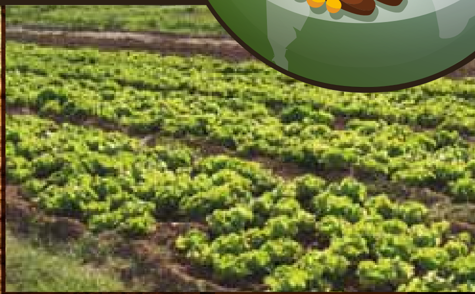
GLOBAL SOIL PARTNERSHIP
TECHNICAL REPORT



State of the Art Report on Global and Regional Soil Information: Where are we? Where to go?

GLOBAL SOIL PARTNERSHIP

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State of the Art Report on Global and Regional Soil Information: Where are we? Where to go?

by

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

Rome 2013

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ISBN 978-92-5-107449-7

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Acknowledgements

The review work presented in this document came from various sources: regional meetings, technical reports, books, journal articles, organization and personal websites, etc.

Dr. Luca Montanarella and Dr. Robert MacMillan are highly acknowledged for the review of the present report. The information on national soil data comes from regional workshops in which national experts presented the status of soil information in their countries.

The following experts are acknowledged for that contribution: Muhrizal Sarwani, Suk-Young Hong, A.F.M. Manzurul Hoque, S.M. Imamul Huq, Satoru Miura, Yusuke Takata, Chencho Norbu, Aniruth Potichan, Tien Minh Tran, Silvino Quevedo Tejada, Rodelio Bello Carating, Srimathie Priyanthika Indraratne, Ranjith Bandara Mapa, Dar-Yuan Lee, Zueng-Sang Chen, Azman AB. Rahman, Ochirbat Batkhishig, Sovuthy Pheav, Jarwar Attar Khan, Yajna Gajadhar, Khadka Ganlin Zhang, Renfang Shen, Maria Lourdes Mendonca, Augusto Gonzalez, Julio Alegre, Mariana Hill, Carlo Gauggel, Rafael Mata, Francisco Ovalles, Rodrigo Ortega, Gilberto Xix Ake, Humberto Goncalves, Jorge Luis Martinez Rayo, Carlos Castilla, Jose Luis Colocho, Hugo Antonio Tobias, Arnulfo Encina Rojas, Jose Ezequiel Villarreal, Ramon Sobral, Olegario Muniz, Pedro Antonio Nunez, Ahmed S.Mahaimed, Imad Ghanma, Ali Abdulla, Nadhir.Eahmed, Mostafa Kotb, Bahman Eskandare, Hedi Hamrouni, Roger Francis, Riad Balaghi, and Mahmoud Alferihat. We would like to thank all those who contributed to this work in one way or another.

We would like to also thank Parviz Koohafkan, Sally Bunning, Stefanie Neno, Gabrielle Zanolli, Maryse Finka and Francis Davis for their support during the preparation of this report.

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ACLEP	Australian Collaborative Land Evaluation Program
ASSS	African Soil Science Society
AFSIS	Africa Soil Information System
ARAs	Agroecological Resource Areas
ASRIS	Australian Soil Resource Information System
CanSIS	Canadian Soil Information System
CeC	Cation Exchange Capacity
CLI	Canada Land Inventory
DN	Digital Numbers
DAAC	Distributed Active Archive Centre
DEM	Digital Elevation Models
DSM	Digital Soil Mapping
DSMW	Digital Soil Map of the World
ESBN	European Soil Bureau Network
ESDAC	European Soil Data Centre
EU	European Union
ESP	Exchangeable Sodium Percentage
EuDASM	European Digital Archive of Soil Map
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GPL	General Public License
GSBI	Global Soil Biodiversity Initiative
GSIF	Global Soil Information Facilities
GSM	Global Soil Map
GSP	Global Soil Partnership
GSS	Global Soil Systems
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied Systems Analysis
INSPIRE	Infrastructure for Spatial Information in Europe
ISCW	Institute of Soil, Climate and Water
ISRIC	International Soil Reference and Information Centre
ISSCAS	Institute of Soil Science, Chinese Academy of Sciences
ISSS	International Society of Soil Science
JOSCIS	Jordan Soil and Climate Information System
JRC	Joint Research Centre
LAC	Latin America and Caribbean
LARI	Lebanese Agricultural Research Institute
LPDB	Land Potential DataBase

MENA	Middle East and North Africa
MLI	Manitoba Land Initiative
MoA	Ministry of Agriculture
NCSR	National Council for Scientific Re-search
NDVI	Normalized Difference Vegetation Index
NGOs	Non-Governmental Organizations
NIR	Near Infrared
NRI	National Resources Inventory
NRCS	National Resources Conservation Service
NSD	National Soil Database
NSDB	National Soil Database
NSMLUP	National Soil Map and Land Use Project
NSW	New South Wales
ORNL	Oak Ridge National Library
OC	Organic Carbon
PCA	Principal Component Analysis
pH	potential of Hydrogen
RDBMS	Relational DataBase Management System
SALIS	Soil and Land Information System
SCS	Soil Conservation Service
SGDB	Soil Geographic Database
SLC	Soil Landscapes of Canada
SOTER	SOil and TERrain
SOTERCAF	SOil and TERrain for Central Africa
SOTERLAC	SOil and TERrain for Latin America and Caribbean
SRTM	Shuttle Radar Topographic Mission
SSURGO	Soil Survey Geography
STATSGO	State Soil Geography
SWALIM	Somali Water and Land Information Management
TEB	Total Exchangeable Bases
TWI	Topgraphic Wetness Index
UN	United Nations
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTM	Universal Transverse Mercator
USA	United States of America
USDA	United States Department of Agriculture
VG	Voluntary Guidelines
WG	Working Group
WISE	World Inventory of Soil Emission Potential
WSR	World Soil Resource

1. INTRODUCTION

1.1 Soil functions

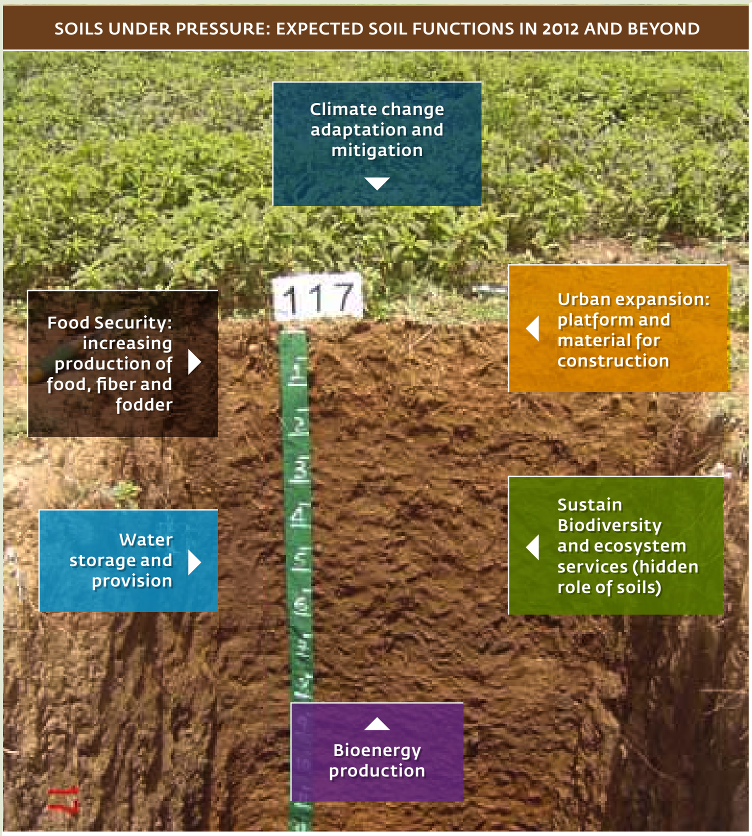
Soil is a natural body consisting of layers (soil horizons) that are composed of weathered mineral materials, organic material, air and water (Bockheim *et al.*, 2005). It is the end product of the combined influence of the climate, relief (slope), organisms (flora and fauna), parent materials (original minerals), and time. The most widely recognized function of soil is its support for food production. Farmers who use soil in crop production know very well that it is the foundation for agricultural production. This is because it is the medium in which growth of food-producing plants occurs. It supplies the plants with nutrients, water, and support for their roots. The plants, in turn, support human and animal life with food and energy. Soil also acts as a repository for seeds, germplasm, and genes for flora and fauna. In general, soil is the medium for preservation and advancement of life on earth (Brady, 1984; Foth and Ellis, 1997). Besides supplying water treatments to plants, soil also supports millions of organisms living in it. These organisms have proven useful in medicine, biodegradation and recycling of waste, as food, as well as being essential in the conversion of minerals and nutrients to readily useable formats for plants and in turn animal nutrition.

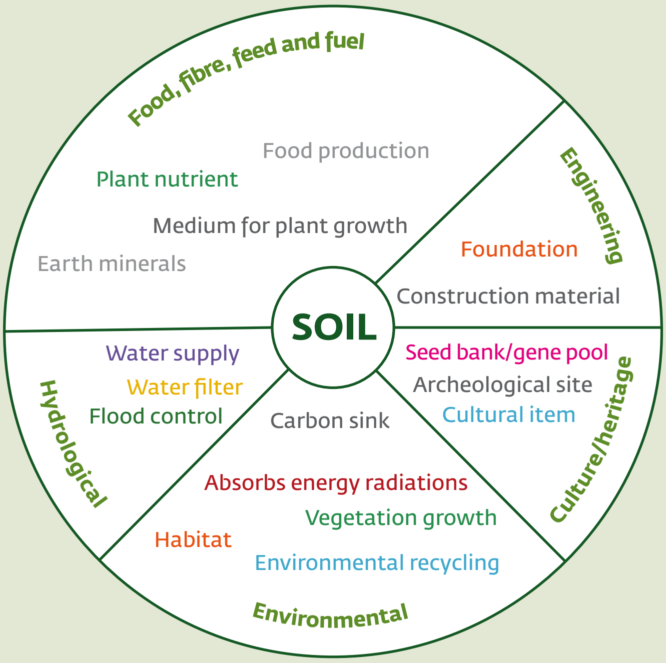
In hydrology, soil interacts with the hydrosphere as a medium that absorbs, purifies, transports, and releases water. In the hydrological cycle, the water that passes through the soil accumulates temporarily in the form of rivers, lakes/oceans/dams, soil water, and groundwater. During the storage process, soil filters the water against pollutants including natural and synthetic compounds. It also acts as a buffer against natural phenomena such as floods and soil erosion. In hydrology, the interaction of soil with the atmosphere has numerous environmental benefits. It can absorb excess energy radiation from the sun and release it gradually. Soil's gaseous exchanges with the atmosphere involve carbon dioxide, nitrogen oxides and methane and are of a magnitude that has been reported to have profound effects on the global climate. In fact, soil has been recognized as the largest terrestrial sink for carbon dioxide and consequently has great importance in mitigating the impacts of climate change (FAO, 2004).

