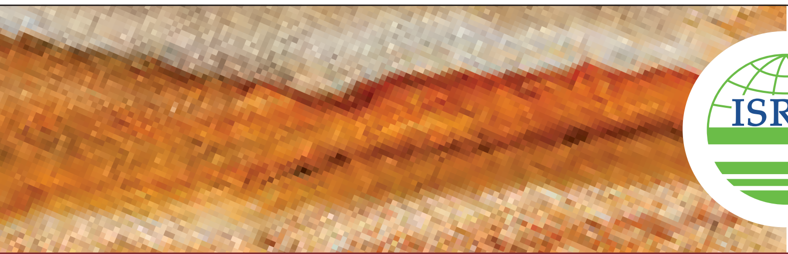
Towards improved soil information for quantification of environmental, societal and economic sustainability



ISRIC World Soil Information

ISRIC Report 2013/05

Niels H. Batjes, Prem S. Bindraban and Hannes I. Reuter

Towards improved soil information for quantification of environmental, societal and economic sustainability

Niels H. Batjes, Prem S. Bindraban and Hannes I. Reuter

ISRIC Report 2013/05

Wageningen, 2013

Director, ISRIC – World Soil Information
PO BOX 353
6700 AJ Wageningen
The Netherlands
E-mail: soil.isric@wur.nl

Additional information on ISRIC – World Soil Information can be accessed through http://www.isric.org

Citation
Batjes NH, Bindraban PS and Reuter HI. Towards improved soil information for quantification of environmental, societal and economic sustainability. Report 2013/05, ISRIC—World Soil Information, Wageningen. 44 pages, 4 figures and 3 tables.

World Soil Information

ISRIC Report 2013/05

Contents

List of Tables

List of Figures

Preface

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

This document discusses soil information needs in support of studies of environmental, societal and economic sustainability at an increasingly fine spatial resolution. These aspects are discussed within the context of ISRIC's emerging *Global Soil Information Facilities* (GSIF), together with the possible institutional implications. GSIF-related activities are currently being embedded in global initiatives such as the FAO-led *Global Soil Partnership* (GSP), *GlobalSoilMap.net*, the ICSU World Data System, and the Global Earth Observation System of Systems (GEOSS) that promote participatory approaches to data sharing.

In order to consolidate its world soil information services, ISRIC – World Soil Information is collaborating with national institutes and international organizations with a mandate for soil resource inventories.

Dr ir HMC (Hein) van Holsteijn
Director, *ad interim*, ISRIC – World Soil Information

Summary

This document discusses soil information needs in support of studies of environmental, societal and economic sustainability at an increasingly fine spatial resolution. First, the need for appropriately scaled, consistent and quality assessed soil information in support of studies of food productivity, soil and water management, soil carbon dynamics and greenhouse gas emissions, and the reduction or avoidance of land degradation are discussed. Soil variables considered most critical for current and likely future model-based assessments are identified and new, cost-effective measurement methods that may reduce the need for conventional laboratory methods are evaluated. Following on from this, the status and prospects for improving the accuracy of soil property maps and tabular information at increasingly detailed scales (finer resolution) for the world is addressed. Finally, the scope for collecting large amounts of 'site specific' and 'project specific' soil (survey) information, possibly through crowd-sourcing, and consistently storing, screening and analysing such data are discussed within the context of ISRIC's emerging *Global Soil Information Facilities* (GSIF), together with the institutional implications. GSIF-related activities are currently being embedded in global initiatives such as the FAO-led *Global Soil Partnership*, *GlobalSoilMap.net*, the ICSU World Data System, and the Global Earth Observation System of Systems (GEOSS) that promote participatory approaches to data sharing.

1 Introduction

Soils are the largest reservoir of carbon, water and nutrients in the terrestrial system and determine the availability of water and nutrients for plant growth and therefore food security, emission of greenhouse gasses, the preservation of biodiversity, and ultimately human livelihood. To address these global development issues, the processes that regulate plant production need to be understood as plants are able to synthesize food directly from carbon dioxide and water using energy from sunlight, provided nutrient levels are not limiting. About one quarter of the global land area has suffered a decline in productivity and in the ability to provide vital soil ecosystem services, largely because of soil carbon losses (UNEP 2012) where soil carbon, held in soil organic matter, is used as an indicator for soil health.

Worldwide, the incremental demand for food combined with the demand for other competing land uses, such as urbanization, recreation, biofuels and bio-based products puts growing pressure on many agricultural systems with concomitant emissions of greenhouse gases (GHG), pollution of the environment, and land degradation (Bouma *et al.* 1998a; Bruinsma 2009; Dent *et al.* 2007; FAO 2011b; Smith 2012; Smith *et al.* 2010). The prevention or restoration of land degradation could be more effective when addressing major developmental issues, such as poverty and food insecurity (Fresco 2009; Gisladottir and Stocking 2005; van Ittersum *et al.* 2012), water scarcity for food production (Immerzeel and Bierkens 2012; Rijsberman 2006; Rockström *et al.* 2012) and mitigation and adaptation to climate change (FAO 2011a; Smith 2011; UNFCCC 2008; Watson *et al.* 2000), in addition to the drivers of change themselves. This situation calls for sustainable agricultural production systems, based on basic production ecological principles (Bindraban 2012; Rabbinge and Bindraban 2012), that duly consider soil and water conservation practices and use an Ecosystems Approach (Robinson *et al.* 2012). Designing such production systems will require the unrestricted access to a range of biophysical and socio-economic databases at an increasingly fine resolution. A possible source of concern here, however, is that free access to such fine resolution data may be misused for say 'land grabbing' purposes (e.g., De Schutter 2011; HLPE 2011; Lorenzo *et al.* 2009), rather than to address selected Millennium Development Goals such as reducing extreme poverty and improving human livelihood (see Rosegrant *et al.* 2006; Sachs *et al.* 2009; UN-MDG 2012).

Knowledge of how different land use and management strategies will affect soil nutrient levels, water delivery, food production, agro-ecosystem carbon dynamics, environmental pollution and greenhouse gas emissions, land degradation and sustainability remains far from complete (e.g., Kogel-Knabner *et al.* 2005; Milne *et al.* 2010; Paustian 2012; Smith *et al.* 2012; Stockmann *et al.* 2013) and the associated uncertainties remain large (e.g., Bindraban *et al.* 2012; IPCC 2006; Mueller *et al.* 2010; Nol *et al.* 2010; Schulp *et al.* 2012; Smaling *et al.* 2011), irrespective of scale.

Estimating or modelling trends or changes in the above will require access to a wide range of databases — climate, terrain, soils and land use/vegetation (or 'activity data'), as well as the main socio-economic drivers— and a range of appropriately scaled tools, each of these having their own, often ill-defined, uncertainties (Hewitt *et al.* 2012; Milne *et al.* 2010; Raupach *et al.* 2005; Ravindranath and Ostwald 2008; Smith *et al.* 2012). Developing, managing, sustaining and utilising such databases at any scale or resolution will require enduring efforts, as will model development and testing.

Advances in information and communication technology (ICT) allow timeless exchange of information and analysis of massive amounts of data at every imaginable scale from field level to large areas. An increasing number of initiatives are being put in place to develop global databases, such as agricultural experiments

(AgTrials 2012), and improving modelled assessments (AgMIP 2012) of agro-ecosystems functioning. There is an urgent need to support these initiatives with soil data as these are often not collected or considered in the analyses, leading to enhanced inaccuracy and poor understanding of the performance of agro-ecosystems.

Soils play a major role in many of the above processes. Nonetheless, they have so far been under considered in many global analyses that provide the basis for the provision of ecosystem services, studies of environmental degradation and issues of competing land uses — more ground work has to be done in the soil science community to fully link up with these global developments (Bindraban *et al.* 2010; Bouma 2001; Hartemink and McBratney 2008; Montanarella and Vargas 2012). In this context, it has been argued, for example, that the soil science community should focus research on the seven soil functions of the European Soil Protection Strategy (i.e., biomass production; storing filtering and transforming nutrients, substances and water; biodiversity pool; physical and cultural environment for humans; source of raw materials; acting as carbon pool; archive of geological and archaeological heritage) to become interesting as a partner in interdisciplinary studies (Bouma and Montanarella 2012).

Whereas the collection of new soil data through field sampling campaigns is still needed, the development of global and local soil databases can be based largely on legacy data (Hartemink *et al.* 2008). In many countries, soil maps and reports are being lost because of lack of attention and means for storage and retrieval. This is often compounded by a loss of institutions that have been responsible for the acquisition and maintenance of soil and land resources data (Hartemink and McBratney 2008; Nachtergaele *et al.* 2012). The situation is particularly alarming in developing countries where valuable —and sometimes unique— data must be digitized in a consistent format before they are permanently lost (Batjes and Bridges 1994; Hallet *et al.* 2006; Panagos *et al.* 2011; Selvarajdou *et al.* 2005; Sombroek 1990). The so safeguarded 'legacy' data, upon screening for accuracy, can provide key inputs for various data compilation and analysis activities, including pedotransfer function development, global agro-ecological zoning, assessments of crop production potential, soil vulnerability to pollution, and soil gaseous emission potentials (e.g., Avellan *et al.* 2012; Bouwman *et al.* 2002; Fischer *et al.* 2010; Mekonnen and Hoekstra 2011; Romero *et al.* 2012; Stehfest and Bouwman 2006).

This overview and discussion paper focusses on main soil data-related challenges for improved, model-based quantification of key global issues at an increasingly fine spatial resolution, and the need to consider options for reducing the associated uncertainties. First, it considers key global issues addressed within the framework of the global conventions (e.g., UNCCD, UNFCCC and UNCDB) and Millennium Development Goals to identify soil variables considered most critical for current and likely future quantification systems. The document also discusses the status and future for improving soil maps and tabular information, both in terms of area-class and soil-property maps (for definitions see Section 3), at an increasingly detailed (fine) resolution. Finally, the feasibility of collating vast amounts of 'site specific' and 'project specific' soil (survey) data, both legacy (historic) and newly collected, through crowd-sourcing, using the web-based *Global Soil Information Facilities* (GSIF) currently under development at ISRIC – World Soil Information, the ICSU (International Council for Science) designated World Data Centre for Soils since 1989, is presented. Institutional implications and requirements for embedding these activities in the framework of larger programmes, such as the *Global Soil Partnership* (GSP, see FAO 2011a) and the Global Agricultural Research Partnership (see CGIAR 2012), are also addressed.

2 Soil data needs at varying levels of detail

2.1 Soil quality as an example

Overall, there are no simple, accessible indicators for soil quality —for a defined use— that can convey a message effectively to colleague scientists and laymen in soil science (Bindraban *et al.* 2000; Bouma 2002; Dumanski and Pieri 2000; FAO 1976; Huber *et al.* 2008; Karlen *et al.* 1997). One way to address this complexity, is to understand the effects of spatial scale (or resolution) at which a soil database is developed on the type of questions that may be asked and the level of detail of conclusions that may be drawn (Batjes and Bridges 1994; Bouma 2002; Bouma *et al.* 1996; Finke 2006; Hartemink *et al.* 2008; Mednick 2010; Middelburg *et al.* 1999; van Ittersum *et al.* 2012; Wang and Melesse 2006).

In conventional soil survey terms, broad scale maps (e.g., <1:1 000 000 such as ESDB 2006; FAO 1995; FAO *et al.* 2012) are appropriate for awareness-raising through assessments at a global or continental level. More detailed maps, or larger scales, will be needed for analyses at national level (e.g., 1:250 000) and regional or catchment level (e.g., 1:25,000) for strategic decision making and (land use) planning. Farm management and land use at the farm level will generally require maps at scale > 1:10,000 (see Landon 1991; Soil Survey Division Staff 1993). Users of soil data increasingly demand gridded information; in digital soil mapping, the concept of scale can better be replaced by resolution and spacing (Bishop *et al.* 2001; McBratney *et al.* 2003).

Several researchers have proposed the ratio between estimated production and potential production or the yield gap, defined as the gap between average farmer's yields and potential yields over some specified spatial and temporal scale of interest, as a land quality indicator for agricultural production (e.g., Bindraban *et al.* 2000; Bouma *et al.* 1998b; Tittonell *et al.* 2008; van Ittersum *et al.* 2012; van Keulen 2007). These indicators are a measure for the combined effect of soil properties, climate and crop characteristics on productivity. Summarizing, for any site, potential production is modelled as a function of crop characteristics, radiation levels and air temperatures, under the assumption of non-limiting supply of water and nutrients (Fig. 1). Rainfall distribution during the growing season of a crop will determine water-limited yields at a given location; comparison of these predicted yields will provide a measure for irrigation needs. As discussed by Bouma *et al.* (1998b), various soil properties are needed to make such an assessment: soil water retention as determined by texture, organic matter content and clay mineralogy, as well as porosity, rootable depth of soil and slope angle as regulators of possible runoff and infiltration.

