range of soil variables presented in the secondary SOTER databases (Table 1).

5. Discussion and conclusions

The secondary SOTER data for Amazon-Brazil, IGP-India, Jordan, and Kenya can be used for a wide range of environmental applications at national scale; this paper focussed on the assessment of SOC stocks. Estimates of SOC stocks using SOTER-methods were comparable to existing estimates based on conventional map-based approaches (Brazil and IGP-India). Further, to our knowledge, the GEFSOC project presented the first estimates of SOC stocks for Kenya and Jordan. Independent SOC estimates of the type presented here are essential to evaluate the output of modelling tools, such as the GEFSOC system.

The *primary* soil geographic and attribute data were typically compiled from multiple sources; data processing often involved complex issues of data acquisition, quality control and data harmonization (see Batjes, 2001). By implication, various sources of uncertainty will always remain in the derived data even though these were based on the best – and sometimes only – available data, thorough data integrity checks, and an elaborate scheme of taxotransfer- and expert-rules to fill gaps in the measured soil analytical data (Batjes, 2003). These possible limitations must be understood and accepted when using the *secondary* SOTER data. Similarly, various sources and types of uncertainty will be attached to the approaches and models used (Burrough, 1986; Smith et al., 1997, 2002). A particularly complex issue is that which relates to the structure or formulation of the decision-rules and the model itself. Projections relating to the development of the different C-pools in soils under changing environmental conditions and land use/management remain difficult (Kogel-Knabner et al., 2005). Estimates of SOC stocks and changes thus will remain fraught with uncertainty, irrespective of scale (IPCC, 2003; Watson et al., 2000; WBGU, 2003); it is important that this uncertainty be quantified (Falloon and Smith, 2003; Raupach et al., 2005). Hence, the present use of 95% confidence intervals for presenting estimates for the median, national scale SOC stocks.

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