In engineering, soil is used both as a construction material and as a foundation to support building infrastructures. Numerous engineering structures are made with soil as a primary construction material. For example, it's used to make blocks for building or used directly in construction such as in dams, mud-houses, roads, etc (Graham, 1989; Indraratna and Nutalaya, 1991). Soil importance as a foundation support cannot be overemphasized: Most structures have their foundations in the soil.

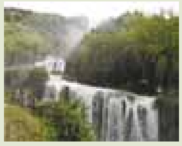
Soil is a source of all life. Its interaction with various aspects of life is summarized in Figure 1.1.

Figure 1.1 Importance and interaction of soil with aspects of life



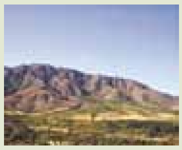


Life support services



- The soil renews, retains, delivers nutrients and provides physical support for plants;
- It sustains biological activity, diversity, and productivity;
- The soil ecosystem provides habitat for seeds dispersion and dissemination of the gene pool for continued evolution.

Provisioning services



- Soil is the basis for the provision of food, fibre, fuel and medicinal products to sustain life;
- It holds and releases water for plant growth and water supply.

Regulating services

- The soil plays a central role in buffering, filtering and moderation of the hydrological cycle;
- It regulates the carbon, oxygen and plant nutrient cycles (such as N, P, K, Ca, Mg and S) affecting the climate and plant production;
- Soil biodiversity contributes to soil pest and disease regulation. Soil micro-organisms process and break-down wastes and dead organic matter (such as manure, remains of plants, fertilizers and pesticides), preventing them from building up to toxic levels, from entering water supply and becoming pollutants.

Cultural services

- Soil provides support for urban settlement and infrastructure;
- In some cultures, soils may also be of specific spiritual or heritage value.
- Soils are the basis for landscapes that provide recreational value.

1.2 Importance of soil information

Soil is derived from weathering products of rocks and the decayed remains of plants and animals that once lived in or on the Earth. It is composed of four major components: minerals, organic matter, air, and water. The proportion of each of these components together with other factors such as climate, vegetation, time, topography, and, increasingly, human activities are important in determining the type of soil at any location in the landscape. For a long time, scientists have endeavoured to develop appropriate and efficient methods for predicting the spatial distribution of soils and their occurrence in the landscape. Soil mapping is the term often used to describe the process of understanding and predicting the spatial distribution of soils. It is a process that involves collecting field observations (including recording soil profile descriptions), analysing soil properties in the laboratory, describing landscape characteristics, and, ultimately, producing soil maps. Soil maps are the most widely used end-products of the soil mapping process since they illustrate the geographic distribution of soil types, soil properties (such as physical, chemical, and biological properties), and landscape characteristics.

Data coming from a soil mapping exercise can be classified as either primary data or secondary data. Primary data are those that have been obtained directly from observations or measurements in the field or in a laboratory. Secondary data are data that have been inferred or derived from the primary data. Examples of secondary data are the soil maps themselves, soil quality ratings, degradation assessments, pedotransfer functions, suitability indices, hydrologic soil groups, textural classes, etc. Secondary and primary soil data together form *Soil Information*. Soil information has a variety of uses worldwide such as assessing soil for its adequacy for a variety of applications, assessing and monitoring natural phenomena, determining productivity, and planning. Some of the major categories of these uses include:

- **Agronomic assessment:** Soil information is used to develop recommendations for best management practices, including determining the need for, and amount of, fertilizers, or other inputs, improving soil productivity, assessing land suitability for crop production, estimating crop yields, determining irrigation needs and scheduling, selecting appropriate crop types, calculating productivity, etc.
- **Engineering applications:** Soil information is used in urban planning, evaluation of construction materials, site selection, foundation design, design of water conveyance and flood control structures, etc.
- **Hydrology and Hydrogeologic assessments:** Including groundwater prospecting, groundwater and surface flow characterization, water pollution, modelling floods and droughts,
- **Environmental assessments:** As assessment of natural phenomenon including climate modelling, land degradation assessment, sediment transport and deposit into water bodies, global circulation, vegetation dynamics, modelling heat and carbon sinks, pollution control, environmental impacts, reclamation, remediation, etc.
- **Policy decisions:** Especially for national planning, resources allocation, economic development, when, where, and what crop or vegetation to promote, conservation of natural resources, formulation of laws and regulation of use of natural resources, preservation of environment, etc.

These uses have various levels of data demand in terms of accuracy, scale/spatial extent, temporal resolution, and details in metadata.

1.3 Need for analysis of soil information

Soil information exists at various spatial scales. Users of this information need to know the potential and limitations of available soil data at the various scales, where soil data is archived and whether there are any access restrictions or information gaps, and opportunities for collaborative work to improve soil information. To this end, a workshop on soil information was organized under Pillar 4 of the Global Soil Partnership "Towards Global Soil Information: activities within the GeoTask Global Soil Data" (http://www.fao.org/fileadmin/templates/GSP/downloads/GSP_SoilInformation_WorkshopReport.pdf). A key outcome of this workshop was the recognition of a need for assessing the state of the art of global and regional information. The present document represents an attempt to assemble relevant information on existing soil data at various scales throughout the world and on-going regional and global soil mapping initiatives. It aims at a) increasing users' awareness on existing soil data and information, b) encouraging informed and accurate application of it, c) understanding user needs in terms of soil data and information and d) understanding demands on soil data and information under the challenges of food security and climate change. The document is organized into four broad sections:

- **Existing soil legacy data and information**
  Existing soil data is a key factor to build accurate soil information. There is a huge reservoir of existing legacy soil data in many countries in the form of soil maps, soil profile descriptions and analyses. Given the time and resources invested in gathering this soil information, it's important to acknowledge these existing datasets and exploit their potential. This document reviews legacy soil data and highlights how this data can be accessed.
- **Soil user needs**
  Knowledge of soil data requirements of the soil user community and related stakeholder groups is important because soil information is generated to benefit the intended users. This document conducted an online survey on user requirements. Although the survey was not exhaustive, it gave highlights on the general nature of information expected from soil scientists and soil maps.
- **State of the art on methods and tools for digital soil mapping**
  Digital soil mapping (DSM) is a new technological advancement that seeks to fulfil the increasing worldwide demand in spatial soil data through more rapid and accurate production and delivery of soil information and increased coverage and improved spatial resolution of mapped areas. New tools and methods are constantly being developed to support DSM. This document explores these tools to highlight their potential for improving user access to accurate soil information.
- **On-going global and regional soil mapping initiatives**
  Several endeavours are being made globally, and in different regions, to coordinate soil information generation, share soil data and improve access to soil information. These endeavours need to be identified and catalogued, acknowledged, and, if possible, coordinated more effectively.

2. SOIL LEGACY DATA AND INFORMATION

The term legacy soil information is used for all existing soil information collected to characterize or map soils. The majority of such information was collected by soil surveys that included landscape and site descriptions, soil profile morphological descriptions and laboratory analysis of the main chemical, physical and biological soil properties. This information has typically been synthesized in paper soil maps that consist of polygons (soil mapping units) containing a description of soil units named and characterized by a national or international soil classification. Detailed, sometimes geo-referenced, information on the sampled soil profiles (point information) has been frequentlycollected and published in reports that accompany soil maps. In recent years there has been a considerable effort to capture this information in digital form (databases, digital maps) and some organizations have compiled and harmonized this local and national soil information at regional to global scales. In addition, for ease of combination with other kinds of information layers in GIS, some soil maps have been rasterized to a regular grid. Global soil maps and databases usually contain information on soil properties associated with the soil units described as being present in the polygons of the map, while global soil profile databases contain information on the soil classification unit they belong to. It is therefore somewhat arbitrary to subdivide the available soil information into categories of "mapped" and "point" information or in "global", "regional" or "national" information as these are often interrelated. We focus first on information presented at a global scale that is of particular interest to global policy makers and modellers. Next the availability of soil information, both in map and soil profile forms, at regional and at national scale is discussed. Detailed local soil surveys, which represent the bulk of soil information collected to date, are not discussed. One of the best general websites that lists the achievements of soil survey to date can be found at: http://www.itc.nl/~rossiter/research/rsrch_ss.html

2.1 Soil maps and soil profile databases at global scale

2.1.1 The FAO-UNESCO Soil Map of the World

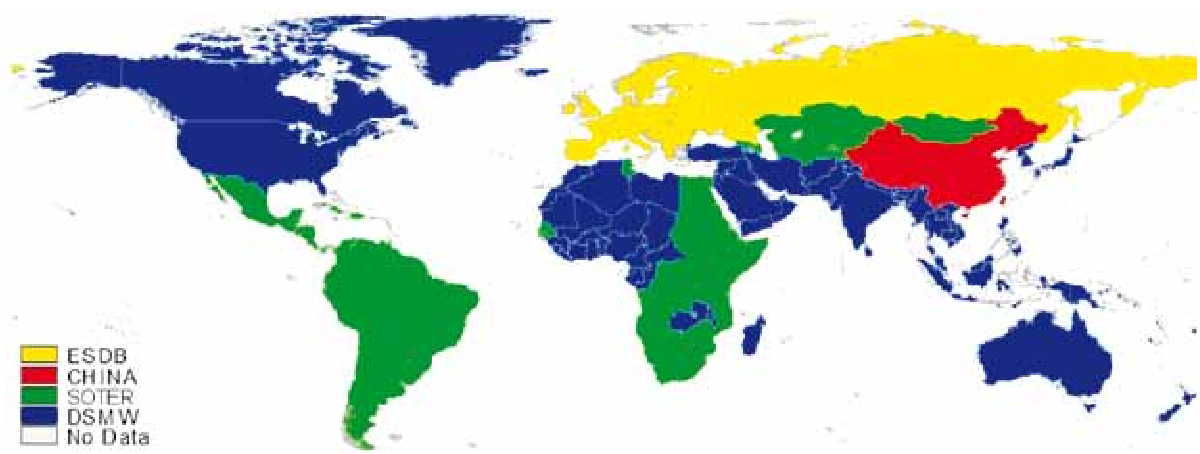
The FAO-UNESCO Soil Map of the World (FAO-UNESCO, 1971-1980) is presently the only, fully consistent, harmonized soil inventory at the global level which is readily available in digital format. It was published between 1974 and 1980 in 19 separate sheets at a mapping scale of 1:5 million. The map was based on information contained in some 11000 separate large-scale maps. Its development started as a project originated by a motion of the ISSS at the Wisconsin congress in 1960. It was first digitized by ESRI in vector format in 1984. The paper map contains 26 major soil groups, which are further subdivided into 106 individual soil units (FAO-UNESCO, 1974). The map was later digitized by FAO (1995) with a grid resolution of 5' x 5' (or 9 km x 9 km at the equator) (Nachtergaele, 2003). The digitized version, known as Digital Soil Map of the World (DSMW), contains a full database in terms of composition of the soil units, topsoil texture, slope class, and soil phase in each of its more than 5000 mapping units. The map is downloadable at: http://www.fao.org/geonetwork/srv/en/resources.get?id=14116&fname=DSMW.zip&access=private.

Transformations of the DSMW to reflect other soil classification systems such as the USDA Soil Taxonomy (Eswaran and Reich, 2005) and the World Reference Base for Soil Resources (FAO/EC/ISRIC, 2003) have also been published, but do not contain any additional information compared to the original map.