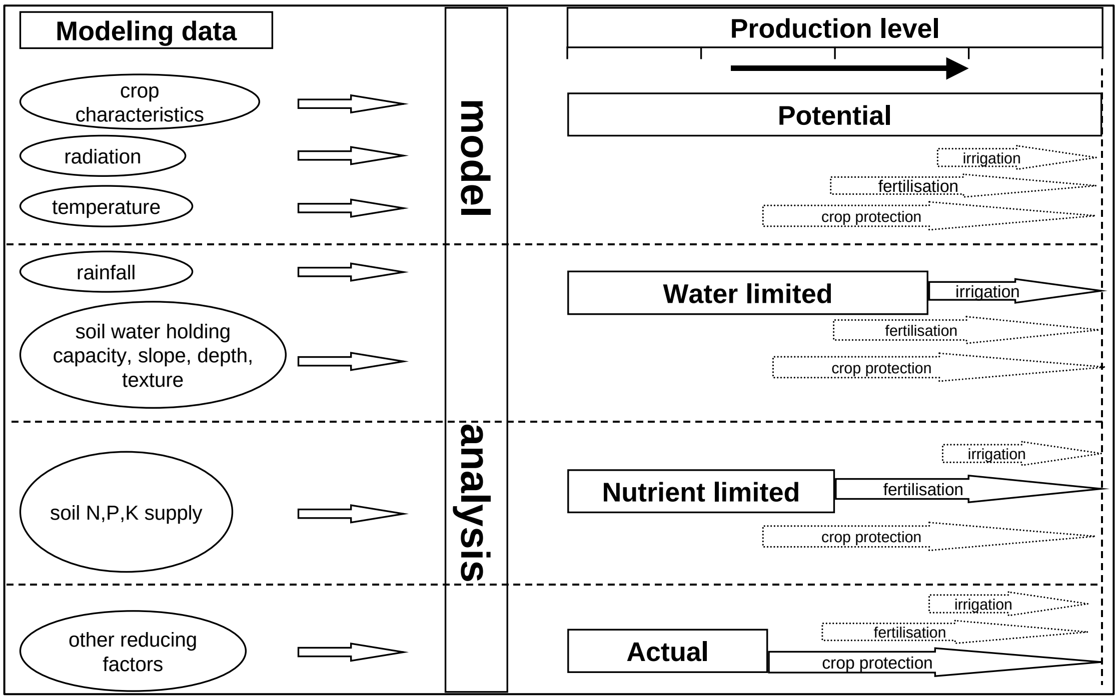


Figure 1
Data needs in relation to modelled, biophysical production levels (Source: Bindraban et al., 2000).

The actual depth to which roots of a given crop (variety) can grow in a given soil will vary depending on the soil type, for example with salinity levels and toxicities, such as exchangeable aluminium. This depth will largely determine the scope for nutrient uptake by a crop and thereby actual production. Similarly, erosion by water can reduce the rootable depth at a given location and thus the amount of water and nutrients available to a crop during the growing season. Soil compaction, resulting from the use of heavy machinery or excessive cattle trampling for example, may reduce infiltration rates, available water content and soil aeration. Thereby, it can also decrease biomass production and crop yields and modify gaseous emissions from the soil. Alternatively, the application of lime to naturally acid soils will be reflected in increased depth of rooting as it alters the amount of water and nutrients available to the crop (Bouma *et al.* 1998b; Sanchez 1976; van Wambeke 1992). Hence, judicious liming as corrective measure for limiting soil characteristics may result in actual production levels exceeding modelled water-limited or nutrient-limited yield levels as reported, for example, for the formerly acid, nutrient-limited soils of the Brazilian Cerrado (Batlle-Bayer *et al.* 2010; Lopes 1996).

In addition to water and nutrients, the incidence of pests, diseases and fires may adversely impact on crop performance and such effects may vary with climate change (e.g., Clark *et al.* 2009; Running 2006; Schultz 2008; Thomson *et al.* 2010). For any region, the actual field-measured yields should be compared with the modelled yields to assess the regional yield gap (see Janssen *et al.* 1990; Jones *et al.* 1988; Smaling and Janssen 1993; van Ittersum *et al.* 2012).

Where the above-mentioned a-biotic and biotic factors determine the ecological production level, closing the yield gap will depend on the ability of governments and farmers to take intervention measures (e.g., fertilizer application, organic matter amendments, crop residue use, tillage, irrigation/drainage practices). Socio-economic conditions such as population density, infrastructure, access to markets and commodity prices, policy environment and policy-incentives determine to a large extent how well governments and farmers are able to take intervention measures (Izac 1997; Koning *et al.* 2001; Rabbinge and Bindraban 2012; Sanchez *et al.* 1997; Tomich *et al.* 2004).

2.2 Minimum soil data set

Soil data are one of the essential components in understanding the complexity of agro-ecosystems for identifying intervention measures towards achieving global development goals. Consensus should be reached on the (minimum and realistic) range of soil properties that should be collected (or generated) to address a range of pressing agricultural and environmental issues (Fig. 2), at a given scale level. These may be taken here as the key issues addressed by the *Global Soil Partnership* for Food Security and Climate Change Mitigation and Adaptation (FAO 2011a), the UN conventions (UNFCCC, UNCDB and UNCDD) and the International Panel for Climate Change (IPCC). Typically, the required attributes (Table 1) may be considered in general (i.e., site level such as location, soil classification, terrain, drainage, effective depth, natural vegetation or land use and management history) and morphological, chemical and physical data at the soil horizon level (Batjes and Bridges 1994; ESDB 2006; Ingram 1993; Soil Survey Staff 2012).

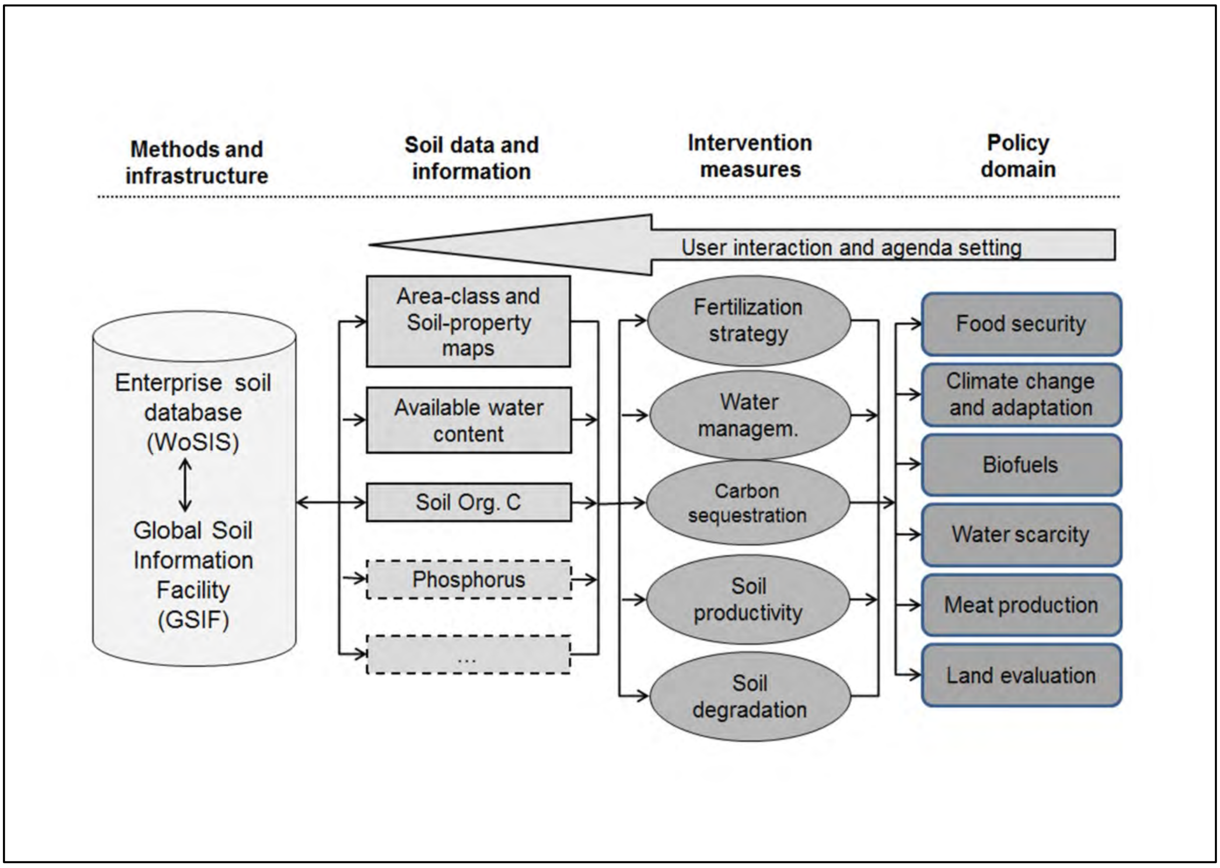


Figure 2
Management and use of soil information in support of research and informed decision making.

In addition to information on geographic distribution and soil mapping unit composition for area-class maps (see Section 3.2) or geo-location for soil-property maps (see Section 3.3), the basic list of 'desired' attributes should at least include: proportion of fragments > 2 mm, particle size distribution (sand, silt, and clay content), bulk density, pH-H_2O, exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+), exchangeable Al^{3+}, cation exchange capacity (CEC), organic carbon content and total nitrogen, with supporting information about the laboratory methods used and laboratory where the analyses were made. The latter information is needed to assess the inter-comparability of soil analytical methods worldwide, as a prerequisite for subsequent data harmonisation (see Cools *et al.* 2006; Kleinman *et al.* 2001; Pleijsier 1989; Rousseva 1997; van Reeuwijk 1998). On a global level, to our knowledge, there is no database yet that allows performing consistent, standardised, soil analytical method transformation and harmonisation, including uncertainty calculations.

Other indicators of soil condition, such as soil Phosphorus retention, moisture storage capacity, and clay mineral type are rarely analysed except in research projects or specific purpose surveys because they tend to be costly, but these indicators can be derived from the proposed basic list of attributes (Table 1).

Table 1
Examples of soil attributes needed for selected environmental studies[a].

Topic	Soil processes	Relevant soil factors
Crop production	Water release, weathering, cation exchange	Fertility status (NPK, micronutrients), pH (Al-toxicity and alkalinity), salinity, soil moisture characteristics and rootable depth
Pollution by heavy metals	Adsorption, solubility	Organic matter content, pH, $CaCO_3$ content, water balance and salinity
Acidification	Weathering, base exchange	$CaCO_3$, exchangeable bases, cation exchange capacity (CEC) and mineralogy
GHG emissions	Organic matter formation/ decomposition (CO_2); methanogenesis and methane oxidation (CH_4); denitrification and nitrification (N_2O)	Organic matter (OM) content; N-content, including N deposition; soil drainage (redox-potential); soil structure/porosity; pH; salinity; soil moisture characteristics; soil fertility; rootable depth; sulphate content (CH_4)

[a] Also, from auxiliary sources, data on climate, land use/vegetation, management practices (e.g., fertilizer application; organic matter amendments; tillage, irrigation and drainage practices; loading with pollutants) and information on main controlling socio-economic factors (e.g., population density, commodity prices, access to markets) and policy-incentives at the appropriate scale (After: Ingram, 1993).

2.3 Derived soil properties

Several properties, as shown in Table 2, can be derived from the more commonly measured soil properties using various procedures. For example, gaps in key soil attributes such as bulk density and water retention can be filled, in secondary databases, using a range of pedotransfer functions (PTF) (e.g., Bernoux *et al.* 1998; Bouma and van Lanen 1986; Pachepsky *et al.* 2006; Saxton *et al.* 1986; Wösten *et al.* 2001) and pedotransfer rules (e.g., Batjes *et al.* 2007; ESB 2003; FAO 1995). Inherently, use of such functions will introduce added uncertainty, which will need to be quantified (e.g., Heuvelink and Brown 2006; Larocque *et al.* 2008; Loosvelt *et al.* 2011; Minasny and McBratney 2002; Raupach *et al.* 2005; Schaap and Leij 1998). Hence, such functions should be always expressed with their uncertainty measures. According to McBratney *et al.* (2011), three tables are needed to indicate whether a user can potentially apply a published PTF to their data: 1) information and statistics about the (input) training data, 2) calibration results of the output parameters and 3) statistics of the validation results of the output parameters using an independent data set. In principle, this type of information can also be accommodated in enterprise databases like WoSIS, ISRIC's World Soil

Information System (Tempel *et al.* 2013), and similar systems (e.g., Soil Survey Staff 2012). Further, as new environmental, societal and economic issues come to the fore, such enterprise databases should be able to incorporate additional sets soil properties as well as new methods of analysis that may be needed by the evolving models.

Table 2
Examples of secondary information that can be derived from measured soil properties[a].

Primary soil data	Derived data
Soil surface colour	Albedo
Organic C, total N, bulk density and gravel content by horizon or layer	Organic C and N pools (e.g., as kg m^{-2} to 1 m depth)
θ(h), bulk density and rooting depth	Water-holding capacity
Heat capacity of soil constituents	heat conductance
Particle size distribution, moisture content and θ(h)	K_{sat}, $K(\theta)$
CEC, organic carbon content, clay content and θ(h)	Clay mineralogy
CEC and exchangeable bases	Soil nutrient status
*p*H	Soil acidity resp. alkalinity
OC, N, clay and $CaCO_3$ content	E_h/pH buffer relationships
Soil Munsell colour, CEC, clay and OC content	Free Fe_2O_3 content

[a] Abbreviations: θ= volumetric water content; h= soil water pressure head; ρ= bulk density; CEC= cation exchange capacity; OC= organic carbon content (After: Batjes and Bridges, 1994).

2.4 Novel measurement techniques

Standard or conventional chemical procedures for soil analysis are generally based on a range of extractants that are used to assess the 'adequacy' of nutrients for plants or as indicators of important soil conditions that affect soil management (e.g., Soil Survey Staff 2011; van Reeuwijk 1995). Although accurate, such methods are often too costly for routine use during large soil sampling and monitoring campaigns for which a range of new measurement techniques is being developed. For example, both mid infrared reflectance spectroscopy (MIR) and visible and near infrared reflectance spectroscopy (VNIR), can be used to analyse soils directly (Brown *et al.* 2006; Guerrero *et al.* 2010; Shepherd and Walsh 2002; Viscarra *et al.* 2010).

