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**World Soil Information**

ISRIC Report 2013/05



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



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**ISRIC Report 2013/05**

Wageningen, 2013

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# 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 gases, 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.

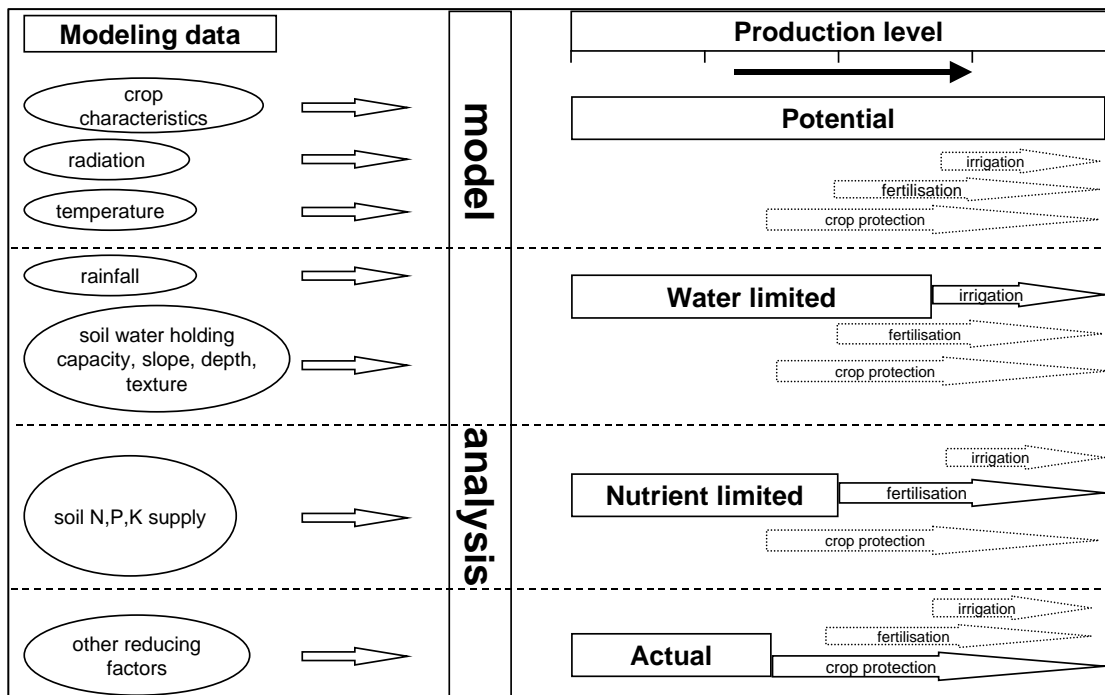
## 2 Soil data needs at varying levels of detail

### 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; Tiftonell *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).