2.1.2 The Harmonized World Soil Database

The Harmonized World Soil Database (HWSD, FAO/IIASA/ISRIC/JRC/CAS, 2006), contains a digital soil map of the world, with soil units classified in the Revised FAO Legend (FAO 1990) at a fixed grid resolution of 1km by 1km, with associated soil properties and soil qualities. This digital global dataset is not fully harmonized, as it is based 40% on the original DSMW and 60% on regional and national updates undertaken after the DSMW was completed. (Figure 2.1)

Figure 2.1 Main legacy soil data sources for HWSD



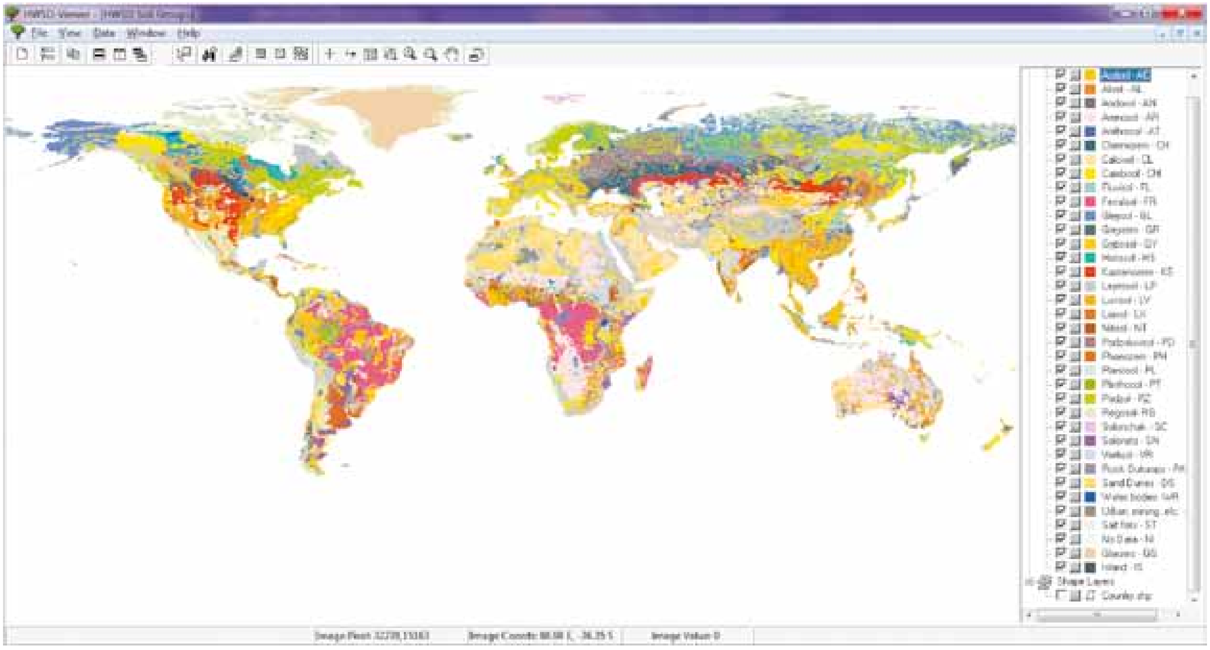
(Source: Nachtergaele et al.,2012)

It should be acknowledged that the 1km grid resolution used in the DSMW parts of the database is not fully justified given the lower resolution of the base material used in the DSMW part of the map. Presently, the HWSD contains over 16000 mapping units, which are used to link to a database of soil attribute data. The result is a 30 arc-second raster database consisting of 21600 rows and 43200 columns with each grid cell linked to the harmonized soil property data. This linkage of mapping units to the soil attribute data offers the opportunity to display or query the database in terms of soil units or in terms of selected soil parameters (such as Organic Carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry both for topsoil as subsoil layers). Although not fully harmonized and consistent, the HWSD contains the most up-to-date and consistent global soil information that is currently available and continuously updated. The Harmonized World Soil Database v1.2, is downloadable at: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/. In addition, the website contains freely downloadable software for visualising, querying, and retrieving the data. Figure 2.2 is an example of the database as visualized through the data viewer.

2.1.3 The WISE global soil profile database

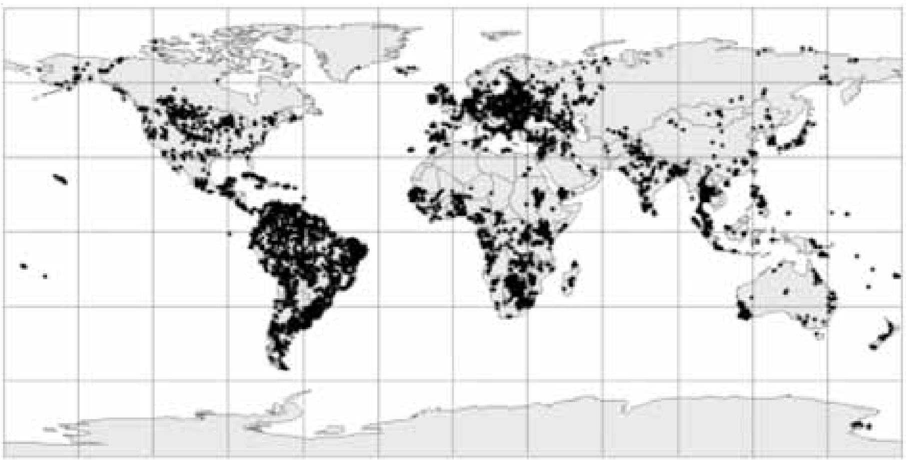
The International Soil Reference and Information Centre (ISRIC) World Inventory of Soil Emission Potential (WISE) International soil profile database is presently the only freely available and comprehensive repository of global primary data on soil profiles. ISRIC was established in 1966 with a focus of serving the international community with information about the world's soils. Through its WISE project, ISRIC has consolidated select attribute data for over 10,250 soil profiles, with some 47,800 horizons, from 149 countries in the world. Profiles were selected from data holdings provided by the Natural Resources Conservation Service (USDA-NRCS), the Food and Agriculture Organization (FAO-SDB), and ISRIC itself (ISRIC-ISIS).

Figure 2.2 HWSD Viewer for visualising and interacting with the soil database



The location of the WISE soil profiles worldwide is illustrated in Figure 2.3. The data can be downloaded at http://www.isric.org/data/isric-wise-global-soil-profile-data-ver-31) .

Figure 2.3 Locations (black dots) of WISE soil database



(source: http://www.isric.org/data/isric-wise-global-soil-profile-data-ver-31*)*

Individual profiles in the ISRIC-WISE database were sampled, described, and analyzed according to the methods and standards in use in the countries from where the data originated. The soil attribute data contained in the ISRIC-WISE database are given in Table 2.1, but not all soil profiles in the database contain all these attributes. In order to harmonize the data, ISRIC developed criteria to streamline analytical methods, soil classification scheme, data formatting, and documentation (Batjes, 2008). This harmonization was an important step towards achieving data quality control and building a

Table 2.1 Measured/observed soil attributes contained in WISE soil database

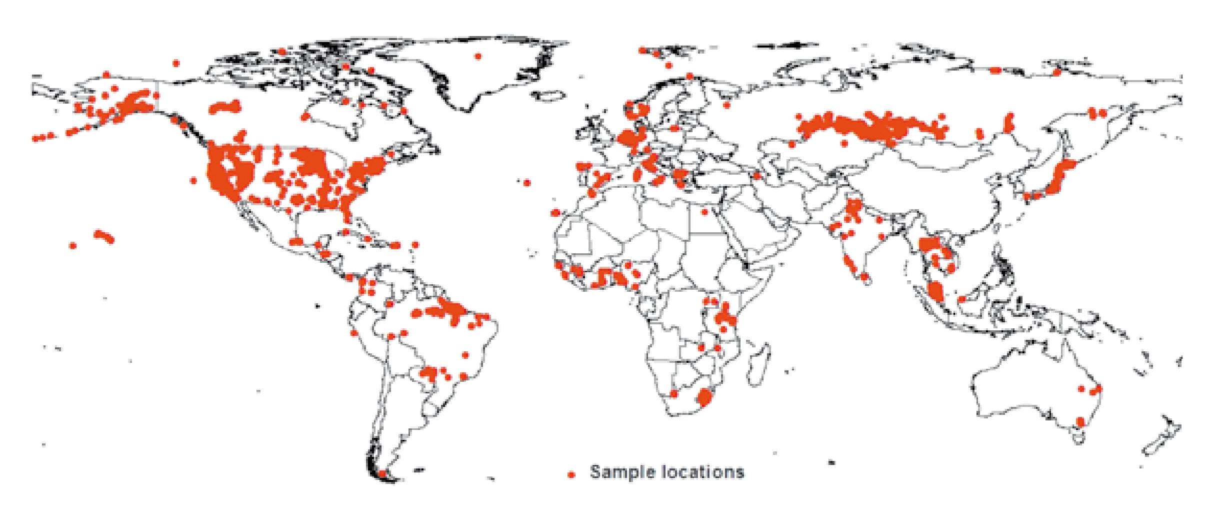
Soil profile description	Landscape characteristics
Depth	Altitude
Soil type	Landform
Number of horizons	Slope
Geographic coordinates (degrees)	Drainage
	Lithology
	Landuse
	Koppen climate
	Physiographic position
Soil properties (analytical data)	
Physical properties	*Chemical properties*
Organic matter content	Total Nitrogen
Texture (Gravel, Sand, Silt, Clay)	Total Carbonate
Bulk density	Total Gypsum
Water retention (10kPa, 33kPa, 1.5MPa)	pH
VIS/NIR Spectral reflectance	Electrical conductivity
Hydraulic conductivity	Exchangeable bases (Ca, Mg, Na, K, Al, Acid)
Soil structure	Cation Exchange Capacity (CeC)
	Base saturation

relational database that can be linked with other secondary data attributes such as mapping units of derived soil maps. Apart from data quality control,ISRIC has also developed a metadata service that allows soil data users to search and retrieve on-line soil data from the depository (http://www.isric.org/data/metadata-service). This is a powerful soil information service tool that helps data users to quickly locate and retrieve the kind of data they need. The tool is also an efficient way of managing soil information for a large pool of data users. It is important to note that all the data at ISRIC are held under the General Public Licence (GPL) (http://www.isric.org/data/data-policy), to encourage wide application of soil information.