When compared with NIR spectroscopy for prediction of soil properties, MIR was found to be superior (Merry and Janik 2001). MIR is increasingly used as a cost-effective method to *predict* a wide range of chemical and physical soil properties that are closely related to the bulk properties of soil (e.g., clay, organic matter, carbonate content, moisture content, cation exchange capacity and some exchangeable cations, and mineralogy) from a single spectrum (Clark 1999; Janik *et al.* 2007; Merry and Janik 2001; Terhoeven-Urselmans *et al.* 2008), see Table 3. Alternatively, MIR technology performs poorly with the commonly used soil analyses that are based on soil solution rather than the soil matrix, such as extractable P, S and N, because of their generally low concentration in the soil environment (e.g., Merry and Janik 2001). Conventionally *measured* values (e.g., SOC by dry combustion, cation exchange capacity) in reference laboratories remain essential to develop regional, spectral libraries for calibration of additional spectral measurements (Cambule *et al.* 2012; Rossel *et al.* 2008; Stevens *et al.* 2008). This points to the usefulness of having large soil reference collections for the world (Brown *et al.* 2006; Shepherd and Walsh 2002; Terhoeven-Urselmans *et al.* 2010), such as maintained by ISRIC – World Soil Information. Further research is needed to test the use of soil reflectance in pedotransfer functions for prediction of soil functional attributes (e.g., Shepherd and Walsh 2002; Stevens *et al.* 2008).

Table 3
Example of soil properties that may be predicted by MIR[a].

Physical properties	Chemical properties
Particle size (clay, silt, sand)	Exchangeable cations: Ca, Mg, K, Na; CEC
Bulk density	Carbon pool: total organic, particulate organic, charcoal; inorganic C; total nitrogen
Volumetric water content (at various tensions from 0 to -15,000 kPa)	Phosphorus buffering index
Quantitative X-ray diffraction (quartz, kaolinite, smectite)	Soil reaction (pH-water, pH-$CaCl_2$)
Quantitative X-ray fluorescence (Ca, Mg, Fe, Al, Si)	Electrical conductivity
Water stable aggregates	Exchangeable sodium percentage

[a] Based on various authors (Merry and Janik, 2001; Janik *et al.* 2007; Viscarra *et al.*, 2010), MIR stands for mid infrared spectroscopy, see text.

Several soil variables, including SOC, can also be measured using cost-effective proximal sensing techniques, such as infrared reflectance spectroscopy or airborne sensed hyper-spectral imagery in the visible (VIS) and near-infrared (NIR) region (Gomez *et al.* 2008; Selige *et al.* 2006; Siegmann *et al.* 2012). Again, these observations will need to be calibrated using conventional laboratory techniques for some 10-20% of the samples (Terhoeven-Urselmans *et al.* 2008; Viscarra *et al.* 2010). According to Brown *et al.* (2006), VNIR soil characterisation has the potential to replace or augment standard soil characterization techniques where rapid and inexpensive analysis is required; for a comprehensive discussion see Viscarra *et al.* (2010). Space borne spectroscopy, however, has been of limited use in retrieving soil data when compared to laboratory or field spectroscopy (Mulder *et al.* 2011).

Most remote sensing techniques are mainly applicable to bare, surface soils. However, new procedures are being developed to filter out the influence of plants from the mixed spectra, so that the residual soil spectra contain enough information for mapping selected soil properties, such as the SOC distribution within agricultural fields (e.g., Bartholomeus *et al.* 2011; Fernandez-Buces *et al.* 2006; Hbirkou *et al.* 2012; Stevens *et al.* 2010). Generally, such mapping approaches will need to be combined with ancillary data and field observations to be effective (Dewitte *et al.* 2012); soil legacy data can be supportive in this respect.

Advances and challenges in airborne electromagnetics and remote sensing of agro-ecosystems and soils, including the newest techniques within active, passive, optical and microwave remote sensing, to measure soil properties and their dynamics are discussed elsewhere (e.g., Anderson and Croft 2009; Malenovský *et al.* 2007; Schaepman *et al.* 2007). Overall, remote sensing is in a strong position to provide meaningful spatial data for use in soil science investigations (Anderson and Croft 2009).

2.5 Data availability versus data sharing

The fact that an attribute can be physically accommodated in a database is no guarantee that measured data will be available for this property as it may not have been measured during the underpinning soil surveys, depending on their stated objective (e.g., exploratory, reconnaissance, semi-detailed or detailed) as explained elsewhere (see Batjes 2009; Landon 1991; Soil Survey Division Staff 1993). For example, the so-called 'mandatory' soil attributes specified for the World Soil and Terrain (SOTER) database (van Engelen and Dijkshoorn 2013) —depth of horizon, matrix colour, texture, pH, CEC, cation composition, content of $CaCO_3$, organic carbon and total nitrogen— often are simply not available, or alternatively *not freely accessible*, for many regions.

There are, for example, over 1480 soil profiles for Tunisia (see Brahim *et al.* 2010) but only 56 thereof were 'available' for inclusion in the SOTER database for the country (Dijkshoorn *et al.* 2008). A similar situation arose for the Democratic Republic of the Congo, Rwanda and Burundi for which only 167 profiles were readily accessible for inclusion in SOTER (see FAO *et al.* 2007; Goyens *et al.* 2007), while much larger sets of profile data are known to be available for the region (see Jones *et al.* 2012; Van Ranst *et al.* 2010), for example some 1833 for Rwanda alone (Verdoodt and Van Ranst 2006). Restricted 'data access' is also common in Europe (see Panagos *et al.* 2013) unlike for the United States of America. These examples, may serve to raise the critical issue of data accessibility and policies for sharing data (Carlson 2011; Guralnick *et al.* 2009; Uhlir and Schröder 2009; Uhlir *et al.* 2009; Webster 1997). As an ICSU World Data Centre, ISRIC aims for 'full and open exchange of primary data, metadata and derived data respecting relevant international and national policies and legislation with regard to intellectual property of the data and personal information.' ISRIC's online Data Policy clearly indicates that 'data are stored and provided to users in accordance with the access category specified by the data provider' (ISRIC 2012).

3 Digital soil maps

3.1 Mapping approaches

In broad terms, there are two types of mapping approaches: area-class and soil-property maps. Most soil information is still presented as (conventional) area-class maps on which a mapping unit is assigned to a class, either presented on paper or in GIS-database format. For this, soil experts must first decipher the relationships between the landscape and regional soil conditions, based on the principles of soil formation (e.g., Jenny 1941); thereafter, soil (type) polygons are drawn based on perceived landscape units. Typically, such area-class maps are made by a long and complex process involving numerous stages, some of which are partially subjective (Batjes 2000; FAO *et al.* 2012; Landon 1991; van Engelen and Wen 1995). As a result, there are no adequate models of uncertainty for this type of map (Goodchild 1994; Heuvelink and Brown 2006).

Typically, area-class maps are made for use at a given scale and for a defined purpose. Intensive surveys require more direct measurements of the properties mapped than do less-intensive surveys, and, normally, their purpose is more specific (Landon 1991; Soil Survey Division Staff 1993). In the GIS era, however, as a result of the ease of processing, boundaries (hence map unit composition) shown on coarse resolution maps are often (erroneously) maintained at finer resolution. So, for example, boundaries originally mapped at a coarse resolution of say 5 x 5 arc minutes will be used to characterize 100 polygons at a finer resolution (30 x 30 arc seconds) with an (assumed) identical map unit composition, which is incorrect.

Digital soil mapping (DSM) techniques offer great opportunities to enhance existing, area-class soil information at an increasingly fine resolution, with quantified uncertainty levels. DSM involves the creation and population of a geographically referenced soil database, generated at a given resolution, by using field and laboratory observation methods coupled with environmental data, termed covariates, through quantitative relationships (Grunwald *et al.* 2011; Hartemink *et al.* 2008; Hartemink *et al.* 2010; Hengl 2009; Minasny *et al.* 2010b). DSM approaches, of different complexity, are being used in international and global projects like e-SOTER (Van Engelen 2011; van Engelen and Dijkshoorn 2013), *GlobalSoilMap.net* (Grunwald *et al.* 2011; Sanchez *et al.* 2009) as well as in several smaller national projects. Although there are recognised synergies between the area-class and soil-property mapping approach, for example where conventional soil maps are updated using digital soil mapping techniques and covariate layers (e.g., Kempen 2011; Minasny *et al.* 2012; Yang *et al.* 2011), these are as yet hardly addressed by the current soil science community. Similarly, for pragmatic reasons, the different mapping approaches are discussed in separate sections in this report.

3.2 Area-class maps

3.2.1 Global scale

In 2008, FAO and the International Institute for Applied Systems Analysis (IIASA) undertook to combine recently compiled regional and national scale updates of soil information with the information presented on the old 1:5 M Digital Soil Map of the World, gridded at 5 by 5 arc minute (DSMW, FAO 1995). The resulting product, known as the Harmonized World Soil Database (HWSD, FAO *et al.* 2012), incorporates information from four main sources: a) regional soil and terrain (SOTWIS) databases, at scale 1:1M to 1:5M, derived from SOTER and the ISRIC-WISE soil profile database — these cover Latin America and the Caribbean, as well as large sections of Southern and Central Africa; b) a recent update of soil information for Europe and northern Eurasia by the European Soil Bureau Network at scale 1:1M; c) the recent update of the 1:1M scale Soil Map of China by the Institute of Soil Science, Chinese Academy of Sciences; and, d) the DSMW for regions not updated under a) to c) above. For practical reasons, the spatial data (mainly soil complexes) were presented at a resolution of about 1 km (30 by 30 arc-second) despite recognized limitations to this assumption (FAO *et al.* 2012, p. 2) — 'The HWSD by necessity presents therefore multiple grid cells with identical attributes occurring in individual soil mapping units as provided on the original vector maps'. For each component soil of a mapping unit, HWSD presents depth-weighted soil property estimates for 13 key attributes, including soil drainage, soil texture, bulk density and content of organic carbon, for 0-30 cm and 30-100 cm. However, no explicit information is provided with HWSD about the possible uncertainty of these predictions.

Further update of the HWSD is planned within the framework of the *Global Soil Partnership* (GSP, see Omuto *et al.* 2012), notably with data for the USA (Fortner and Price 2012; USDA-NRCS 2012), Canada (CANSIS 2011), Australia (ASRIS 2011) and West Africa (to be updated using SOTER); updates for other countries, for example in Asia and the Middle East Region, are anticipated on the longer-term, subject to the establishment of Regional Soil Partnerships within the *Global Soil Partnership* (FAO 2011a). Inherently, such activities will require adequate funding mechanisms.

As indicated by Nachtergaele *et al.* (2012) and others, the technological progress in terms of database development in itself is not a guarantee for enhanced quality or applicability of the HWSD data. Basically, through GIS and data-viewers, the derived information on global soil resources has been made more accessible to potential users and decision makers; this, with the risk that the 'appropriateness for use' of this inherently broad scale, thus generalized, database may be overlooked in studies that use the dis-aggregated data. By its nature, the HWSD may be considered for broad scale application, for example, at national scale for regions that lack more detailed data, but the associated uncertainties are inherently high. Alternatively, this type of generalised information may not be used for modelling yield analyses at experimental field level, as in agronomic trials.

3.2.2 National and subnational scale

The FAO has prepared an overview of country scale soil maps (1:1M to 1:250,000) for Africa south of the Sahara, Northern Africa, the Near-East, Asia and the Pacific (see Nachtergaele 1999; Omuto *et al.* 2012) with many countries only having partial information, and this generally in a non-digital format. Alternatively, comprehensive soil GIS-databases exist for China (Zhang and Wu 2012), various countries in Africa (Jones *et al.* 2012; Paterson and Mushia 2012), Latin America (Cerri *et al.* 2012; Lal *et al.* 2006), and Asia (Rossiter 2004). Many of these soil databases, however, are at an exploratory (broad) scale implying a coarse resolution. In Africa, for example, only Rwanda has full GIS coverage at 1:50,000 scale (Imerzekene and Ranst 2001; Van Ranst *et al.* 2010).

3.2.3 Project and site scale

Semi-detailed and detailed surveys (≥ 1:25,000) are generally carried out on an *ad hoc* basis to answer specific user questions (Finke 2006; Soil Survey Division Staff 1993). They are largely implemented for feasibility assessments or to contribute to the implementation of a development project (Landon 1991). Such projects increasingly include the measurement, monitoring and verification of changes in carbon stocks and GHG emissions associated with defined land use interventions in a defined study area (de Brogniez *et al.* 2011; Milne *et al.* 2010; Ravindranath and Ostwald 2008).

High-value, intensive agriculture is increasingly practised in parts of Africa, Asia and South America (McBratney *et al.* 2005). For these areas, Global Positioning System (GPS) referenced descriptive and analytical soil data is being collected at a very fine resolution (<10 m) using novel approaches (Aimrun *et al.* 2007; Paterson and Mushia 2012). These data may be used in precision farming applications for accurate and cost-effective application of fertilizers and other amendments, and to assess the associated GHG emissions and net CO_2-costs. However, as they are commercially owned and privately managed, these fine resolution datasets are not (presently) available for public use (Paterson and Mushia 2012) or for crowd-sourcing (see Section 4).

3.3 Soil property maps

Conventional soil survey is gradually being replaced by new, more cost-effective approaches. Since 2008, the *GlobalSoilMap.net* consortium is working towards a new digital soil map of the world using state-of-the-art and emerging technologies for soil mapping and predicting soil properties at fine (~100 m or 3 arc seconds) resolution (Hartemink *et al.* 2008; Malone *et al.* 2009; Sanchez *et al.* 2009). Key soil attributes that describe soil moisture, soil nutrient capacity, soil depth, the level of acidity and alkalinity, salinity, soil density and the proportion of clay, sand and silt have been considered in the initial stage of the project, but this list may later be expanded based on user-requests. Predictions will be made to a depth of 2 m (if possible) with data reported for six depth intervals of 0-5, 5-15, 15-30, 30-60, 60-100 and 100-200 cm (*GlobalSoilMap.net* 2011).