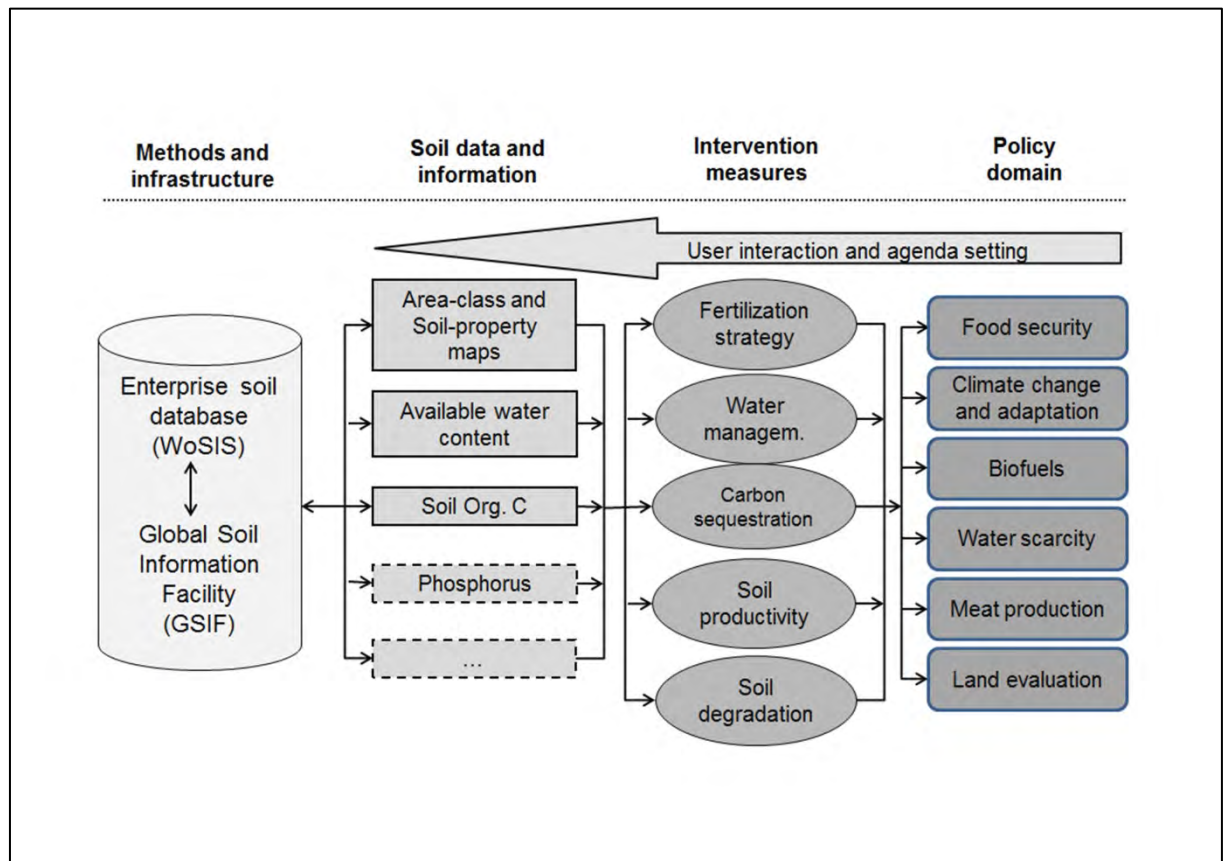
In addition to water and nutrients, the incidence of pests, diseases and fires may adversely impact on crop performance and such effects may vary with climate change (e.g., Clark *et al.* 2009; Running 2006; Schultz 2008; Thomson *et al.* 2010). For any region, the actual field-measured yields should 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<sub>2</sub>O, exchangeable bases (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>), exchangeable Al<sup>3+</sup>, 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<sup>a</sup>.*

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 <sub>3</sub> content, water balance and salinity
Acidification	Weathering, base exchange	CaCO <sub>3</sub> , exchangeable bases, cation exchange capacity (CEC) and mineralogy
GHG emissions	Organic matter formation/ decomposition (CO <sub>2</sub> ); methanogenesis and methane oxidation (CH <sub>4</sub> ); denitrification and nitrification (N <sub>2</sub> O)	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 <sub>4</sub> )

<sup>a</sup> 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<sup>a</sup>.*

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 <sup>-2</sup> to 1 m depth)
$\theta(h)$ , bulk density and rooting depth	Water-holding capacity
Heat capacity of soil constituents	heat conductance
Particle size distribution, moisture content and $\theta(h)$	$K_{sat}$ , $K(\theta)$
CEC, organic carbon content, clay content and $\theta(h)$	Clay mineralogy
CEC and exchangeable bases	Soil nutrient status
pH	Soil acidity resp. alkalinity
OC, N, clay and CaCO <sub>3</sub> content	E <sub>h</sub> /pH buffer relationships
Soil Munsell colour, CEC, clay and OC content	Free Fe <sub>2</sub> O <sub>3</sub> content

<sup>a</sup> Abbreviations:  $\theta$ = volumetric water content; h= soil water pressure head;  $\rho$ = 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<sup>a</sup>.

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 <sub>2</sub> )
Quantitative X-ray fluorescence (Ca, Mg, Fe, Al, Si)	Electrical conductivity
Water stable aggregates	Exchangeable sodium percentage

<sup>a</sup> 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<sub>3</sub>, 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 ( $\geq 1:25,000$ ) 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<sub>2</sub>-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* (NDVI) 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).