2.1.4 Measured Global Organic Soil Carbon and Nitrogen

This database contains worldwide soil carbon and nitrogen data for more than 3,500 soil profiles. It was started by Zinke *et al.* (1986) with the collection and analysis of soil samples from California. Afterwards, additional data came from soil surveys of California, Italy and Greece, Iran, Thailand, Vietnam, various tropical Amazonian areas, U.S. forest soils, and from other published soil surveys. The main samples for laboratory analyses were collected at uniform soil depth increments and included bulk density determinations, but samples reported in the literature did not always have this uniformity. For the latter group of samples, only profiles that were sampled to a meter depth or to actual depth were used. Where bulk densities were not reported estimates were made from regressions based on organic carbon content of the soil samples associated with the profile. The methods used for analytical carbon determinations were dry combustion, 'wet combustion', or loss on ignition with adjustments made to the values obtained with the last two methods. Nitrogen was determined by the Kjeldahl method on the soil fine earth fraction and reported as total organic nitrogen (Zinke *et al.*, 1986). Figure 2.4 shows the distribution of the sample locations for the database. The data can be downloaded at http://daac.ornl.gov/SOILS/guides/zinke_soil.html

Figure 2.4 Location of global soil carbon and nitrogen data (Zinke *et al.*, 1986)



(Zinke *et al.*, 1986)

2.2 Global datasets of derived soil properties.

The WISE database discussed in the section 2.1.3 contains measured soil properties associated with a geo-referenced soil profile. The HWSD contains derived soil properties obtained by taxo-transfer functions that estimate a value for a soil property from a soil's taxonomic soil unit name, its topsoil texture class and the depth at which it occurs. Pedo-transfer functions, more generally, estimate the value of a soil property using values of one or more other known soil properties and site characteristics. The spatial distribution of these measured or estimated properties is one subject of pedometrics and is the basis for Digital Soil (Property) Mapping discussed in Chapter 4. It is important to realize that there is a fundamental difference between describing soil as a natural body with a morphology and a range of properties and characteristics as done in WISE and mapped in DSMW and HWSD, and the measurement and mapping of the distribution of soil properties only, as is frequently done in Digital Soil Mapping. However, the main user community and policy makers are often more interested in the value (and the change) of specific soil properties than in the spatial distribution of soil units described as extensive natural bodies. Another issue in this respect is the accuracy of geo-referenced values associated with map polygons and point locations. In soil maps values are reported as a distribution within a mapping unit or in a regular raster grid cell, while in continuous DSM mapping of soil properties values concern unique points and the distribution of values between points. A number of soil property maps available for the whole world are discussed in the following sections.

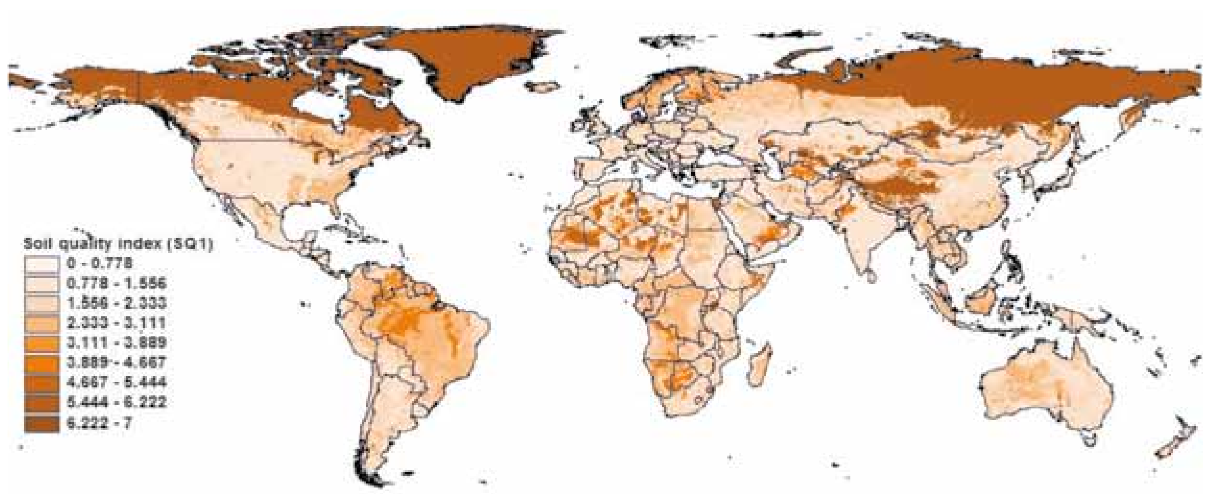
2.2.1. Derived soil properties at global scale.

Apart from holding primary WISE datasets, ISRIC, in cooperation with FAO and IIASA, has also developed algorithms for deriving other secondary datasets. These datasets are available at http://www.isric.org/data/data-download. The harmonized dataset of derived (or estimated) soil properties for the world was created using the soil distribution shown on the 1:5 million DSMW and soil parameter estimates derived from ISRIC's global soil profile database. (Batjes, 2002, 2003, 2006 and Batjes *et al.* 1995, 1997). This dataset considers 19 soil variables that are commonly required for agro-ecological zoning, land evaluation, crop growth simulation, modelling of soil gaseous emissions, and analyses of global environmental change. They include: soil drainage class, organic carbon content, total nitrogen, C/N ratio, pH (H_2O), CECsoil, CECclay, effective CEC, base saturation, aluminium saturation, calcium carbonate content, gypsum content, exchangeable sodium percentage (ESP), electrical conductivity, particle size distribution (i.e. content of sand, silt and clay), content of coarse fragments (> 2 mm), bulk density, and available water capacity (-33 to -1500 kPa). These estimates are presented as aggregated mean values by DSMW mapping unit for fixed depth intervals of 20 cm up to 100 cm (or less when appropriate). The associated soil property values were derived from analyses of some 10, 250 profiles held in ISRIC-WISE using a scheme of taxonomy-based taxo-transfer rules complemented with expert-rules. The type of rules used to derive the various soil property values have been flagged in the database to provide an indication of the possible confidence in the derived data. These can be downloaded at: http://www.isric.org/sites/default/files/private/datasets/wise5by5min_v1b_0.zip.

2.2.2. Soil quality indicators for agriculture at global scale

Soil quality is the capacity of a specific type of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al.*, 1997). On the basis of soil parameters provided by the HWSD global soil database, IIASA and FAO have calculated seven key soil qualities important for crop production at the global scale in the framework of the Global Agro-ecological Zoning project (GAEZ). They include soil quality with respect to: nutrient availability, nutrient retention capacity, rooting conditions, oxygen availability to roots, excess salts, toxicities, and workability. These soil qualities are considered to be related to the agricultural use of the soil and more specifically to maize crop requirements and tolerances (Fischer *et al.*, 2008). Figure 2.5 is an example of one of the soil qualities with respect to nutrient availability, which is a deciding factor for successful low level input farming and to some extent also for intermediate input levels. In this example, the important soil characteristics used in estimating the soil quality of the topsoil (0-30 cm) are: Texture/Structure, Organic Carbon (OC), pH and Total Exchangeable Bases (TEB). For the subsoil (30-100 cm), the most important characteristics considered were: Texture/structure, pH and Total Exchangeable Bases (TEB) (Fischer *et al.*, 2008). Other soil quality indices are freely downloadable from the FAO GeoNetwork GAEZ website at: http://www.fao.org/nr/gaez/en/.

Figure 2.5 Global soil quality with respect to nutrient availability



(Fischer et al., 2008)

2.2.3 Global Annual Soil Respiration Data

The Distributed Active Centre (DAAC) for global soil, a repository maintained by the Oak Ridge National Library (ORNL) in Tennessee, U.S.A, contains derived data on a number of soil properties (http://daac.ornl.gov/cgi-bin/dataset_lister.pl?p=19). Although some of these are outdated, some such as the global annual soil respiration data are unique and therefore mentioned here.

This data set is a compilation of soil respiration rates (g C m^{-2} yr^{-1}) from terrestrial and wetland ecosystems reported in the literature prior to 1992 (Raich and Schelsinger, 1992, 2001). The soil respiration rates are reported to have been measured in a variety of ecosystems to examine rates of microbial activity, nutrient turnover, carbon cycling, root dynamics, and a variety of other soil processes. The data can be freely downloaded from the following website:
http://daac.ornl.gov/SOILS/guides/raich_respiration_guide.html.

2.2.4 Global Distribution of Plant-Extractable Water Capacity of Soil

This dataset is also distributed by DAAC and gives the plant-extractable water capacity of soil, defined as the amount of water that can be extracted from the soil to fulfil evapotranspiration demands. Its derivation involved creation of a representative soil profile, characterized by horizon (layer) particle size data and thickness, from each soil unit of the DSMW. In this database, soil organic matter was estimated empirically from climate data while plant rooting depths and ground coverage were obtained from a vegetation characteristic dataset. At each 0.5- by 0.5- degree grid cell where vegetation is present, unit available water capacity (cm water per cm soil) was estimated from the sand, clay, and organic content of each idealised profile horizon, and integrated over horizon thickness. Summation of the integrated values over the lesser of profile depth and root depth produced an estimate of the plant-extractable water capacity of soil. The data can be downloaded at http://daac.ornl.gov/SOILS/guides/DunneSoil.html.

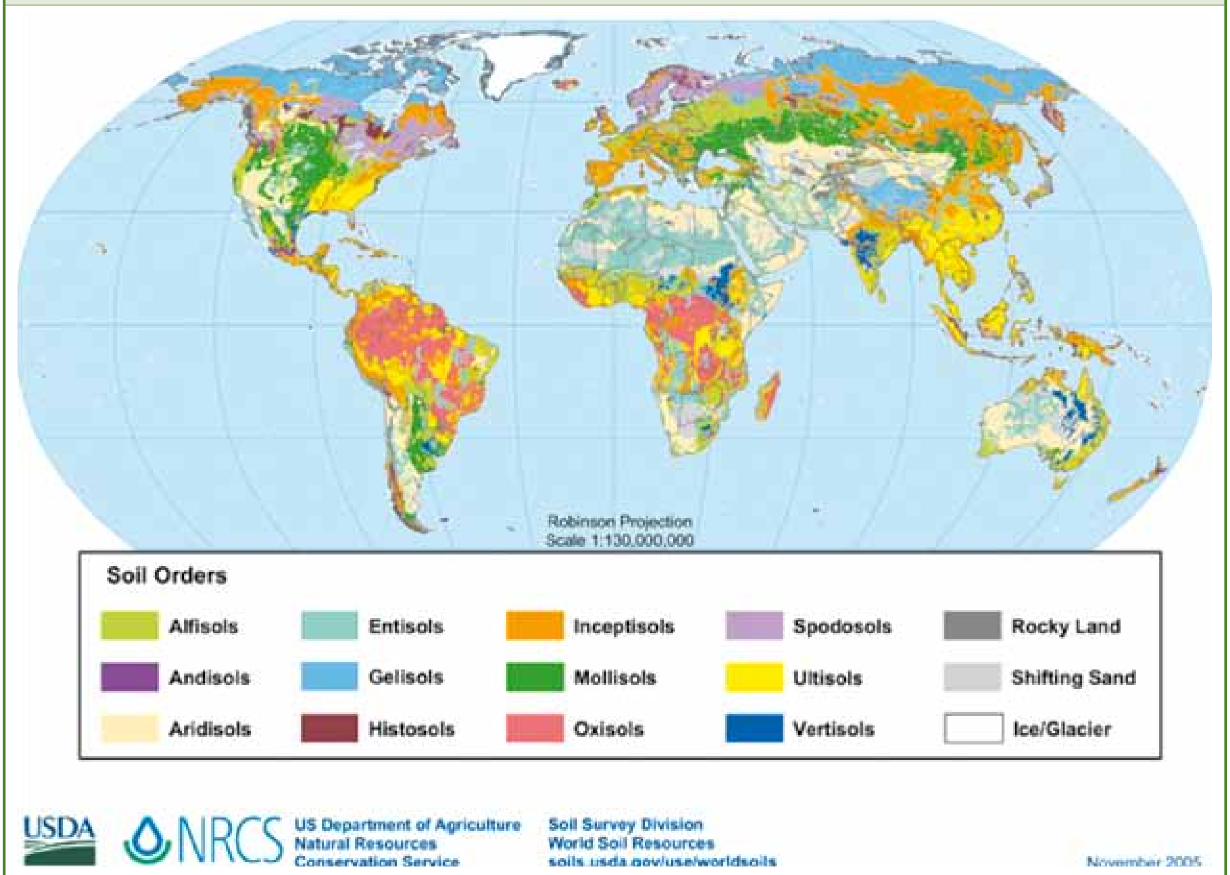
2.2.5 Global assessment of soil phosphorous retention potential