The geo-statistical approaches, such as kriging, co-kriging and regression kriging, still draw heavily on soil legacy data, derived from conventional soil survey, and a range of covariates such as climate, terrain, parent material and land cover (e.g., Hengl 2009; Heuvelink and Brown 2006; Minasny *et al.* 2010a). Additionally, remote sensing imagery, e.g. long-term time series of *Normalized Difference Vegetation Index* (NDV) values derived from MODIS (Moderate Resolution Imaging Spectroradiometer) imagery, can serve as a proxy for soil development.

More qualitative approaches to digital soil mapping, such as the classification tree approach, can be considered when quantitative mapping is thought to be unfeasible due to limited data availability (Odgers *et al.* 2012; Stoorvogel *et al.* 2009; Willcock *et al.* 2012). Conventional soil maps can be brought up-to-date using such cost-effective techniques (Hengl *et al.* 2012; Mora-Vallejo *et al.* 2008; Stoorvogel *et al.* 2009), for example, in areas where the depth of peat layers has changed since the original survey due to land use change (Kempen *et al.* 2009).

For Africa, new data are being collected in 60 sentinel sites using probabilistic sampling and novel, cost-effective measurement techniques (AfSIS 2012). For data poor regions, the Africa Soil Information System (AfSIS) still draws heavily on soil legacy data collated from conventional soil survey (Leenaars 2012; Odeh *et al.* 2012) for making soil property maps. The resulting soil property values are presented on a grid basis, starting with a 1 km resolution and ultimately a 100 m grid for the entire world. This new soil product will be enhanced by interpretation and functionality options that aim to assist better decisions in a range of global issues like food production and hunger eradication, climate change mitigation, and environmental degradation (Sanchez *et al.* 2009).

An innovative and key element of digital soil mapping is that the overall uncertainty of the prediction(s) is determined by combining uncertainties of the input data, a spatial inference model, and the soil functions used (e.g., Hengl 2009; Heuvelink and Brown 2006; Malone *et al.* 2009). Several pilot projects are underway to support the concepts and theories that underlie *GlobalSoilMap.net* of which work in Australia is probably the most advanced (Minasny *et al.* 2010b). Experimentation with various novel approaches, by researchers in many countries, is gradually leading towards consensus on a preferred consistent approach, indicating the potential to overcome some of the limitations imposed by labour-intensive and costly conventional soil surveys. Alternatively, as with any new approach, a number of scientific and operational challenges still need to be resolved (Hartemink *et al.* 2008; Lagacherie *et al.* 2006; Nachtergaele *et al.* 2012) and collaboration needs to be established with other disciplines as well.

4 Towards crowd-sourcing

Most land users and farmers in developing countries do not have access to even the most basic, quantitative information about the fertility of their fields (see Gilbert 2012). Nonetheless, communities that live with limited resources may have developed efficient land and water management systems to compensate for resource scarcity (Barrera-Bassols and Zinck 2003; Krasilnikov and Tabor 2003; Liniger and Critchley 2007). To convince such small farmers to adopt new sustainable land management (SLM) practices, any new techniques for increasing crop yield must bring extra benefits. Aragó Galindo *et al.* (2012) discuss the possibility of adopting precision agriculture principles for site-specific management, but the offered technology must be appropriate for such farmers. In such a context, taking soil samples and sending them to a qualified laboratory for analysis is often not realistic (Paterson and Mushia 2012). One possible solution, would be to provide local extension workers or agro-dealers with portable soil testing kits, for example for determining soil nutrient status (Fisher 2012) or soil carbon fractions (Stiles *et al.* 2011). Small farmers could then take their composite samples to these extension workers who in return would provide them with simple management-related recommendations. An operational example of such an initiative is the Africa Soil Health Consortium (ASHC 2012), aimed at improving soil fertility, food production and ultimately livelihoods of small farmer communities. Alternatively, in Victoria and South Australia, a 'portable' MIR spectrometer was taken to agricultural field days to provide on-site analysis of soil samples from pits or samples provided by farmers (Merry and Janik 2001).

Nowadays, GPS built in mobile phones allows to geo-locate sample sites within several metres (Arroqui *et al.* 2012). As a result, in principle, extension officers or agro-dealers could upload any geo-referenced field data to Global Soil Information Facilities, using crowd-sourcing facilities such as those being implemented by ISRIC (WSP 2012). Different graphical user interfaces are being developed, some of which may also be run in offline mode, for example in locations with limited internet access (Tempel *et al.* 2013).

The submitted data, upon screening and validation, can be used for making new digital soil maps using advanced geo-statistical methods, for example using ISRIC's emerging Global Soil Information Facilities, thereby gradually refining the information on soil properties for the world at an increasingly fine resolution while reducing the associated uncertainties.

For carbon sequestration projects aimed at CO_2 mitigation, more detailed field procedures (monitoring, reporting and verification) will probably be needed to achieve the desired accuracy required by the carbon market (de Brogniez *et al.* 2011; Milne *et al.* 2010; Ravindranath and Ostwald 2008; van Wesemael *et al.* 2010). Nonetheless, any newly collated soil and site data should also be up-loaded to a central enterprise database, such as WoSIS, using tailor-made data entry templates, thereby allowing for a wider and more cost-effective use of the newly collated data than initially foreseen for the SLM or C-sequestration projects alone. A possible application, for instance, would be to crowd-source results of field SOC and associated measurements, collected using consistent protocols, for use with the online Carbon Benefit Project (CBP) tools (GEF-CBP 2012; Milne *et al.* 2010). Geo-statistical analyses of such newly collated data, in combination with the already available legacy data and covariate layers in GSIF, may ultimately provide the level of local or regional soil detail needed for use with the complex, process-model based, tool of the CBP system. Similarly, results of agricultural experiments (e.g., AgTrials 2012) could be linked to WoSIS, ultimately to improve/validate modelled assessments of agro-ecosystems functioning (e.g., AgMIP 2012).

5 Institutional setting

To help address the above issues, in 2010 ISRIC started developing a comprehensive package of software tools, known as Global Soil Information Facilities (GSIF). As depicted in Figure 3, the emerging web-based facilities will focus on further development of procedures for making conventional class-area maps as well as DSM-generated soil property maps. Specific attention will be placed on the possible integration of soil-property mapping and area-class mapping approaches, but this research is still in the early stages. For the latter, ISRIC aims to fine-tune the Soil and Terrain Database (SOTER) methodology (Dobos *et al.* 2010; Pourabdollah *et al.* 2012; van Engelen and Dijkshoorn 2013), ultimately for application to the entire world, a long-term objective of the SOTER programme (Nachtergaele and Oldeman 2002; Oldeman and van Engelen 1993). The proposed digital soil mapping component within GSIF is outlined elsewhere (see GSIF 2012; Hengl 2009).

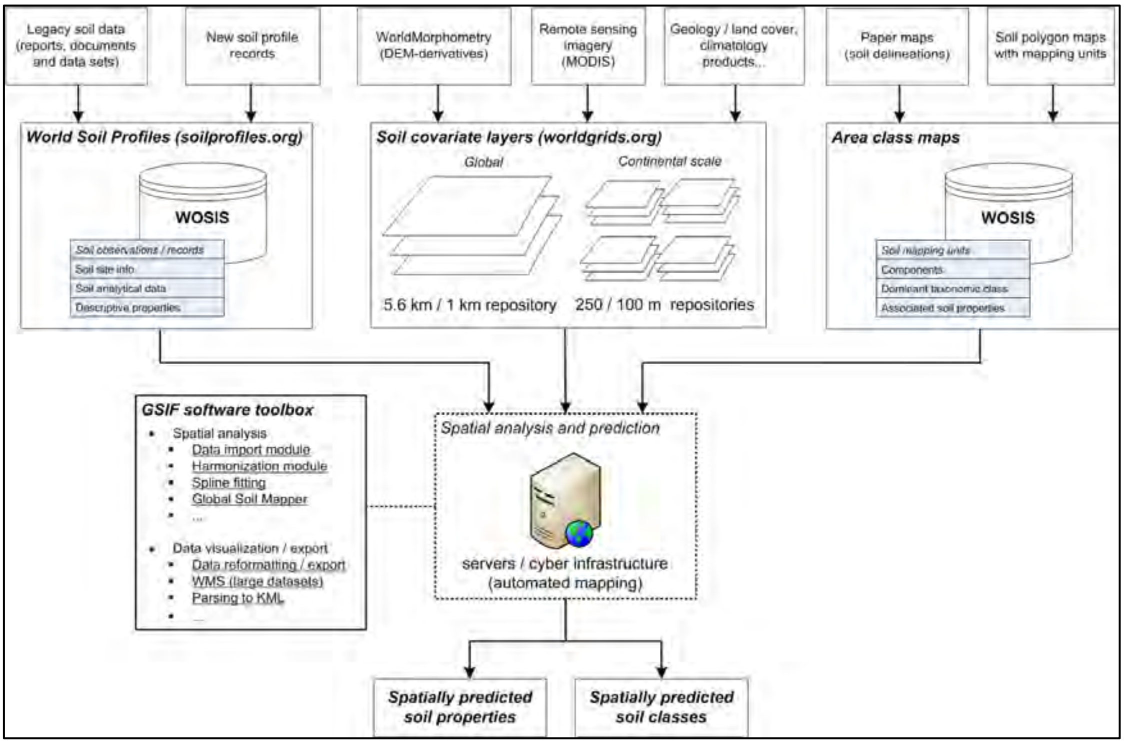


Figure 3
Proposed main components and general work-flow of the Global Soil Information Facilities (Source: GSIF, 2012).

While methodology development and testing will remain an on-going effort in the international arena, ISRIC together with local and regional stakeholders will focus on the production of consistent soil maps for the world, initially at a coarse resolution (1 to 5 km). Priority will be given to the production of digital soil maps for Africa at 1 km resolution (GSIF 2013b). Subsequently, the first version of a 1 km resolution map product for the entire world, known as *SoilGrids1km*, will be generated using geo-statistical approaches embedded in GSIF for selected soil properties and depth intervals (GSIF 2013a). Regularly updated versions of this emerging global product will be released as the methodology evolves and additional input data, soil as well as covariates, are collated and analysed by ISRIC and its partners.

A prototype of the online system is operational for internal use at ISRIC. Several components such as *worldsoilprofiles.org*, a portal for data entry and harmonisation, and *worldgrids.org*, a repository of mainly 5.6 km resolution covariate layers (Reuter and Hengl 2012), have been launched in 2012 for global use and testing. During the coming three years, the GSIF components will be developed further. In conjunction with this, a training programme has been rolled out to build a user network to stimulate use of the facilities, obtain feedback for improvements and further develop GSIF components through collaboration.

The development of GSIF also catalyses institutional collaboration. Capacity building and collaboration with national soil science institutes around the world on data collection, data screening, transformation, mapping and subsequent distribution of the derived information are considered essential and crucial for the relevance of the outcome of global soil-related activities for agricultural and climate change related research and development. Such activities may be envisaged, for instance, within the broader framework of the FAO-led *Global Soil Partnership* (FAO 2011a) and the Global Agricultural Research Partnership (CGIAR 2012).

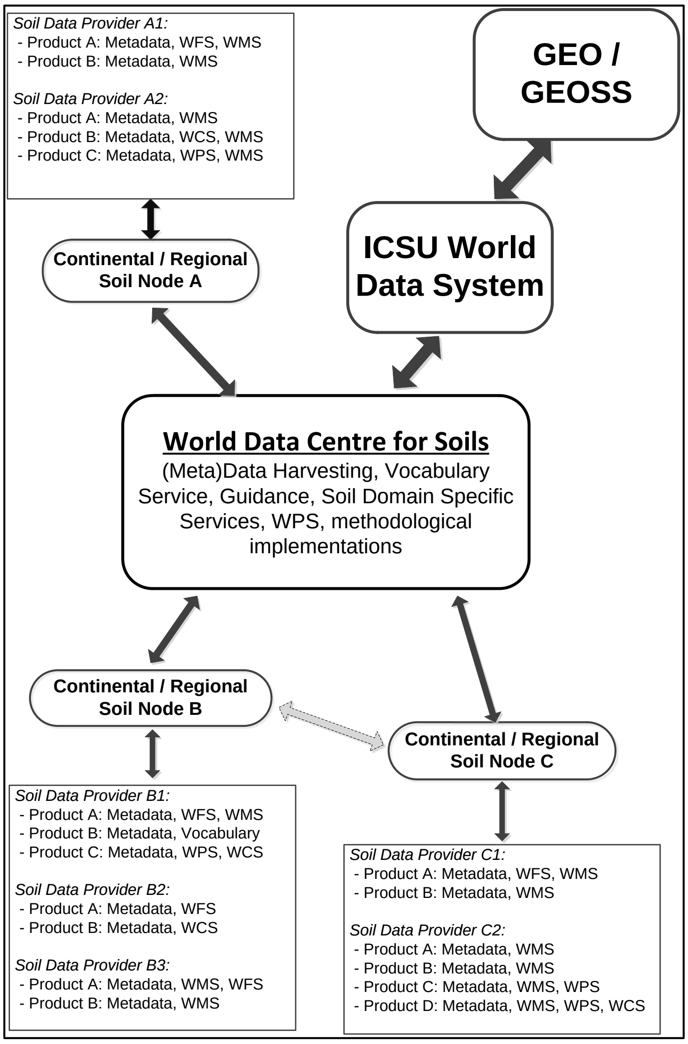


Figure 4
Schematic representation of regional soil data centres that feed into the ICSU World Data Centre for Soils, the World Data System and ultimately the Global Earth Observation System of Systems (GEOSS)
(Abbreviations: WFS, Web Feature Service; WCS, Web Coverage Service; WMS, Web Map Service; WPS, Web Processing Service).