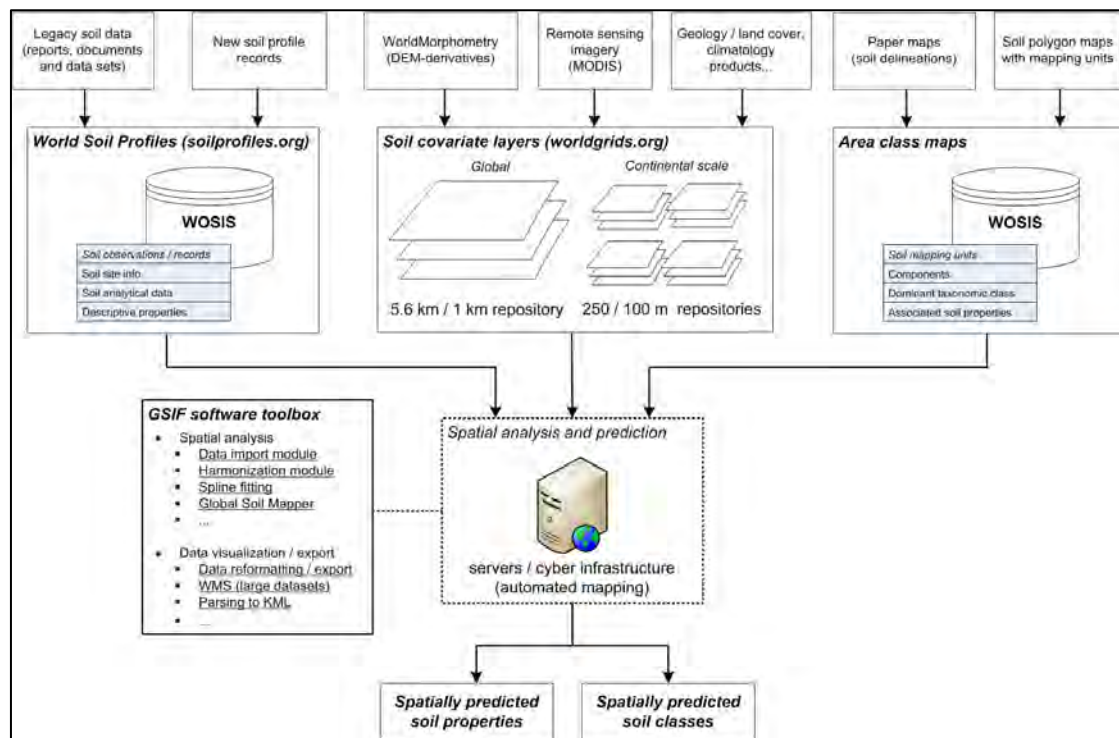
The submitted data, upon screening and validation, can be used for making new digital soil maps using advanced geo-statistical methods, for example using ISRIC's emerging Global Soil Information Facilities, thereby gradually refining the information on soil properties for the world at an increasingly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

For carbon sequestration projects aimed at CO<sub>2</sub> 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).



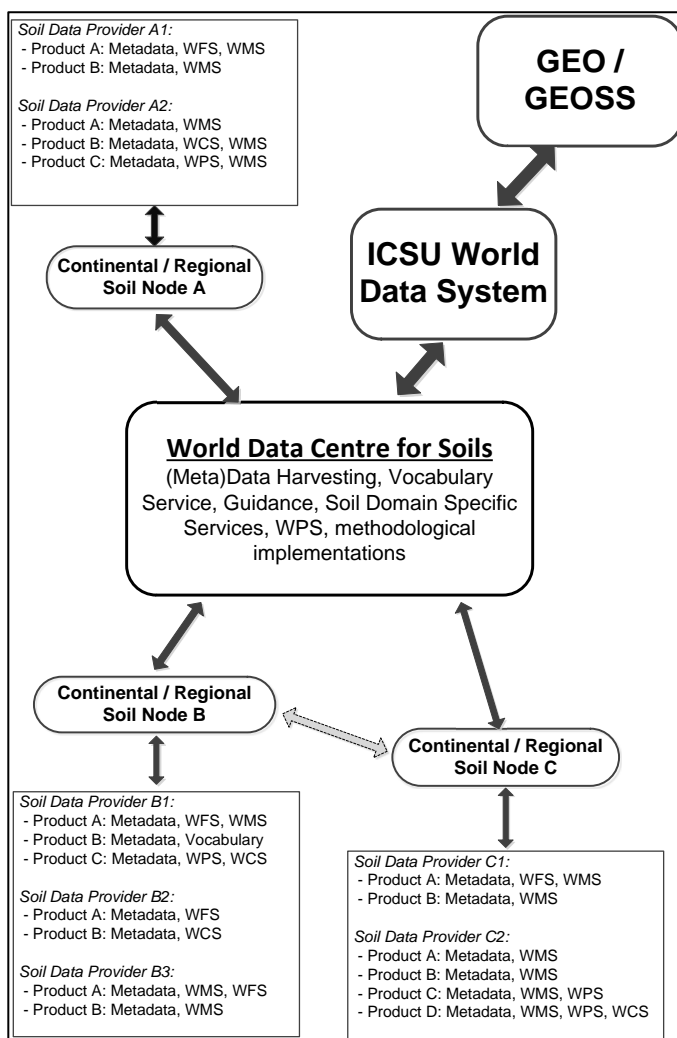
**Figure 3**

*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 2011 a) 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.

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