This is a database of the inherent capacity of soils to retain phosphorus (P retention) in various forms. It was built by considering the main controlling factors of P retention processes such as pH, soil mineralogy, and clay content. First, estimated values for these properties were used to rate the inferred capacity for P retention of the component soil units of each DSMW map unit (or grid cell) using four classes (i.e., Low, Moderate, High, and Very High). Subsequently, the overall soil phosphorus retention potential was assessed for each mapping unit, taking into account the P-ratings and relative proportion of each component soil unit. Each P retention class was assigned to a likely fertilizer P recovery fraction, derived from the literature, thereby permitting spatially more detailed, integrated model-based studies of environmental sustainability and agricultural production at the global and continental level (< 1:5 million). Although the uncertainties still remain high, the analysis provides an approximation of world soil phosphorus retention potential. The data can be freely accessed at http://www.isric.org/sites/default/files/private/datasets/Soil_Phosphorus_Retention_Potential_v1.zip

2.2.6 World soil map indices at NRCS

The Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) has produced a number of soil maps and soil indices based on global climate, the FAO-UNESCO Digital Soil Map of the World and a number of modelling functions. The maps are: global soil groups, soil moisture regimes, soil temperature regimes, land quality, soil organic carbon, water holding capacity, etc. These maps are said to be drafts. They can be downloaded at http://soils.usda.gov/use/worldsoils/mapindex/order.html. Figure 2.6 portrays global soil regions as an example of the available maps. The soil map shows the distribution of the 12 soil orders according to US soil taxonomy.

Figure 2.6 Global soil orders



(*source:* http://soils.usda.gov/use/worldsoils/)

2.3 Regional and (inter)continental Soil Information products

The advantage of having regional and continental soil information products is that they often provide a finer resolution than global soil maps and are, in principle, easier to harmonize because they use a single methodology (SOTER) and/or a single soil classification system which should, in principle, make border harmonization between countries easier.

2.3.1 Regional Soil and Terrain (SOTER) databases

SOTER (an acronym for SOil and TERrain) is a methodology developed at ISRIC for storing and handling soils and terrain data. The methodology was initiated in 1986 by Wim Sombroek and taken up by the International Society of Soil Science (ISSS). At the time of its formulation, the long term aim of SOTER was to provide a global soil database at 1:1 million scale to replace the FAO/UNESCO Soil map of the World. The project was actively supported by FAO and UNEP. Underlying the SOTER methodology is the identification of areas of land with a distinctive, often repetitive, pattern of landform, lithology, surface form, slope, parent material, and soil. Tracts of land distinguished in this manner are named SOTER units. Each SOTER unit thus represents one unique combination of terrain and soil characteristics. The database is composed of sets of files for use in a Relational DataBase Management System (RDBMS) and in a Geographic Information System (GIS) (van Engelen and Wen, 1995).

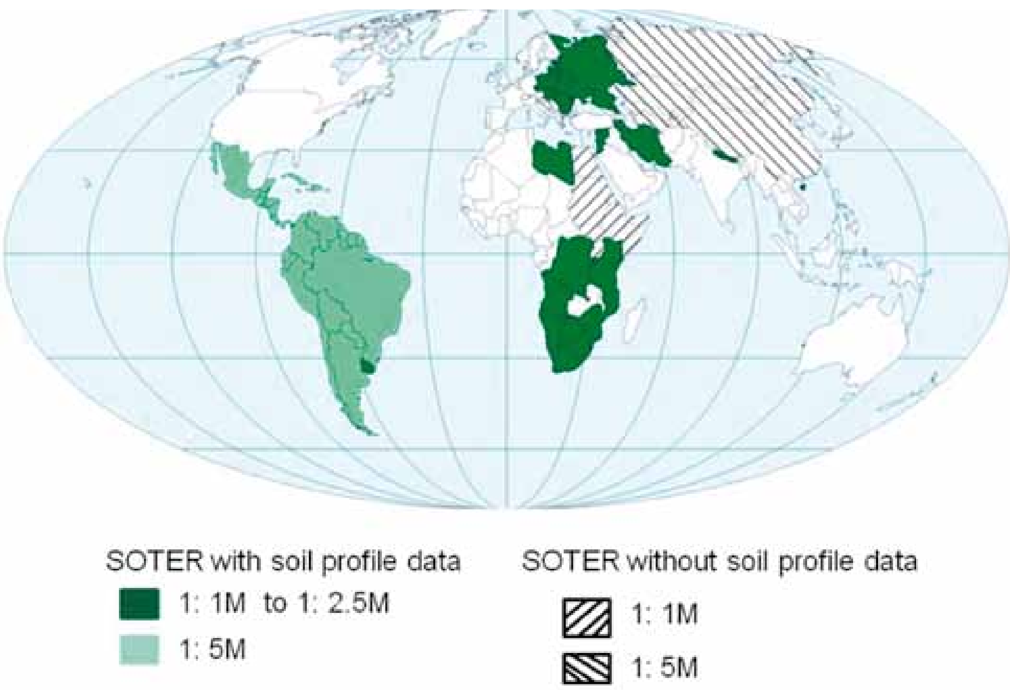
The SOTER regional soil databases were assembled from national legacy data such as maps (e.g. national exploratory and/or reconnaissance soil maps, topographic maps, land cover maps, etc) and attribute soil data. Regional SOTER databases prepared to date consist of:

- SOTER for Latin America and the Caribbean (FAO/ISRIC/, 1998),
- SOTER for Eastern and Northern Africa (FAO/IGADD/Italian Cooperation, 1998),
- SOTER for Northern Eurasia (FAO/IIASA/Dokuchaiev Institute/Academia Sinica, 1999).
- SOTER for Central and Eastern Europe (FAO/ISRIC, 2000)
- SOTER for Southern Africa (SOTERSAF, FAO/ISRIC, 2003),
- SOTER for Central Africa (SOTERCAF, FAO/ISRIC, 2007),

These SOTER databases are available on CD-ROM from FAO and downloadable on-line from ISRIC at http://www.fao.org/nr/land/pubs/digital-media-series/en/ and http://www.isric.org/projects/soil-and-terrain-database-soter-programme

These regional soil databases have been developed at different scales ranging from 1:5 million to 1:500 000, largely related to the scale of the original national soil information. Although the information sources were assembled according to the same SOTER methodology, there were variations in specific level of soil map and soil profile information in each region, which resulted in variation in the scale and contents of the end products (Figure 2.7). These differences, as well as data gaps, the emergence of new information (digital elevation models) and development of new ways to process soil data (digital soil mapping) prompted the revision of the SOTER methodology in a project led by ESBN. The results of this revised methodology (referred to as e-SOTER) have been summarized by Van Engelen (2012).

Figure 2.7 Coverage of SOTER database



(source: http://www.isric.org/content/data-and-applications*)*

The regional SOTER databases were a major input in the Harmonized World Soil Database and, as such, have significantly contributed to the development of this global product. However, the long term future of SOTER is somewhat in doubt, as countries can provide direct inputs to upgrade HWSD without preparing first a SOTER database. At the time of writing ESBN is still considering preparing a new SOTER product for Europe.

The regional SOTER databases are discussed in more detail at the national level (section 2.4) as they are often the most recent, most complete and/or largest scale soil product available for many countries.

2.3.2 Northern Circumpolar Soils Map

This data set consists of a circumpolar map of dominant soil characteristics, with a scale of 1:10,000,000, covering the United States, Canada, Greenland, Iceland, northern Europe, Russia, Mongolia, and Kazakhstan. The map was created using the Northern and Mid Latitude Soil Database. The map is in ESRI Shapefile format, consisting of 11 regional areas. Polygons have attributes that give the percentage polygon area that is a given soil type. (Tarnocai *et al.*, 2002). The map was used to prepare a Soil Atlas of the Northern Circumpolar Region (JRC, 2004), available at http://eusoils.jrc.ec.europa.eu/library/maps/Circumpolar/index.html.

This map and database are of great importance for climate change studies, but unfortunately are made at a very small scale. The soils in the northern latitudes store up to half of the Earth's soil carbon; about twice the amount of the carbon stored in the atmosphere. The importance of this carbon sink is immeasurable. Permanently frozen ground keeps this organic carbon locked in the soil and, together with extensive peat lands, ensures that northern circumpolar soils are a significant carbon sink. The impact of global warming on soil and the increased temperatures in the Arctic and boreal regions are causing permafrost-affected areas to thaw thus ensuring that the huge mass of poorly decomposed organic matter that is presently locked in the frozen soil will start to decompose. As a result of this decay, significant quantities of greenhouse gases (e.g. CO_2, CH_4, N_2O) could be released into the atmosphere. These emissions can initiate a snow-ball effect that will increase greenhouse gas concentrations in the atmosphere at an accelerating rate and greatly intensify the processes driving climate change.