A data policy tailored to the needs of data providers and users all over the world is actively being pursued (ISRIC 2012), in line with on-going developments within the ICSU World Data System to 'enable universal and equitable access to quality-assured scientific data, data services, products, and information, and to ensure long-term data stewardship' (see Fox and Harris 2012; ICSU-WDS 2011). Within the WDS, regular members such as the WDC-Soils hosted by ISRIC, are nodes that deal directly with 'data curation and data analysis services'. Each of these 'central' nodes may then exchange or harvest data from a range of regional nodes, each of which may provide a range of services (e.g., metadata service or web feature service) drawn from a larger range of national data providers (Fig. 4). Simultaneously, through the distributed WDS-network, validated soil data will feed into the Global Earth Observation System of Systems (GEOSS 2012), using agreed exchange protocols (e.g., OGC 2012; Pourabdollah *et al.* 2012; Vandenbroucke *et al.* 2011). The United Nations have also initiated an international programme to disclose unique knowledge, services and high-quality geographic information products to contribute to global development (UNSDI 2012). Ultimately, these initiatives will allow scientists, decision makers and other user communities to access an extraordinary range of multi-disciplinary information necessary to address the world's current pressing issues, at multiple scale levels. Various working groups of the International Union of Soil Sciences (IUSS), such as the working group on Soil Information Standards (SIS), can play a key role here to develop internationally agreed upon protocols and common methodologies for soil data exchange (e.g., SoilML) and analysis.

6 Discussion

There is a recognised and pressing need for improved analyses of environmental, societal and economic sustainability. Numerous initiatives and programmes are being implemented throughout the world to address pressing global issues and these demand a concentrated and coordinated international effort. These are aimed at, for instance, reducing the yield gap to ensure food security for the growing world population, addressing competing claims for land (e.g., food production versus biofuels or urbanisation), maintaining or enhancing soil health, improving human livelihood, mitigation and adaptation to climate change, as well as conserving biodiversity. Although diverse in scope, all these initiatives require soil information to be presented at an appropriate resolution, with quantified accuracy.

Improved soil databases and GIS maps, at an increasingly fine resolution, are necessary to gradually reduce the uncertainties generated through the extrapolation of often still limited (field) data. Four dimensions are important here, space, depth and time. Data needs will vary with the agro-ecosystem under consideration and socio-economic context (e.g., scale of farm operation, amount of agro-chemical inputs, irrigated or rain-fed production systems, and level of mechanization).

Using GPS, soil and other surveyors can now localize any site in the world within an accuracy of one meter. Access to large storage media and advanced digital analysis systems, and the development of model libraries (Heuvelink and Brown 2006), continue to increase. Consequently, vast volumes of data can be uploaded, screened for inconsistencies, analysed and ultimately shared using distributed networks. Different map resolutions and soil properties will be required depending on the type of applications (i.e., questions being asked by the user) for which the data will be used. A range of novel approaches, such as embedded in GSIF, will offer new opportunities for rapid, accurate, dense and cost-effective data collection through crowd-sourcing, followed by intensive data screening and analysis procedures.

Defined protocols for data sharing, as described in an agreed-upon data policy (see, ISRIC 2012), is critical here. In principle, these policies should be in line with those adopted for the Global Earth Observation System of Systems (GEOSS) and the ICSU World Data System (WDS) which aim for a world in which '*universal and equitable access to high quality scientific data and information is a reality.'*

Capacity building and collaboration with national soil science institutes around the world on data collection, data screening, transformation, mapping and subsequent distribution of the derived information will be essential to create ownership of the newly derived data as well as the necessary expertise and capacity to further develop and test the system worldwide. Such activities can take place, for instance, within the broader framework of the FAO-led *Global Soil Partnership* (FAO 2011a) and Global Agricultural Research Partnership (CGIAR 2012) with support from various public and private sector organizations that have an interest in resolving environmental and agricultural issues associated with climate, societal and economic change (e.g., Smith *et al.* 2012). Within such a global, collaborative setting, ISRIC – World Soil Information aims to become the preferred repository and distributor of quality-assessed soil information for the world within the overall setting of the distributed ICSU World Data System, building on its original mandate from the UNESCO General Council in 1964.

The challenges of implementing and institutionalizing such an interoperable system —tailored to meet the needs of modern international interdisciplinary science and policy making— through which soil data and information may freely be accessed and used according to voluntary rules on attribution, citation and recognition, version control and appropriate use (as described in the ISRIC Data Policy) are significant, especially given the increasing size of data flows. These challenges can, however, be addressed when data management is institutionalized in knowledge centres, data collection is reprioritized and policy supports these basic requirements towards sustainable development.

Acknowledgements

This report draws on fruitful discussions with numerous colleagues. The Global Soil Information Facilities (GSIF) are being developed and implemented by a dedicated group at ISRIC in close collaboration with a growing international network of experts.

References

AfSIS 2012. Africa Soil Information System http://www.africasoils.net/

AgMIP 2012. Agricultural Model Intercomparison and Improvement Project (AgMIP) http://www.agmip.org/

AgTrials 2012. AgTrials—The Global Agricultural Trial Repository http://www.agtrials.org/

Aimrun W, Amin M, Ahmad D, Hanafi M and Chan C 2007. Spatial variability of bulk soil electrical conductivity in a Malaysian paddy field: key to soil management. *Paddy and Water Environment* 5, 113-121

Anderson K and Croft H 2009. Remote sensing of soil surface properties. *Progress in Physical Geography* 33, 457-473

Aragó Galindo P, Granell C, Molin P and Huerta Guijarro J 2012. Participative site-specific agriculture analysis for smallholders. *Precision Agriculture*, 1-17

Arroqui M, Mateos C, Machado C and Zunino A 2012. RESTful Web Services improve the efficiency of data transfer of a whole-farm simulator accessed by Android smartphones. *Computers and Electronics in Agriculture* 87, 14-18

ASHC 2012. Africa soil health consortium http://www.cabi.org/ashc/default.aspx?site=231&page=4141

ASRIS 2011. ASRIS: Australian Soil Resource Information System, CSIRO Land and Water http://www.asris.csiro.au/index_other.html

Avellan T, Zabel F and Mauser W 2012. The influence of input data quality in determining areas suitable for crop growth at the global scale – a comparative analysis of two soil and climate datasets. *Soil Use and Management* 2, 249–265

Barrera-Bassols N and Zinck JA 2003. Ethnopedology: a worldwide view on the soil knowledge of local people. *Geoderma* 111, 171-195

Bartholomeus H, Kooistra L, Stevens A, van Leeuwen M, van Wesemael B, Ben-Dor E and Tychon B 2011. Soil Organic Carbon mapping of partially vegetated agricultural fields with imaging spectroscopy. *International Journal of Applied Earth Observation and Geoinformation* 13, 81-88

Batjes NH 2000. Effects of mapped variation in soil conditions on estimates of soil carbon and nitrogen stocks for South America. *Geoderma* 97, 135-144

Batjes NH 2009. Harmonized soil profile data for applications at global and continental scales: updates to the WISE database. *Soil Use and Management* 25, 124-127

Batjes NH and Bridges EM 1994. Potential emissions of radiatively active gases from soil to atmosphere with special reference to methane: development of a global database (WISE). *Journal of Geophysical Research* 99(D8), 16479-16489

Batjes NH, Al-Adamat R, Bhattacharyya T, Bernoux M, Cerri CEP, Gicheru P, Kamoni P, Milne E, Pal DK and Rawajfih Z 2007. Preparation of consistent soil data sets for SOC modelling purposes: secondary SOTER data sets for four case study areas. *Agriculture, Ecosystems and Environment* 122, 26-34

Batlle-Bayer L, Batjes NH and Bindraban PS 2010. Changes in organic carbon stocks upon land use conversion in the Brazilian Cerrado: A review. *Agriculture, Ecosystems & Environment* 137, 47-58

Bernoux M, Arrouays D, Cerri C, Volkoff B and Jolivet C 1998. Bulk densities of Brazilian Amazon soils related to other soil properties. *Soil Science Society of America Journal* 62, 743-749

Bindraban PS 2012. The Need for Agro-Ecological Intelligence to Preparing Agriculture for Climate Change. *Journal of Crop Improvement* 26, 301-328

Bindraban PS, Batjes NH, Leenaars JGB and Bai Z 2010. Relevance of soil and terrain information in studies of major global issues. In: Gilkes RJ and N Prakongkep (editors), *Proceedings of the 19th World Congress of Soil Science, Soil Solutions for a Changing World*. International Union of Soil Sciences, 1-6 August, Brisbane, Australia, pp 38-41 http://www.iuss.org/19th%20WCSS/Symposium/pdf/0710.pdf

Bindraban PS, Stoorvogel JJ, Jansen DM, Vlaming J and Groot JJR 2000. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. *Agriculture, Ecosystems and Environment* 81, 103-112

Bindraban PS, van der Velde M, Ye L, van den Berg M, Materechera S, Kiba DI, Tamene L, Ragnarsdóttir KV, Jongschaap R, Hoogmoed M, Hoogmoed W, van Beek C and van Lynden G 2012. Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability* 4, 478–488

Bishop TFA, McBratney AB and Whelan BM 2001. Measuring the quality of digital soil maps using information criteria. *Geoderma* 103, 95-111

Bouma J 2001. The role of soil science in the land use negotiation process. *Soil Use and Management* 17, 1-6

Bouma J 2002. Land quality indicators of sustainable land management across scales. *Agriculture, Ecosystems & Environment* 88, 129-136

Bouma J and van Lanen HAJ 1986. Transfer functions anf threshold values: from soil characteristics to land qualities. In: Beek KJ, PA Burrough and DE McCormack (editors), *Quantified land evaluation procedures*. ITC Publication No. 6, ITC, Enschede, pp 106-110

Bouma J and Montanarella L 2012. *The soil and water nexus for sustainable livelihoods*, Institute for Advanced Sustainability Studies (IASS), Potsdam, 26 p *http://www.globalsoilweek.org/wp-content/uploads/GSW_IssuePaper_Soil-and-Water.pdf*

Bouma J, Varallyay G and Batjes NH 1998a. Principal land use changes anticipated in Europe. *Agriculture, Ecosystems and Environment* 67, 103-119

Bouma J, Batjes NH and Groot JJR 1998b. Exploring land quality effects on world food supply. *Geoderma* 86, 43-59

Bouma J, Booltink HWG, Stein A and Finke P 1996. Reliability of soil data and risk assessment of data applications. In: Nettleton WD, AG Hornsby, RB Brown and TL Coleman (editors), *Data reliability and risk assessment in soil interpretations*. Soil Science Society of America, Madison WI, pp 63-79

Bouwman AF, Boumans LJM and Batjes NH 2002. Modeling global annual N2O and NO emissions from fertilized fields. *Global Biogeochem. Cycles* 16, 1080

Brahim N, Bernoux M, Blavet D and Gallali T 2010. Tunisian Soil Organic Carbon Stocks. *International Journal of Soil Science* 5, 34-40

Brown DJ, Shepherd KD, Walsh MG, Dewayne Mays M and Reinsch TG 2006. Global soil characterization with VNIR diffuse reflectance spectroscopy. *Geoderma* 132, 273-290

Bruinsma J 2009. *Ther resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050?*, Economic and Social Development Department, Food and Agriculture Organization of the United Nations Rome, 33 p *http://cgiar.us2.list-manage1.com/track/click?u=08ae10c64755d59976763ea1f&id=5bf81f9632&e=231ac3cccb*

Cambule AH, Rossiter DG, Stoorvogel JJ and Smaling EMA 2012. Building a near infrared spectral library for soil organic carbon estimation in the Limpopo National Park, Mozambique. *Geoderma* 183–184, 41-48

CANSIS 2011. Canada national soil database, Agriculture and Agrifood Canada *http://res.agr.ca/cansis/*

Carlson D 2011. A lesson in sharing. *Nature* 469, 293-293

Cerri CEP, Tornquist CG, Bernoux M, Cooper M, Sparovek G, de Lourdes Mendoca-Santos M and Cerri CC 2012. Integrated digital, spatial and attribiute databases for soils in Brazil. In: Pan Ming Huang, Yuncong Li and ME Sumner (editors), *Handbook of Soil Sciences: Resource management and environmental aspects (2nd ed.)*. CRC Press, Boca Raton, pp 29-1/29

CGIAR 2012. Global Agricutural Research Partnership (formerly the Consultative Group on International Agricultural Research) *http://www.cgiar.org/*

Clark KL, Skowronski N and Hom J 2009. Invasive insects impact forest carbon dynamics. *Global Change Biology* 16, 88-101

Clark RN 1999. Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy. In: Rencz AN (editor), *Manual of Remote Sensing, Volume 3, Remote Sensing for the Earth Sciences*. John Wiley and Sons, New York, pp 3- 58

Cools N, Verschelde P, Quataert P, Mikkelsen J and De Vos B 2006. *Quality assurance and quality control in forest soil analysis: 4th FSCC interlaboratory comparison* Forest Soil Coordinating Centre, Research Institute for Nature and Forest, Geraardsbegen (BE), 66 + annexes (on CD-Rom) p http://www.inbo.be/files/bibliotheek/52/167252.pdf

de Brogniez D, Mayaux P and Montanarella L 2011. *Monitoring, Reporting and Verification systems for Carbon in Soils and Vegetation in African, Caribbean and Pacific countries*, Publications Office of the European Union, Luxembourg, 99 p http://eusoils.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/other/EUR24932.pdf

De Schutter O 2011. How not to think of land-grabbing: three critiques of large-scale investments in farmland. *Journal of Peasant Studies* 38, 249-279