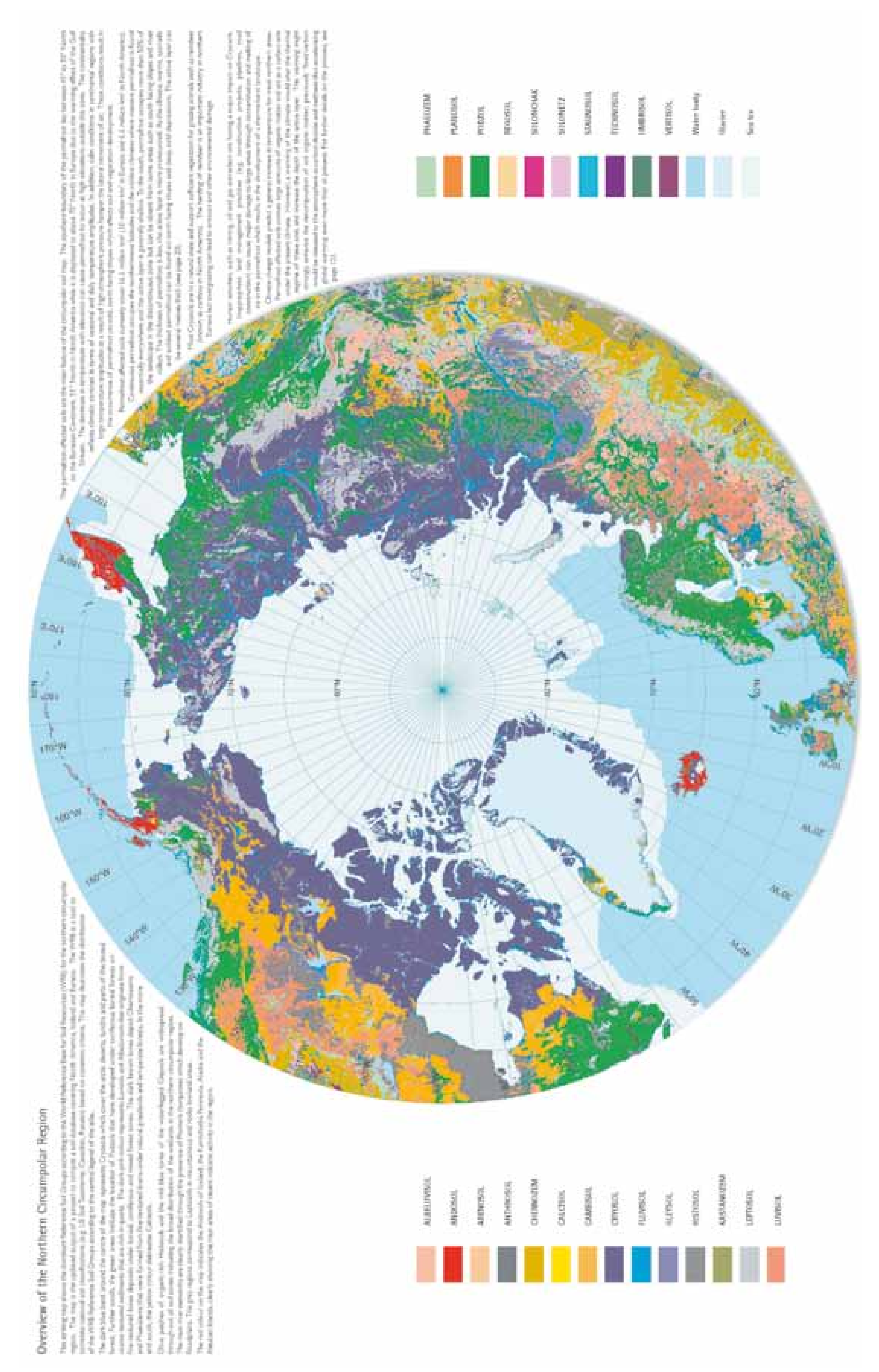


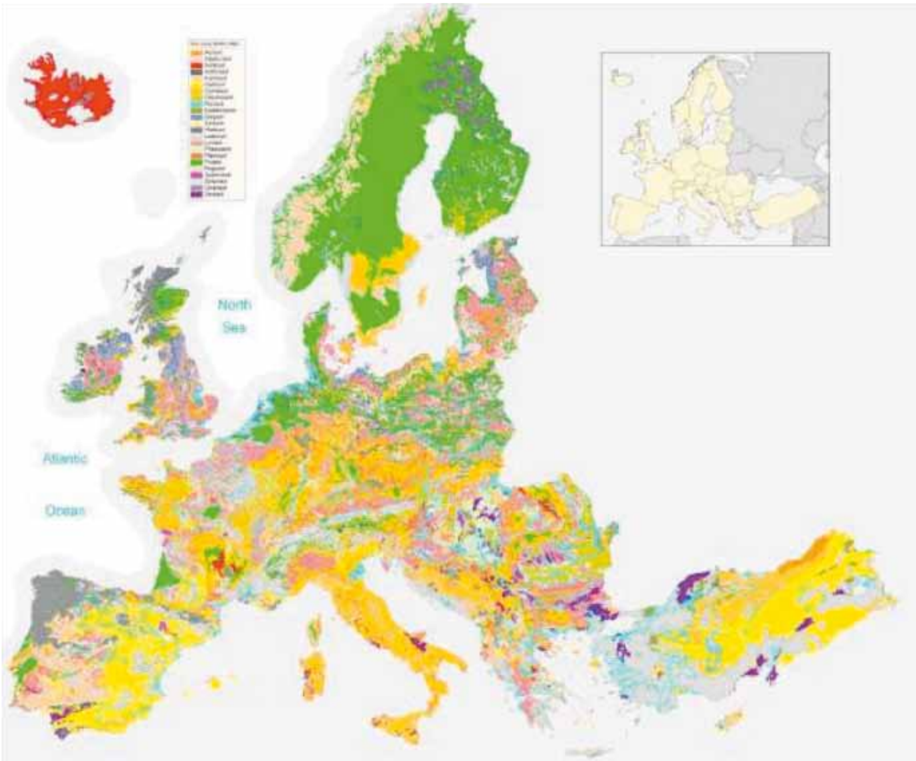
Figure 2.8 Northern circumpolar soil map

(JRC, 2008)

2.3.3 The European Geographic and Soil Profile Database

The European Commission, through the Joint Research Centre and its European Soil Bureau Network (ESBN), has prepared a 1:1 Million soil map of Europe with associated databases and applications (Fig 2.9). In addition, ESBN is currently storing over 560 measured soil profiles (Figure 2.10) and soil attributes from over 2650 horizons from member states (soil profiles, soil particle-size fractions, pH in water, organic carbon content (%), and dry bulk density) (Hiederer *et al.*, 2006). It has also developed methods for deriving analytical soil profiles from the existing legacy soil data (Hollis *et al.*, 2006). In addition to this soil database, ESBN has also archived soil legacy maps and is producing new soil maps. The network is presently building a soil information system for archived database with links to the soil database at the respective soil institutions of the member states.

Figure 2.9 Soil Map of the European Union and bordering countries



(source: Soil Atlas of Europe).

Figure 2.10 Distribution of measured soil profile data in Europe

(*source:* http://eusoils.jrc.ec.europa.eu)

2.3.4 Africa Soil Profile Database

ISRIC World Soil Information is compiling legacy soil profile data for Sub Saharan Africa, as a project activity of the AfSIS project (Globally integrated Africa Soil Information Service project). http://www.africasoils.net/data/legacyprofile

Africa Soil Profiles database, v. 1.0 (January 2012) identifies > 15700 unique soil profiles inventoried from a wide variety of data sources. From the > 14600 profiles that are geo-referenced, soil layer attribute data are available for > 12500 and soil analytical data for > 10000 profiles. Soil attribute values are standardized according to e-SOTER conventions and validated according to basic rules. Odd values are flagged. The degree of validation, and associated reliability of the data, varies because reference soil profile data, that are previously and thoroughly validated, are compiled together with non-reference soil profile data of lesser inherent representativeness.

Updated milestone versions of this dataset have been posted online and made available to the project. The continuously growing dataset will also be made available through the World Soil Information Service upon continuation of the project activity. The current version is released here http://www.isric.org/data/africa-soil-profiles-database-version-01-0 version 1.0.(Leenaars, 2012).

These datasets could not have been compiled without the support of countries in the region, some of which have soil databases superior to those available in many industrial countries. This is particularly the case for Botswana, Kenya, Rwanda and South Africa. A comprehensive discussion of soil maps and databases in the tropics is given by Nachtergaele and Van Ranst (2003).

2.4 Continental soil Atlas

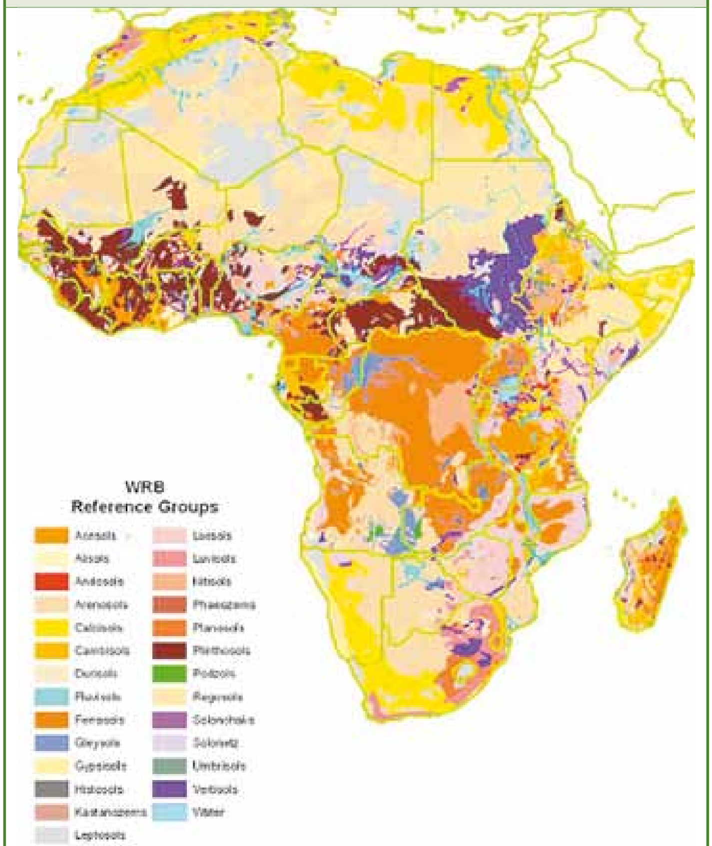
2.4.1 Soil Atlas of Europe

More than 20 years of collaboration between European soil scientists has resulted in the publication by the European Commission of the first ever "Soil Atlas of Europe". Based on soil data and information collected within the European Soil Information System (EUSIS) developed by the Joint Research Centre, the atlas illustrates in 128 pages of maps, tables, figures and graphs, the richness of European soil resources and the need for their sustainable management. The Atlas compiles existing information on different soil types in easily understandable maps covering the entire European Union and bordering countries. The publication is intended for the general public, aiming to 'bridge the gap' between soil science and public knowledge. By addressing the non-specialized audience, the Atlas will increase public awareness and understanding of the diversity of soils and of the need to protect this precious resource. In addition to the maps, the "Soil Atlas of Europe" contains an introduction to soil that explains the role and importance of soil, how soil is created, how to identify the soil in your garden, soil as a source of raw materials and the relationship between soil, agriculture, our cultural heritage, forests. Soil mapping and classification are also explained together with an illustrative and informative guide to the major soil types of Europe. The Atlas is available for download at:http://eusoils.jrc.ec.europa.eu/projects/soil_atlas/Atlas_Contents.html

2.4.2 Soil Atlas of Latin America and the Caribbean

The publication of the first Soil Atlas of Latin America and the Caribbean aims at presenting the relevance of soils as a natural resource and particularly its role in climate change and the carbon cycle. It is expected that such a publication will increase the visibility of the environment and its key natural resources to decision-makers, the Latin American public in general and particularly its education community. The Soil Atlas of Latin America and the Caribbean belongs to the series of Soil Atlases published by the JRC in recent years. Its publication is foreseen for 2013.

Figure 2.11 Soil atlas of Africa



(*Source:* http://eusoils.jrc.ec.europa.eu/)

2.4.3 Soil Atlas of Africa

The soil Atlas of Africa is being produced by the Institute of Environment and Sustainability (IES) of the JRC in collaboration with ESBN, ISRIC, FAO, African Soil Science Society (ASSS), and the African Union (http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/index.html). This atlas shows the distribution of the main soil types in Africa (Figure 2.11). It also contains derived maps at continental scale with descriptive text (e.g. vulnerability to desertification, soil nutrient status, carbon stocks and sequestration potential, irrigable areas and water resources) and more detailed sources of soil information for Africa. Its publication is foreseen for 2012.