Dent DL, Asfary AF, Giri C, Govil K, Hartemink AE, Holmgren P, Keita-Ouane F, Navone S, Olsson L, Ponce-Hernandez R, Rockstrom J, Shepherd G, Abdelgawad G, Batjes NH, Beltran JM, Brink A, Dronin N, Essahli W, Ewald G, Illueca o, Kant S, Krug T, Wolfgang Kueper, Wenlong L, MacDevette D, Nachtergaele F, Ndiang'ui N, Poulisse J, Schmullius C, Singh A, Sonneveld B, Sverdrup H, Brusselen Jv, Lynden Gv, Warren A, Bingfang W and Zhongze W 2007. Land, *Global Environmental Outlook (GEO4) - Environment for Development*. UNEP, Nairobi, pp 81-114

Dewitte O, Jones A, Elbelrhiti H, Horion S and Montanarella L 2012. Satellite remote sensing for soil mapping in Africa: An overview. *Progress in Physical Geography* 36, 514-538

Dijkshoorn JA, van Engelen VWP and Huting JRM 2008. *Soil and landform properties for LADA partner countries (Argentina, China, Cuba, Senegal and The Gambia, South Africa and Tunisia)*, ISRIC – World Soil Information and FAO, Wageningen 23 p http://www.isric.org/isric/webdocs/docs/ISRIC_Report_2008_06.pdf

Dobos E, Daroussin J and Montanarella L 2010. A quantitative procedure for building physiographic units supporting a global SOTER database. *Foldrajzi Ertesito/Hungarian Geographical Bulletin* 59, 181-205

Dumanski J and Pieri C 2000. Land quality indicators: research plan. *Agriculture, Ecosystems & Environment* 81, 93-102

ESB 2003. *European Soil Database (scale 1:1,000,000; distr. ver. 2.0)*, European Soil Bureau (on behalf of the Contributing Organisations), IES, JRC-EU, Isprahttp://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDBv2/fr_intro.htm

ESDB 2006. *European soil database v. 2.0*, European Soil Portal – Soil data and information systems http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/index.htm

FAO 1976. *A framework for land evaluation*. Soils Bulletin No. 32, Food and Agriculture Organization of the United Nations, Romehttp://www.fao.org/docrep/X5310E/x5310e00.htm

FAO 1995. *Digital Soil Map of the World and derived properties (ver. 3.5)*. FAO Land and Water Digital Media Series # 1, FAO, Rome, 23 p http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116

FAO 2011a. Global Soil Partnership for Food Security and Climate Change Mitigation and Adaptation http://www.fao.org/globalsoilpartnership/en/

FAO 2011b. *The state of the world's land and water resources for food and agriculture - Managing systems at risk*, Summary Report. Food and Agriculture Organization of the United Nations, Rome, 47 p

FAO, ISRIC and UG 2007. *Soil and terrain database for central Africa (Burundi and Rwanda 1:1 million scale; Democratic Republic of the Congo 1:2 million scale)*. Land and Water Digital Media Series 33, Food and Agricultural Organization of the United Nations, ISRIC - World Soil Information and Universiteit Gent, Romehttp://www.isric.org/sites/default/files/ISRIC_Report_2006_07.pdf

FAO, IIASA, ISRIC, ISSCAS and JRC 2012. *Harmonized World Soil Database (version 1.2)*, Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis, ISRIC - World Soil Information, Institute of Soil Science - Chinese Academy of Sciences, Joint Research Centre of the European Commission, Laxenburghttp://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HWSD_Documentation.pdf

Fernandez-Buces N, Siebe C, Cram S and Palacio JL 2006. Mapping soil salinity using a combined spectral response index for bare soil and vegetation: A case study in the former lake Texcoco, Mexico. *Journal of Arid Environments* 65, 644-667
Finke P 2006. Quality assessment of digital soil maps: producers and users perspectives. In: Lagacherie P, A McBratney and M Voltz (editors), *Digital soil mapping: An introductory perspective*. Elsevier, Amsterdam, pp 523-541
Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M and de Wit M 2010. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass and Bioenergy* 34, 159-172
Fisher M 2012. Precision ag in the developing world. *CSA News*, 4-9
Fortner JR and Price AB 2012. United States Soil Survey Databases. In: Pan Ming Huang, Yuncong Li and ME Sumner (editors), *Handbook of Soil Sciences: Resource management and environmental aspects (2nd ed.)*. CRC Press, Boca Raton, pp 28-1/12
Fox P and Harris R 2012. ICSU and the challenges of data and information management for international science. In: Minster J-B *et al.* (editors), *Proceedings of 1st ICSU-WDS Conference Global Data for Global Science (3–6 September 2011), Kyoto University, Kyoto, Japan* ICSU-WDS International Programme Office Kyoto, pp 1-12 http://isds.nict.go.jp/wds-kyoto-2011.org/pdf/IS301.pdf
Fresco LO 2009. Challenges for food system adaptation today and tomorrow. *Environmental Science & Policy* 12, 378-385
GEF-CBP 2012. *Carbon Benefits Project: Modelling, Measurement and Monitoring*, UNEP's Division of Global Environment Facility Coordination (DGEF), UNEP's Division of Early Warning and Assessment (DEWA), Colorado State University (CSU), and World Wide Fund for Nature (WWF), Nairobi http://www.unep.org/climatechange/carbon-benefits/
GEOSS 2012. Global Earth Observation System of Systems (GEOSS) http://www.earthobservations.org/geoss.shtml
Gilbert N 2012. Dirt poor -The key to tackling hunger in Africa is enriching its soil. *Nature* 483, 525-527
Gisladottir G and Stocking M 2005. Land degradation control and its global environmental benefits. *Land Degradation & Development* 16, 99-112
GlobalSoilMap.net 2011. *Specifications - Version 1 GlobalSoilMap.net products (Release 2.1)*, 50 p http://www.globalsoilmap.net/system/files/GlobalSoilMap_net_specifications_v2_0_edited_draft_Sept_2011_RAM_V12.pdf
Gomez C, Viscarra Rossel RA and McBratney AB 2008. Soil organic carbon prediction by hyperspectral remote sensing and field vis-NIR spectroscopy: An Australian case study. *Geoderma* 146, 403-411
Goodchild MF 1994. Sharing imperfect data. In: Singh A (editor), *Proceedings UNEP and IUFPRO international workshop in cooperation with FAO in developing large environmental databases for sustainable development*. UNEP/GRID, Sioux Falls, pp 102-110
Goyens C, Verdoodt A, Van de Wauw J, Baert G, van Engelen VWP, Dijkshoorn JA and Van Ranst E 2007. Base de données numériques sur les sols et le terrain (SOTER) de l'Afrique Centrale (RD Congo, Rwanda et Burundi). *Etude et Gestion des Sols* 14, 207-218
Grunwald S, Thompson JA and Boettinger JL 2011. Digital soil mapping and modeling at continental scales: Finding solutions for global issues. *Soil Science Society of America Journal* 75, 1201-1213
GSIF 2012. Global Soil Information Facilities (GSIF) Project, ISRIC - World Soil Information http://www.isric.org/projects/global-soil-information-facilities-gsif
GSIF 2013a. SoilGrids1km - Updatable soil property and class map for the word, ISRIC - World Soil Information http://www.isric.org/content/soilgrids
GSIF 2013b. Soil property maps of Africa at 1 km, ISRIC - World Soil Information http://www.isric.org/data/soil-property-maps-africa-1-km
Guerrero C, Rossel RAV and Mouazen AM 2010. Diffuse reflectance spectroscopy in soil science and land resource assessment. *Geoderma* 158, 1-2

Guralnick R, Constable H, Wieczorek J, Moritz C and Peterson AT 2009. Sharing: lessons from natural history's success story. 462, 34-34

Hallet SH, Bullock P and Baillie I 2006. Towards a World Soil Survey Archive and Catalogue. *Soil Use and Managment* 22, 227-228

Hartemink AE and McBratney A 2008. A soil science renaissance. *Geoderma* 148, 123-129

Hartemink AE, McBratney A and Mendoca-Santos ML (editors) 2008. Digital soil mapping with limited data. Springer, 445 p

Hartemink AE, Hempel J, Lagacherie P, MacBratrney AB, McKenzie NJ, MacMillan RA, Minasny B, Montenarella L, Mendoca Samtos ML, Sanchez PA, Walsh M and Zhang Gl 2010. GlobalSoilMap.net: A new digital soil map of the world. In: Boetinger JL and e al. (editors), *Digital Soil mapping: Brdiging research, environm ental application, and operation*. Springer-Verlag, Dordrecht, pp 423-427

Hbirkou C, Pätzold S, Mahlein A-K and Welp G 2012. Airborne hyperspectral imaging of spatial soil organic carbon heterogeneity at the field-scale. *Geoderma* 175–176, 21-28

Hengl T 2009. *A practical guide to geostatistical mapping*. Published by www.lulu.com (ISBN: 978-90-9024981-0)

Hengl T, Nikolić M and MacMillan RA 2012. Mapping efficiency and information content. *ITC Journal* doi:10.1016/j.jag.2012.02.005

Heuvelink GBM and Brown JD 2006. Towards a soil information system for uncertain soil data In: Lagacherie P, A McBratney and M Voltz (editors), *Digital soil mapping: An introductory perspective*. Elsevier, Amsterdam, pp 97-106

Hewitt C, Mason S and Walland D 2012. The Global Framework for Climate Services. 2, 831-832

HLPE 2011. *Land tenure and international investments in agriculture. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*, Rome, 56 p http://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE-Land-tenure-and-international-investments-in-agriculture-2011.pdf

Huber S, Prokop G, Arrouays D, Banko G, Bispo A, Jones RJA, Kibblewhite MG, Lexer W, Möller A, Rickson RJ, Shishkov T, Stephens M, Toth G, Van den Akker JJH, Varallyay G, Verheijen FGA and Jones ARe 2008. *Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria*, Office for the Official Publications of the European Communities, Luxembourg, 339 p http://eusoils.jrc.ec.europa.eu/projects/envasso/documents/ENV_Vol-I_Final2_web.pdf

ICSU-WDS 2011. ICSU World Data System (WDS), International Council for Science http://icsu-wds.org/

Imerzekene S and Ranst Ev 2001. Une banque de données pédologiques et son SIG pour une nouvelle politique agricole au Rwanda *Bull. Séanc. Acad. R. Sci. Outre-Mer* 47, 299-329

Immerzeel WW and Bierkens MFP 2012. Asia's water balance. 5, 841-842

Ingram J 1993. *IGBP-DIS / GCTE global soils database workshop (October 8-9, 1992, Silsoe)*, International Geosphere-Biosphere Program Data and Information System, Parishttp://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDgQFjAA&url=ftp%3A%2F%2Fftp.bgc.mpg.de%2Fpub%2Foutgoing%2Fchurkina%2FGlobal_Soil_Data_Products%2FDocument%2Fproposal.rtf&ei=ocLqUlmmG8Wo0AXotYHYAg&usg=AFQjCNEosenLE81QmXtsFgBl_gyAoVWTRg&bvm=bv.1355534169,d.d2k&cad=rja

IPCC 2006. *IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and other Land Use*. IPCC National Greenhouse Gas Inventories Programme, Hayama (JP)

ISRIC 2012. *Data Policy*, ISRIC - World Soil Information (WDC - Soils) Wageningen, 6 p http://www.isric.org/sites/default/files/ISRIC_Data_Policy.pdf

Izac AMN 1997. Developing policies for soil carbon management in tropical regions. *Geoderma* 79, 261-276

Janik LJ, Merry RH, Forrester ST, Lanyon DM and Rawson A 2007. Rapid Prediction of Soil Water Retention using Mid Infrared Spectroscopy. *Soil Sci Soc Am J* 71, 507-514

Janssen BH, Guiking FCT, van der Eijk D, Smaling EMA, Wolf J and van Reuler H 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46, 299-318

Jenny H 1941. *Factors of Soil Formation: A System of Quantified Pedology*. McGraw-Hill, New York (Reprinted in 1994 by Dover Publications, Mineaola, NY)

Jones A, Breuning-Madsen H, Brossard M, Dampha A, Dewitte O, Jones R, Kilasara M, Le Roux P, Micheli E, Montanarella L, Spaargaren O, Tahar G, Thiombiano L, Van Ranst E, Yemefack M and R. Z (editors) 2012. Soil Atlas of Africa. European Commission, Publications Office of the European Union, European Union, Luxembourg, 176 p

Jones JW, Tsuji GY, Hoogenboom G, Hunt LA, Thornton PK, Wilkens PW, Imamura DT, Bowen WT and Suingh U 1988. Decision support system for agrotechnology transfer; DSSAT v3. In: Tsuji GY, G Hoogenboom and PK Thonrton (editors), *Understanding options for agricultural production*. Kluwer Academic Publishers, Dordrecht (NL), pp 157-177

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF and Schuman GE 1997. Soil quality: a concept, definition and framework for evaluation. *Soil Science Society of America Journal* 61, 4-10

Kempen B 2011. Updating soil information with digital soil mapping. PhD Thesis, Wageningen University, Wageningen, 218 pp http://edepot.wur.nl/187198

Kempen B, Brus DJ, Heuvelink GBM and Stoorvogel JJ 2009. Updating the 1:50,000 Dutch soil map using legacy soil data: A multinomial logistic regression approach. *Geoderma* 151, 311-326

Kleinman PJA, Sharpley AN, Gartley K, Jarrell WM, Kuo S, Menon RG, Myers R, Reddy KR and Skogley EO 2001. Interlaboratory comparison of soil phosphorus extracted by various soil test methods. *Communications in Soil Science and Plant Analysis* 32, 2325-2345