2.5. National soil information

Two major general sources of national soil information are the digital archive of soil maps maintained at the JRC and the world soil survey archive and catalogue maintained at Cranfield University, United Kingdom.

2.5.1. Digital Archive of Soil Maps (EuDASM) and GeoNetwork

The Joint Research Centre (JRC), ISRIC-World Soil Information and FAO jointly worked to scan national soil legacy maps existing in hard copies at their premises. This effort has converted more than 6,000 paper soil maps from 135 countries into scanned digital copies. EuDASM's objective is to transfer paper-based soil maps into a digital format with the maximum possible resolution to ensure their preservation and easy disclosure. This is a tremendous resource of historical data, even though the digital maps have not been georeferenced. However, most scanned maps have overprinted grids which allow users to geo-reference the maps in GIS software. The scanned maps cover most countries in Africa, Asia, Europe and Latin America. The maps can be freely downloaded from the website http://eusoils.jrc.ec.europa.eu/ESDB_Archive/. More information about this database can be obtained from Panagos *et al.* (2011).

FAO's GeoNetwork gives access to environmental and related spatial data and information in order to support decision making. A significant number of soil maps and derived soil information is available at this site http://www.fao.org/geonetwork/srv/en/main.home that also contains metadata.

2.5.2 World Soil Survey Archive and Catalogue (WOSSAC) and ISRIC's document repository

The WOSSAC Archive is based at Cranfield University, UK. The archive consists of a soil reports section, soil maps and albums section, soil books section, aerial photography section, and a satellite imagery section of images collected in the past 80 years in more than 250 territories, principally by British companies and soil survey staff. The aims of WOSSAC are:

- To establish an accessible archive of hard copies of endangered soil survey reports, maps and other relevant materials.
- To establish an interactive online catalogue of all surveys known, including those in the Archive at Cranfield and those remaining in company and private hands elsewhere.
- Although WOSSAC is concentrating on British-sourced materials, its aim is to link the WOSSAC catalogue with other major databases, to form a global network of information on soil surveys.

ISRIC's repository http://library.wur.nl/isric/ contains a rich collection of books and reports on soils. Presently, the WOSSAC Archive holds materials for some 276 countries and territories worldwide, some of which enjoy a better depth of coverage and representation than others (http://www.wossac.com/archive/index.cfm).

2.5.3 National soil maps, geographic databases and soil profile information

Sub-Saharan Africa

A number of soil data and derived soil products are available for many Sub-Saharan African countries as national archived data in individual countries. Many of those have been scanned by the EuDASM archive (section 4.1). There are SOTER databases for large parts of Sub-Saharan Africa, such as SOTER for Southern Africa (SOTERSAF), for Central Africa (SOTERCAF), and for North-Eastern Africa.(SOTERNE).

SOTERSAF was compiled from the SOTER database for Southern Africa at a scale of 1:1 M. The initial dataset covered national soil maps from *Angola*, *Mozambique Namibia*, *South Africa*, *Swaziland*, and *Tanzania*. The SOTER methodology was applied to these maps by national soil institutes and FAO consultants. The SOTER database was then restructured and the GIS files were slightly modified by ISRIC, using the 90 m digital elevation model (DEM) derived from Shuttle Radar Topographic Mission (SRTM). The database can be found at http://www.isric.org/projects/soter-south-africa or can be obtained on CD ROM from FAO.

SOTERCAF for Central Africa (SOTERCAF, version 1.0), including the *Democratic Republic of Congo*, *Burundi* and *Rwanda*, was compiled following the SOTER methodology with collaboration from FAO, ISRIC, and the University of Ghent. Information about the data can be found at http://www.isric.org/sites/default/files/private/datasets/sotercaf_Total_set.zip.

SOTER for north-eastern Africa contains land resource information on soils, physiography, geology and vegetation for the following ten countries in the Great Horn of Africa: *Burundi*, *Djibouti*, *Egypt*, *Eritrea*, *Ethiopia*, *Kenya*, *Rwanda*, *Somalia*, *Sudan* and *Uganda*. The information is accessible with an easy-to-use viewer program and with individual soil properties with class values. A land suitability assessment for irrigated and upland crops for each unit is included. The scale of the source material is variable and ranges between 1:1 million and 1:2 million. More information about this dataset can be found at FAO or through the following website: http://www.fao.org/catalog/book_review/giii/w7374-e.htm.

National SOTER databases (SOTERNAT) are available in Africa for *Kenya*, *Nigeria*, *Senegal* and *The Gambia*, prepared by ISRIC in collaboration with FAO. For these and other countries in Sub-Saharan Africa the following table 2.2 gives a summary of national soil maps.

Table 2.2 National Soil Maps in Sub-Saharan Africa.

Country	>1:250 000	1:250 000	1:500 000	1:1 000 000	SOTER database	Year
Angola					* SOTERCAF	2006
Benin	CPCS					1978
Botswana				FAO	SOTERSAF	1990
Burkina Faso			CPCS			1976
Burundi		Local			SOTERCAF	1980
Cameroon			ST			1991
Cape Verde					*	
Central African Republic	CPCS					1978
Chad				CPCS		
Comoros					*	
Congo Democratic Rp					*SOTERCAF	2006
Congo People Rp.				CPCS		1976
Côte d'Ivoire	CPCS					
Djibouti					*SOTERNE	1998
Equatorial Guinea					*	
Eritrea				FAO	SOTERNE	1988
Ethiopia				FAO	SOTERNE	1988
Gabon	CPCS					1977
Gambia	Local				SOTERNAT	1976
Ghana	FAO					1990

Table 2.2 (Continued)

Country	>1:250 000	1:250 000	1:500 000	1:1 000 000	SOTER database	Year
Guinea					*	
Guinea Bissau					*	
Kenya				FAO	SOTERNAT	1988
Lesotho		Local				1983
Liberia			FAO			1990
Madagascar				CPCS		1968
Malawi		FAO				1991
Mali			ST			1983
Mauritius	CPCS					1984
Mozambique				FAO	SOTERSAF	1991
Namibia				FAO	SOTERSAF	2003
Niger					*	
Nigeria			Local		SOTERNAT	1981
Rwanda	ST				SOTERCAF	1990
Sao Tome & Principe					*	
Senegal	CPCS				SOTERNAT	1980
Seychelles	Local					1966
Sierra Leone					*	
Somalia					*SOTERNE	1998
South Africa		Local			SOTERSAF	2006
Sudan					*SOTERNE	1965
Swaziland		Local			SOTERSAF	1968
Tanzania				FAO	SOTERSAF	1990
Togo	CPCS					1979
Uganda				FAO	SOTERNE	1988
Zambia				FAO		1991
Zimbabwe				Local		1979

**Partial or information at scale smaller than 1:1 Million. Year = Year first published.*

Soil Classification schemes: Local Systems, CPCS (French), FAO-1974, ST=USDA Soil Taxonomy.

Middle East and North Africa (MENA)

The majority of countries in the MENA region have rich soil datasets housed at their national institutes. However, these datasets still exist as hard copy maps and often do not cover the whole country. In some countries, the hard copies are in the process of being converted into digital copies. Few on-line sources exist in this region, apart from those maps inventoried by EuDASM (section 3.1). Digital geo-referenced soil profile information is scarce, apart from that stored in Jordan. Some of the information mentioned in Table 2.3 is not in the public domain (for instance the Soil Map of Saudi Arabia). There is no SOTER product available in the region, except for a national SOTER in Syria and Tunisia and the Egypt part of the SOTER for Northern and eastern Africa.

Table 2.3 National Soil Maps in the North Africa and the Middle East

Country	>1:250 000	1:250 000	1:500 000	1:1 000 000	SOTER	Year
Algeria					*	
Egypt				FAO	*SOTERNE	1976
Iran				ST		1996
Iraq					*	
Israel			Local			1977
Jordan		ST				1994
Kuwait	ST					1997
Lebanon	FAO			ST(1985)		2006
Lybia					*	
Oman		ST				1990
Mauretania					*	
Morocco					SOTERNAT?	2006?
Palestine					*	
Qatar	ST					2005
Saudi Arabia				ST		1995
Syria			SOTERNAT			1996
Tunisia			CPCS		SOTERNAT	2008
UAE					*	
Yemen					*	

** Partial or very small scale national information only. Best national soil database is a SOTER or the FAO-Unesco DSMW. ST=Soil Taxonomy FAO=FAO Legend SOTERNAT=National SOTER study. SOTERNE =SOTER east and northeast Africa. CPCS= French soil classification.*

Asia

National geographic soil databases in Asia are summarized in Table 2.4. Soil information availability appears to be extremely varied with a number of countries having - to our knowledge - no national soil maps better, or more recent than, the one contained in the Digital Soil Map of the World and HWSD. This appears to be the case for *Afghanistan*, *Bhutan*, *Cambodia*, *Korea Democratic Republic*, *Laos*, *Myanmar*, *Sri Lanka* and *Vietnam*. In other countries such as India, more detailed national soil information exists, but is not in the public domain. Some countries have developed sophisticated soil information databases on-line. In this respect, attention is drawn to Korea (http://asis.rda.go.kr.), China (http://www.geodata.cn.) illustrated in Figure 2.12, and Nepal (http://www.isric.org/data/soil-and-terrain-database-nepal) .

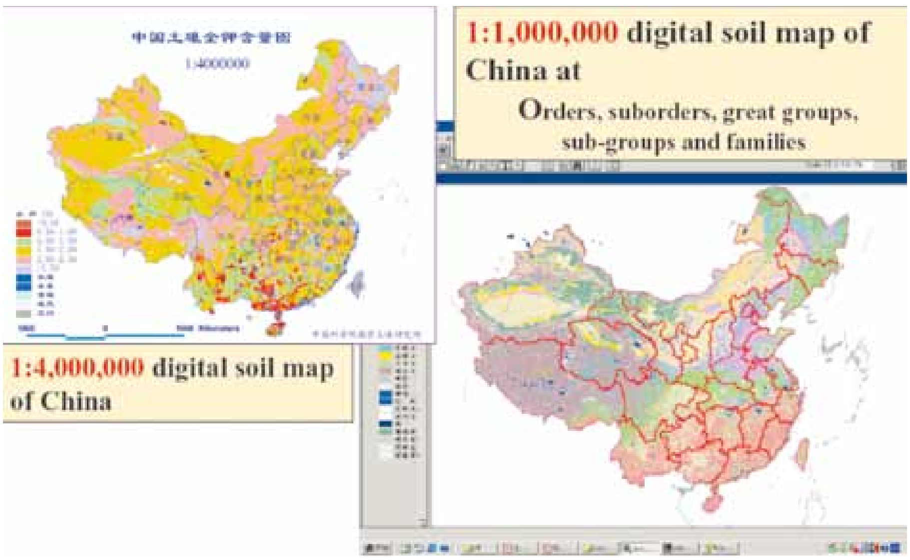
The digital soil and physiographic database for northern and central Eurasia (SOTEREA) covers China, Mongolia and all countries of the former Soviet Union. The database was derived from several sources such as the 1:2.5 Million Soil Map of the Former Soviet Union prepared by Friedland in the Dokuchaiev Institute, Moscow; the soil map of China at 1:4 million scale prepared by the Institute of Soil Science Chinese Academy of Science in Nan-Jing; and the SOTER database for China. Apart from selected examples in the report on soils of China, the database contains neither soil profile descriptions or soil analysis results.