Kogel-Knabner I, Lutzow Mv, Guggenberger G, Flessa H, Marschner B, Matzner E and Ekschmitt K 2005. Mechanisms and regulation of organic matter stabilisation in soils. *Geoderma* 128, 1-2

Koning N, Heerink N and Kauffman S 2001. Food insecurity, soil degradation and agricultural markets in West Africa: why current policy approaches fail. *Oxford Development Studies* 29, 189-207

Krasilnikov PV and Tabor JA 2003. Perspectives on utilitarian ethnopedology. *Geoderma* 111, 197-215

Lagacherie P, McBratney A and Voltz M (editors) 2006. Digital soil mapping: An introductory perspective. Elsevier, Amsterdam, 350 p

Lal R, Cerri CC, Bernoux M, Etchevers J and Cerri CEP (editors) 2006. Carbon sequestration in soils of Latin America. Food Products Press, New York, 554 p

Landon JR 1991. *Booker Tropical Soil Manual*. Longman Scientific & Technical, New York, 474 p

Larocque GR, Bhatti JS, Gordon AM, Luckai N, Wattenbach M, Liu J, Peng C, Arp PA, Liu S, Zhang CF, Komarov A, Grabarnik P, Sun J, White T, Jakeman AJ, Voinov AA, Rizzoli AE and Chen SH 2008. Uncertainty and sensitivity issues in process-based models of carbon and nitrogen cycles in terrestrial ecosystems. In: Jakeman AJ, AA Voinov, AE Rizzoli and SH Chen (editors), *Environmental Modelling, Software and Decision Support*. Developments in Integrated Environmental Assessment. Elsevier, Amsterdam, pp 307-327

Leenaars JGB 2012. *Africa soil profile database – A compilation of georeferenced and standardised legacy soiol profile data for Sub Saharan Africa (version 1.0)*. Report 2012/03, Africa Soil Information Service (AfSIS) and ISRIC - World Soil Information, Wageningenhttp://www.isric.org/sites/default/files/isric_report_2012_03.pdf

Liniger HP and Critchley W 2007. *Where the land is greener: Case studies and analysis of soil and water conservation initiatives worldwide* CTA, UNEP, FAO and CDE, Berne, 504 p

Loosvelt L, Pauwels VRN, Cornelis WM, De Lannoy GJM and Verhoest NEC 2011. Impact of soil hydraulic parameter uncertainty on soil moisture modeling. *Water Resources Research* 47

Lopes AS 1996. Soils under Cerrado: A Success Story in Soil Management. *Better Crops International* 10, 9-15

Lorenzo C, Vermeulen S, Leonard R and Keeley J 2009. *Land grab or development opportunity? Agricultural investment and international land deals in Africa* International Institute for Environment and Development, Food and Agricultural Organization of the United Nations, and International Fund for Agricultural Development, London/Rome, 120 p http://www.ifad.org/pub/land/land_grab.pdf

Malenovský Z, Bartholomeus HM, Acerbi-Junior FW, Schopfer JT, Painter TH, Epema GF and Bregt AK 2007. Scaling dimensions in spectroscopy of soil and vegetation. *International Journal of Applied Earth Observation and Geoinformation* 9, 137-164

Malone BP, McBratney AB, Minasny B and Laslett GM 2009. Mapping continuous depth functions of soil carbon storage and available water capacity. *Geoderma* 154, 138-152

McBratney A, Whelan B, Ancev T and Bouma J 2005. Future Directions of Precision Agriculture. *Precision Agriculture* 6, 7-23

McBratney AB, Mendonça Santos ML and Minasny B 2003. On digital soil mapping. *Geoderma* 117, 3-52

McBratney AB, Minasny B and Tranter G 2011. Necessary meta-data for pedotransfer functions. *Geoderma* 160, 627-629

Mednick AC 2010. Does soil data resolution matter? State Soil Geographic database versus Soil Survey Geographic database in rainfall-runoff modeling across Wisconsin. *Journal of Soil and Water Conservation* 65, 190-199

Mekonnen MM and Hoekstra AY 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences* 15, 1577-1600

Merry RH and Janik LJ 2001. Mid Infrared Spectroscopy for rapid and cheap analysis of soils. In: Rowe B, D Donaghy and N Mendham., (editors), *Science and Technology: Delivering Results for Agriculture?*, Proceedings of the 10th Australian Agronomy Conference, January 2001, Hobart, Tasmania.http://www.regional.org.au/au/asa/2001/3/c/merry.htm

Middelburg JJ, Liss PS, Dentener FJ, Taminski T, Kroeze C, Malingreau J-P, Noväl M, Panikov NS, Plant R, Starink M and Wanninkhof R 1999. Relations between scale, model approach and model parameters. In: Bouwman AF (editor), *Approaches to Scaling of Trace Gas Fluxes in Ecosystems*. Elsevier, Amsterdam, pp 219-232

Milne E, Sessay M, Paustian K, Easter M, Batjes NH, Cerri CEP, Kamoni P, Gicheru P, Oladipo EO, Minxia M, Stocking M, Hartman M, McKeown B, Peterson K, Selby D, Swan A, Williams S and Lopez PJ 2010. Towards a standardized system for the reporting of carbon benefits in sustainable land management projects. In: Abberton M, R Conant and C Batello (editors), *Grassland carbon sequestration: management, policy and economics (Proceedings of the Workshop on the role of grassland carbon sequestration in the mitigation of climate change, Rome, April 2009)*, FAO, pp 105-117 http://www.fao.org/docrep/013/i1880e/i1880e00.htm

Minasny B and McBratney AB 2002. Uncertainity analysis for pedotransfer functions. *European Journal of Soil Science* 53, 417-429

Minasny B, Sulaeman Y and McBratney AB 2010a. Is soil carbon disappearing? The dynamics of soil organic carbon in Java. *Global Change Biology* 17, 1917–1924

Minasny B, Malone BP and McBratney AB (editors) 2012. Digital Soil Assessments and Beyond (Proc. of the 5th Global Workshop on Digital Soil Mapping 2012, Sydney, Australia). CRC Press, 482 p

Minasny B, McBratney AB, Boettinger JL, Howell DW, Moore AC, Hartemink AE and Kienast-Brown S 2010b. Methodologies for Global Soil Mapping - Digital Soil Mapping. In: Hartemink AE and AB McBratney (editors). Progress in Soil Science. Springer Netherlands, pp 429-436

Montanarella L and Vargas R 2012. Global governance of soil resources as a necessary condition for sustainable development. *Current Opinion in Environmental Sustainability*, *(Corrected proof)*

Mora-Vallejo A, Claessens L, Stoorvogel J and Heuvelink GBM 2008. Small scale digital soil mapping in Southeastern Kenya. *CATENA* 76, 44-53

Mueller L, Schindler U, Mirschel W, Shepherd TG, Ball BC, Helming K, Rogasik J, Eulenstein F and Wiggering H 2010. Assessing the productivity function of soils. A review. *Agron. Sustain. Dev.* 30, 601-640

Mulder VL, de Bruin S, Schaepman ME and Mayr TR 2011. The use of remote sensing in soil and terrain mapping - A review. *Geoderma* 162, 1-19

Nachtergaele FO 1999. From the Soil Map of the World to the Digital Global Soil and Terrain Database: 1960-2002. In: Sumner ME (editor), *Handbook of Soil Science*. CRC Press, Boca Raton, pp H5-17

Nachtergaele FO and Oldeman LR 2002. World soil and terrain database (SOTER): past, present and future. *Transactions 17th World Congress of Soil Science*. International Union of Soil Sciences (IUSS), Bangkok, pp 653/1-653/10

Nachtergaele FO, Van Engelen VWP and Batjes NH 2012. Qualitative and quantitative aspects of world and regional soil databases and maps. In: Pan Ming Huang, Yuncong Li and ME Sumner (editors), *Handbook of Soil Sciences: Resource management and environmental aspects (2nd ed.)*. CRC Press, Boca Raton, pp 27-1/10

Nol L, Heuvelink GBM, Veldkamp A, de Vries W and Kros J 2010. Uncertainty propagation analysis of an N_2O emission model at the plot and landscape scale. *Geoderma* 159, 9-23

Odeh IOA, Leenaars J, Hartemink A and Amapu I 2012. The challenges of collating legacy data for digital mapping of Nigerian soils. *Digital Soil Assessments and Beyond - Proceedings of the Fifth Global Workshop on Digital Soil Mapping*, pp 453-458

Odgers NP, Libohova Z and Thompson JA 2012. Equal-area spline functions applied to a legacy soil database to create weighted-means maps of soil organic carbon at a continental scale. *Geoderma* 189, 153-163

OGC 2012. OGC® Standards and Supporting Documents, Open Geospatial Consortium www.opengeospatial.org

Oldeman LR and van Engelen VWP 1993. A World Soils and Terrain Digital Database (SOTER) - An improved assessment of land resources. *Geoderma* 60, 309-335

Omuto C, Nachtergaele F and Vargas Rojas R 2012. *State of the Art Report on Global and Regional Soil Information: Where are we? Where to go?*, FAO, Italy, 69 p
http://www.fao.org/docrep/017/i3161e/i3161e.pdf

Pachepsky YA, Rawls WJ and Lin HS 2006. Hydropedology and pedotransfer functions. *Geoderma* 131, 308-316

Panagos P, Jones A, Bosco C and Senthil Kumar PS 2011. European digital archive on soil maps (EuDASM): Preserving important soil data for public free access. *International Journal of Digital Earth* 4, 434-443

Panagos P, Hiederer R, Van Liedekerke M and Bampa F 2013. Estimating soil organic carbon in Europe based on data collected through an European network. *Ecological Indicators* 24, 439-450

Paterson DG and Mushia NM 2012. Soil databases in Africa. In: Pan Ming Huang, Yuncong Li and ME Sumner (editors), *Handbook of Soil Sciences: Resource management and environmental aspects (2nd ed.)*. CRC Press, Boca Raton, pp 32-1/9

Paustian K 2012. Agriculture, farmers and GHG mitigation: a new social network? *Carbon Management* 3, 253-257

Pleijsier K 1989. Variability in soil data. In: Bouma J and AK Bregt (editors), *Land Qualities in Space and Time*. PUDOC, Wageningen, pp 89-98

Pourabdollah A, Leibovici DG, Simms DM, Tempel P, Hallett SH and Jackson MJ 2012. Towards a standard for soil and terrain data exchange: SoTerML. *Computers & Geosciences*, (Available online 12 January 2012)

Rabbinge R and Bindraban PS 2012. Making More Food Available: Promoting Sustainable Agricultural Production. *Agricultural Sciences in China* 11, 1-8

Raupach MR, Rayner PJ, Barrett DJ, DeFries RS, Heimann M, Ojima DS, Quegan S and Schmullius CC 2005. Model-data synthesis in terrestrial carbon observation: methods, data requirements and data uncertainty specifications. *Global Change Biology* 11, 378-397

Ravindranath NH and Ostwald M 2008. *Carbon inventory methods - Handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects*. Advances in Global Change Research, Volume 29. Springer, Heidelberg, 304 p

Reuter HI and Hengl T 2012. Worldgrids-a public repository of global soil covariates. *Digital Soil Assessments and Beyond - Proceedings of the Fifth Global Workshop on Digital Soil Mapping*. 5th Global Workshop on Digital Soil Mapping, Sydney, NSW, pp 287-292 http://www.scopus.com/inward/record.url?eid=2-s2.0-84866358192&partnerID=40&md5=901151b971271cf29ddd25452bf97699

Rijsberman FR 2006. Water scarcity: Fact or fiction? *Agricultural Water Management* 80, 5-22

Robinson DA, Hockley N, Dominati E, Lebron I, Scow KM, Reynolds B, Emmett BA, Keith AM, de Jonge LW, Schjønning P, Moldrup P, Jones SB and Tuller M 2012. Natural Capital, Ecosystem Services, and Soil Change: Why Soil Science Must Embrace an Ecosystems Approach. *Vadose Zone Journal* 11

Rockström J, Falkenmark M, Lannerstad M and Karlberg L 2012. The planetary water drama: Dual task of feeding humanity and curbing climate change. *Geophys. Res. Lett.* 39, L15401

Romero CC, Hoogenboom G, Baigorria GA, Koo J, Gijsman AJ and Wood S 2012. Reanalysis of a global soil database for crop and environmental modeling. *Environmental Modelling and Software*

Rosegrant MW, Ringler C, Benson T, Diao X, Resnick D, Thurlow J, Torero M and Orden D 2006. *Agriculture and Achieving The Millennium Development Goals*. Agriculture & Rural Development Department, The World Bank, Washington, 104 p

Rossel RAV, Jeon YS, Odeh IOA and McBratney AB 2008. Using a legacy soil sample to develop a mid-IR spectral library. *Australian Journal of Soil Research* 46, 1-16

Rossiter D 2004. Digital soil resource inventories: status and prospects. *Soil Use and Management* 20, 296-301

Rousseva SS 1997. Data transformations between soil texture schemes. *European Journal of Soil Science* 48, 749-758

Running SW 2006. Is Global Warming causing more, larger wildfires? *Science* 313, 927-928

Sachs JD, Baillie JEM, Sutherland WJ, Armsworth PR, Ash N, Beddington J, Blackburn TM, Collen B, Gardiner B, Gaston KJ, Godfray HCJ, Green RE, Harvey PH, House B, Knapp S, Kumpel NF, Macdonald DW, Mace GM, Mallet J, Matthews A, May RM, Petchey O, Purvis A, Roe D, Safi K, Turner K, Walpole M, Watson R and Jones KE 2009. Biodiversity Conservation and the Millennium Development Goals. *Science* 325, 1502-1503

Sanchez PA 1976. *Properties and management of soils in the tropics*. Wiley, New York

Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac A-MN, Mokwunye AU, Kwesiga FR, Chipata Z, Ndiritu CG and Woomer PL 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh RJ, PA Sanchez and F Calhoun (editors), *Replenishing soil fertility in Africa*. American Society of Agronomy and the Soil Science Society of America, SSSA Special Publication Number 51, Indiana (IN), pp 1-46

Sanchez PA, Ahamed S, Carre F, Hartemink AE, Hempel J, Huising J, Lagacherie P, McBratney AB, McKenzie NJ, Mendonca-Santos MdL, Minasny B, Montanarella L, Okoth P, Palm CA, Sachs JD, Shepherd KD, Vagen T-G, Vanlauwe B, Walsh MG, Winowiecki LA and Zhang G-L 2009. Digital Soil Map of the World. *Science* 325, 680-681

Saxton KE, Rawls WJ, Romberger JS and Papendick RI 1986. Estimating Generalized Soil-water Characteristics from Texture. *Soil Sci Soc Am J* 50, 1031-1036

Schaap MG and Leij FJ 1998. Database-related accuracy and uncertainty of pedotransfer functions. *Soil Science* 163, 765-779

Schaepman ME, Clevers JGPW and Dent DL 2007. Preface. *International Journal of Applied Earth Observation and Geoinformation* 9, 89-90

Schulp CJE, Verburg PH, Kuikman PJ, Nabuurs GJ, Olivier JGJ, de Vries W and Veldkamp T 2012. Improving National-Scale Carbon Stock Inventories Using Knowledge on Land Use History. *Environmental Management*, 1-15

Schultz MG, A. Heil, J. J. Hoelzemann, A. Spessa, K. Thonicke, J. G. Goldammer, A. C. Held, J. M. C. Pereira, and M. van het Bolscher 2008. Global wildland fire emissions from 1960 to 2000. *Global Biogeochem. Cycles* 22, GB2002, doi:10.1029/2007GB003031

Selige T, Bohner J and Schmidhalter U 2006. High resolution topsoil mapping using hyperspectral image and field data in multivariate regression modeling procedures. *Geoderma* 136, 235-244

Selvarajdou S-K, Montanarella L, Spaargaren O and Dent D 2005. *European Digital Archive of Soil Maps (EuDASM): Soil maps of Latin America and the Caribbean Islands*. EUR 21822 EN, Office for Official Publications of the European Communities, Luxembourg, 227 p http://eusoils.jrc.it/esdb_archive/EuDASM/latinamerica/pdf/eur21821en.pdf

Shepherd K and Walsh M 2002. Development of reflectance spectral libraries for characterization of soil properties. *Soil Science Society of America Journal* 66, 988–998.
Siegmann B, Jarmer T, Selige T, Lilienthal H, Richter N and Höfle B 2012. Using hyperspectral remote sensing data for the assessment of topsoil organic carbon from agricultural soils. 85312C-85312C
Smaling EMA and Janssen BH 1993. Calibration of quefts, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* 59, 21-44
Smaling EMA, Lesscher JP, van Beek CL, De Jager A, Stoorvogel JJ, Batjes NH and Fresco LO 2011. Where do we stand, twenty years after the assessment of soil nutrient balances in Sub-Saharan Africa? In: Lal R and BA Stewart (editors), *World soil resources and food security*. CRC Press, Padstow (GB)
Smith P 2011. Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learned in the last 20 years? *Global Change Biology* 18, 35-43
Smith P 2012. Soils and climate change. *Current Opinion in Environmental Sustainability* 4, 539-544
Smith P, Gregory PJ, Van Vuuren D, Obersteiner M, Havlík P, Rounsevell M, Woods J, Stehfest E and Bellarby J 2010. Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 2941-2957
Smith P, Davies CA, Ogle S, Zanchi G, Bellarby J, Bird N, Boddey RM, McNamara NP, Powlson D, Cowie A, van Noordwijk M, Davis SC, Richter DDEB, Kryzanowski L, van Wijk MT, Stuart J, Kirton A, Eggar D, Newton-Cross G, Adhya TK and Braimoh AK 2012. Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology* 18, 2089-2101
Soil Survey Division Staff 1993. *Soil survey manual*, Handbook 18. Soil Conservation Service, U.S. Department of Agriculture, Washington
Soil Survey Staff 2011. *Soil Survey Laboratory Information Manual (Ver. 2.0)*. Soil Survey Investigation Report No. 45, National Soil Survey Center, Soil Survey Laboratory, USDA-NRCS, Lincoln (NE), 506 p *ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab_Info_Manual/SSIR_45.pdf*
Soil Survey Staff 2012. *National Cooperative Soil Survey soil characterization data*, Soil Survey Laboratory, National Soil Survey Center, USDA-NRCS - Lincoln (NE) *http://ncsslabdatamart.sc.egov.usda.gov/*
Sombroek WG 1990. Geographic quantification of soils and changes in their properties. In: Bouwman AF (editor), *Soils and the Greenhouse Effect*. John Wiley and Sons, Chichester, pp 225-244
Stehfest E and Bouwman L 2006. N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems* 74, 207-228
Stevens A, van Wesemael B, Bartholomeus H, Rosillon D, Tychon B and Ben-Dor E 2008. Laboratory, field and airborne spectroscopy for monitoring organic carbon content in agricultural soils. *Geoderma* 144, 395-404
Stevens A, Udelhoven T, Denis A, Tychon B, Lioy R, Hoffmann L and van Wesemael B 2010. Measuring soil organic carbon in croplands at regional scale using airborne imaging spectroscopy. *Geoderma* 158, 32-45
Stiles CA, Hammer RD, Johnson MG, Ferguson R, Galbraith J, O'Geen T, Arriaga J, Shaw J, Falen A, McDaniel P and Miles R 2011. Validation testing of a portable kit for measuring an active soil carbon fraction. *Soil Science Society of America Journal* 75, 2330-2340
Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, Minasny B, McBratney AB, Courcelles VdRd, Singh K, Wheeler I, Abbott L, Angers DA, Baldock J, Bird M, Brookes PC, Chenu C, Jastrow JD, Lal R, Lehmann J, O'Donnell AG, Parton WJ, Whitehead D and Zimmermann M 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment* 164, 80-99
Stoorvogel JJ, Kempen B, Heuvelink GBM and de Bruin S 2009. Implementation and evaluation of existing knowledge for digital soil mapping in Senegal. *Geoderma* 149 161–170

Tempel P, van Kraalingen D, Mendes de Jesus J and Reuter HI 2013. *Towards an ISRIC World Soil Information Service (WOSIS ver. 1.0)*. ISRIC Report 2013/02, ISRIC - World Soil Information, Wageningen, 188 p http://www.isric.org/sites/default/files/ISRIC_Report_2013_02.pdf

Terhoeven-Urselmans T, Schmidt H, Georg Joergensen R and Ludwig B 2008. Usefulness of near-infrared spectroscopy to determine biological and chemical soil properties: Importance of sample pre-treatment. *Soil Biology and Biochemistry* 40, 1178-1188

Terhoeven-Urselmans T, Vagen TG, Spaargaren O and Shepherd KD 2010. Prediction of soil fertility properties from a globally distributed soil mid-infrared spectral library. *Soil Science Society of America Journal* 74, 1792-1799

Thomson LJ, Macfadyen S and Hoffmann AA 2010. Predicting the effects of climate change on natural enemies of agricultural pests. *Biological Control* 3, 296-306

Tittonell P, Vanlauwe B, Corbeels M and Giller K 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil* 313, 19-37

Tomich TP, Chomitz K, Francisco H, Izac A-MN, Murdiyarso D, Ratner BD, Thomas DE and van Noordwijk M 2004. Policy analysis and environmental problems at different scales: asking the right questions. *Agriculture, Ecosystems & Environment* 104, 5-18

Uhlir PF and Schröder P 2009. Open data for global science. *Data Science Journal* 6, 36-53

Uhlir PF, Chen RS, Gabrynowicz JI and Janssen K 2009. Toward implementation of the Global Earth Observation System of Systems data sharing principles. *Journal of Space Law* 35, 201-289

UN-MDG 2012. *The Millennium Development Goals Report 2012*, United Nations, New York, 68 p http://www.un.org/millenniumgoals/pdf/MDG%20Report%202012.pdf

UNEP 2012. The benefits of soil carbon - managing soils for multiple, economic, societal and environmental benefits, *UNEP Yearbook - Emerging issues in our global environment 2012*. United Nations Environmental Programme, Nairobi, pp 19-33

UNFCCC 2008. *Challenges and opportunities for mitigation in the agricultural sector*, 101 p http://unfccc.int/resource/docs/2008/tp/08.pdf

UNSDI 2012. United Nations Spatial Data Infrastructure (UNSDI) http://www.unsdi.nl/

USDA-NRCS 2012. U.S. General Soil Map (STATSGO2), Natural Resources Conservation Service, United States Department of Agriculture http://soils.usda.gov/survey/geography/statsgo/

Van Engelen VWP 2011. Standardizing soil data (*e-SOTER* regional pilot platform as EU contribition to a Global Soil Information System). *International Innovation* June, 48-49

van Engelen VWP and Wen TT 1995. *Global and National Soils and Terrain Digital Databases (SOTER): Procedures Manual (rev. ed.)*. (Published also as FAO World Soil Resources Report No. 74), UNEP, IUSS, ISRIC and FAO, Wageningen, 125 p http://www.isric.org/isric/webdocs/docs/SOTER_Procedures_Manual_1995.pdf

van Engelen VWP and Dijkshoorn JA 2013. *Global and National Soils and Terrain Digital Databases (SOTER) - Procedures manaual (Ver. 2.0)*. ISRIC Report 2013/04, IUSS, ISRIC and FAO, Wageningen, 191 p http://www.isric.org/sites/all/modules/pubdlcnt/pubdlcnt.php?file=/sites/default/files/ISRIC_Report_2013_04.pdf&nid=331

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonel P and Hochman Z 2012. Yield gap analysis with local to global relevance – a review. *Field Crops Research* (in press)

van Keulen H 2007. Quantitative analyses of natural resource management options at different scales. *Agricultural Systems* 94, 768-783

Van Ranst E, Verdoodt A and Baert G 2010. Soil Mapping in Africa at the Crossroads: Work to Make up for Lost Ground. *Bull. Séanc. Acad. R. Sci. Outre-Mer* 56, 147-163

van Reeuwijk LP 1995. *Procedures for soil analysis (5th ed.)*. Technical Paper 9, ISRIC, Wageningen http://www.isric.org/Isric/Webdocs/Docs/ISRIC_TechPap09_2002.pdf

van Reeuwijk LP 1998. *Guidelines for quality management in soil and plant laboratories*, FAO, Rome, 143 p http://www.fao.org/docrep/W7295E/W7295E00.htm

van Wambeke A 1992. *Soils of the Tropics — Properties and appraisal*. McGraw-Hill New York, 343 p van Wesemael B, Paustian K, Andrén O, Cerri C, Dodd M, Etchevers J, Goidts E, Grace P, Kätterer T, McConkey B, Ogle S, Pan G and Siebner C 2010. How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO_2 fluxes in agricultural soils? *Plant and Soil*, 1-13

Vandenbroucke D, Crompvoets J, Janssen K, Bamps C, Masser I, Salvemini M, Loenen Bv, Probert M and Eiselt B 2011. *Spatial Data Infrastructures in Europe: State of play spring 2011*, Spatial Applications Divison, K.U.Leuven Research & Development, 65 p http://inspire.jrc.ec.europa.eu/reports/stateofplay2011/INSPIRE__NSDI_SoP_-_Summary_Report_2011_-_v6.2.pdf

Verdoodt A and Van Ranst E 2006. Environmental assessment tools for multi-scale land resources information systems: A case study of Rwanda. *Agriculture, Ecosystems & Environment* 114, 170-184

Viscarra R, Raphael A, McBratney AB and Minasny B 2010. *Proximal Soil Sensing*. Springer, 468 p

Wang X and Melesse AM 2006. Effects of STATSGO and SSURGO inputs on SWAT model's snowmelt simulation. *Journal of the American Water Resources Association (JAWRA)* 42, 1217-1236

Watson RT, Noble IR, Bolin B, Ravindramath NH, Verardo DJ and Dokken DJ 2000. *Land Use, Land-Use Change, and Forestry (a special Report of the IPCC)*. Cambridge University Press, Cambridge, 377 p

Webster F 1997. Threat to full and open access to data. *Science International* 65, 11-12

Willcock S, Phillips OL, Platts PJ, Balmford A, Burgess ND, Lovett JC, Ahrends A, Bayliss J, Doggart N, Doody K, Fanning E, Green J, Hall J, Howell KL, Marchant R, Marshall AR, Mbilinyi B, Munishi PKT, Owen N, Swetnam RD, Topp-Jorgensen EJ and Lewis SL 2012. Towards Regional, Error-Bounded Landscape Carbon Storage Estimates for Data-Deficient Areas of the World. *PLoS ONE* 7, e44795

Wösten JHM, Pachepsky YA and Rawls WJ 2001. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. *Journal of Hydrology* 251, 123-150

WSP 2012. World Soil Profiles — towards a unified, web-based soil profile database, ISRIC - World Soil Information http://worldsoilprofiles.org/

Yang L, Jiao Y, Fahmy S, Zhu A-X, Hann S, Burt JE and Qi F 2011. Updating Conventional Soil Maps through Digital Soil Mapping. *Soil Sci. Soc. Am. J.* 75, 1044-1053

Zhang G-L and Wu Y-Y 2012. Development and use of soil maps and databases in China. In: Pan Ming Huang, Yuncong Li and ME Sumner (editors), *Handbook of Soil Sciences: Resource management and environmental aspects (2nd ed.)*. CRC Press, Boca Raton, pp 30-1/16

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

More information: www.isric.org

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