Table 2.4 National Soil Maps in Asia (excluding Russia and former Soviet Union Republics)

Country	>1:250 000	1:250 000	1:500 000	1:1 000 000	Small scale map	Year
Afghanistan					*	
Azerbaijan			Russian		SOTEREA	1975
Bangladesh		ST				1985
Buthan					*	
China				Local/ST		2004
Cambodia				FAO		1990
Georgia					SOTEREA	1984
India			ST			1992
Indonesia					*	
Japan				Local		1990
Kazakhstan					SOTEREA	1976
Korea				ST		1985
Korea Dem. Rep.					*	
Laos					*	
Malaysia			Local			1980
Myanmar					*	
Mongolia				Local	SOTEREA	
Nepal		SOTERNAT				2005
Pakistan					ST (1:2M)	1993
Philippines				ST		1995
Sri Lanka				Local		1988
Thailand		ST				2000
Uzbekistan					SOTEREA	
Vietnam				Local		1966

** = Only partial information available. FAO=FAO1974 Soil Classification ST= USDA Soil Taxonomy.*
SOTERNAT = National SOTER study SOTEREA = SOTER of northern Eurasia. Local= Local classification system.

Figure 2.12 Examples of digitized soil maps of China



(Source: Shi, 2012)

Latin America and Caribbean (LAC)

National soil databases for the different countries in the LAC region are illustrated in Table 2.5. The SOTER database for Latin America and the Caribbean (SOTERLAC) was first published as a CDROM by FAO in 1998. An updated version is now available at ISRIC. The database contains over 1800 soil profiles, soil attribute data, and derived soil properties and can be downloaded from: (http://www.isric.org/sites/default/files/private/datasets/SOTERLAC2.zip). The derived soil properties in this database are presented by soil unit for fixed depth intervals of 0.2 m to 1 m depth.

Table 2.5 National Soil Maps in Latin America and the Caribbean as per SOTERLAC.

Country	>1:250 000	1:250 000	1:500 000	1:1 000 000	Small scale map	SOTER	Year
Argentina				ST		SOTERLAC	
Bolivia				ST/FAO		SOTERLAC	
Brazil					Local (1:5M)	SOTERLAC	
Chile					ST (1:6M)	SOTERLAC	
Colombia	ST					SOTERLAC	
Costa Rica	ST					SOTERLAC	
Cuba		Local				SOTERLAC	
Ecuador				ST		SOTERLAC	
El Salvador		ST				SOTERLAC	
Guatemala					ST/FAO(1:2M)	SOTERLAC	
Honduras				ST/FAO		SOTERLAC	
Mexico		FAO/WRB				SOTERLAC	
Nicaragua			ST			SOTERLAC	
Panama					ST(1:2M)	SOTERLAC	
Paraguay			ST/FAO			SOTERLAC	
Peru					ST(1:5M)	SOTERLAC	
Rep. Dominica		ST				SOTERLAC	
Uruguay				ST/Local		SOTERLAC	
Venezuela		ST				SOTERLAC	

In addition to the Geographic Databases a number of countries have developed on-line access to soil information. This is, for instance, the case for Argentina , Columbia, Guatemala, Mexico, Paraguay, República Dominica and Paraguay. These and some other countries in the LAC region have prepared digital soil profile databases as illustrated in Table 2.6

Table 2.6 Soil profile databases and on-line soil information in countries of the LAC region

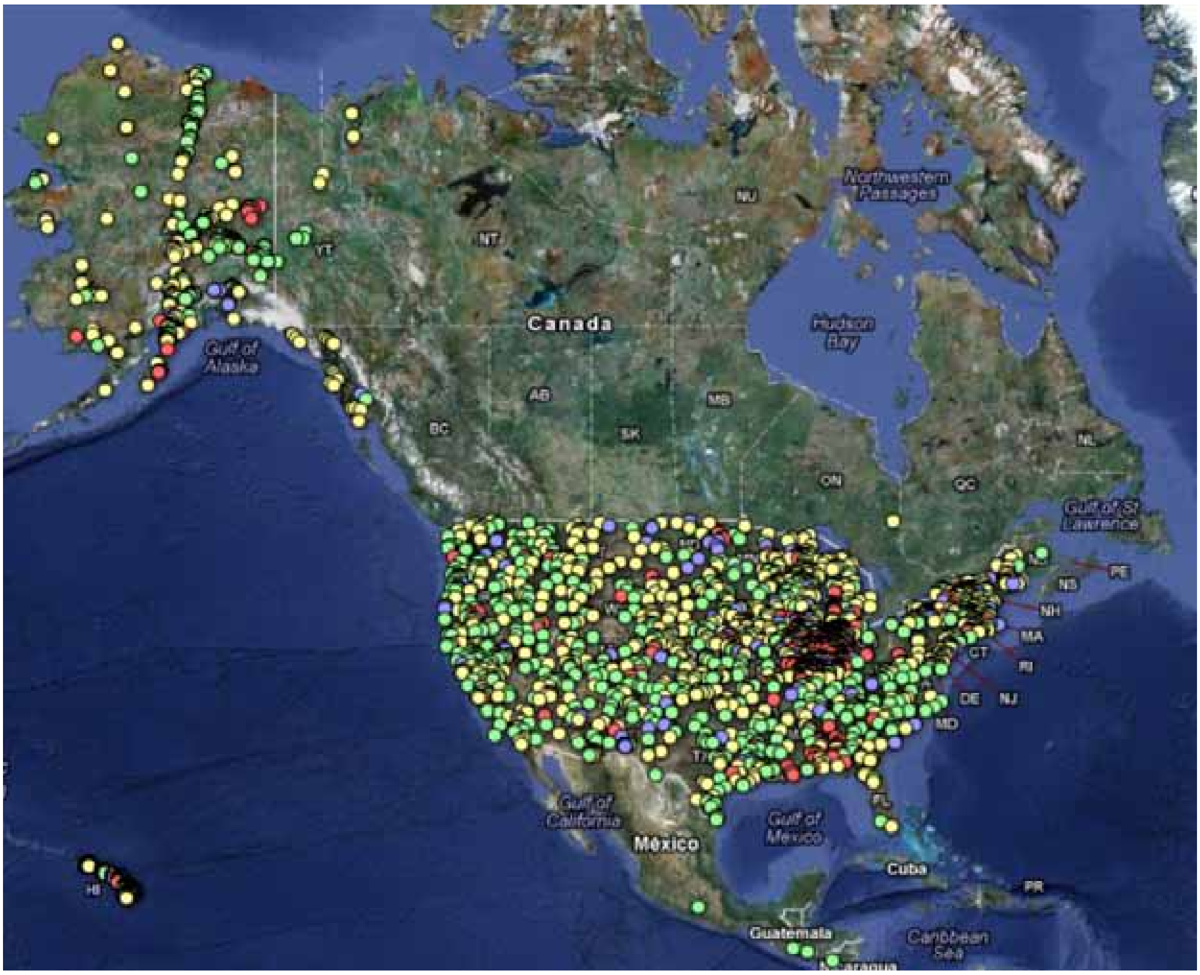
Country	Soil profile database available	Soil information available in internet
Argentina	Yes	http://geointa.inta.gov.ar
Bolivia	No	No
Brazil	Yes	No
Chile	No	No
Colombia	Yes	http://geoportal.igac.gov.co:8888/siga_sig/Agrologia.seam
Costa Rica	No	No
Cuba	Yes (73000)	No
Ecuador	Yes (2439)	No
El Salvador	No	No
Guatemala	No	www.maga.gob.net
Honduras	Yes (2000)	No
Mexico	Yes (9549)	http://www.inegi.org/mx/geo/contenidos/recnat/edafologia/InfoEscala.aspx
Nicaragua	Very few and dispersed in different institutions	No
Panama	Yes (19193)	No
Paraguay	Yes (695)	http://www.geologiadelparaguay/Suelos.html and http://es.scribd.com.doc/51410928/10/Map-Taxonomia-del-Suelo
Peru	No	No
República Dominica	Yes (100)	www.ambiente.gob.do
Uruguay	Yes (1200)	www.renare.gob.uy and www.cebra.com.uy/renare/
Venezuela	Yes (3000)	No

North America (United States of America)

The National Resources Conservation Service (NRCS) was originally established by US Congress in 1935 as the Soil Conservation Service (SCS) and later expanded to become the leader for all natural resources, ensuring private lands are conserved, restored, and made more resilient to environmental challenges such as climate change. NRCS works with landowners through conservation planning and assistance designed to benefit the soil, water, air, plants, and animals and also with consequences on productive lands and healthy ecosystems. It works with landowners because 70% of the land in the United States is privately owned (http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/about).

The NRCS publishes standardized digital soil geographic databases of the USA at two scales: 1:63,360 to 1:12,000 (previously named SSURGO) and 1:250,000 (previously named STATSGO). In addition, soils data are included in the time-series point samples of the National Resources Inventory (NRI). The soil database currently archived by the Service contains more than 20,000 pedons of U. S. Soils (Figure 2.13).

Figure 2.13 Location of NSCS soil profiles in North America



(http://ncsslabdatamart.sc.egov.usda.gov)

Canadian soil information service (CanSIS)

The Canadian Soil Information Service (CanSIS) manages and provides access to soil and land resource information on behalf of the federal, provincial, and territorial governments of Canada (http://sis.agr.gc.ca/cansis/). It maintains the national repository of soil information such as soil data, maps, technical reports, and standards and procedures through its National Soil Database (NSDB) (http://sis.agr.gc.ca/cansis/nsdb/intro.html). The NSDB includes GIS coverage at a variety of scales and the characteristics of each soil series. The principal types of NSDB data holdings are summarized at http://sis.agr.gc.ca/cansis/nsdb/intro.html .

National soil databases in Europe

The European Soil Bureau Network prepared the Soil Geographical Database for Europe (SGDBE) at 1:1 M scale. The latest version is available at: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB_Data_Distribution/ESDB_data.html

Rather surprisingly, this regional inventory is for many medium-sized and large countries in Western Europe the most detailed national soil map available, The German, UK (England and Wales part only) and Italian detailed national soil maps are not in the public domain.. Smaller European countries often have highly detailed soil maps (Belgium for instance is completely covered at 1:10 000 scale). Most countries in Central and Eastern Europe (including the European part of Russia) are covered by a SOTER database at 1:2.5 M scale (FAO/ISRIC/, 2000) that incorporates soil profile information. Some soil profile information is contained in SGDBE (see below) and as previously illustrated (Figure 2.10) is rather scarce compared to other continents. The main reason is that these profiles (and the more detailed soil maps) are not in the public domain in many European countries.

Soil Geographical Database of Europe at scale 1:1.000.000 Version 1 of this database (SGDBE) was digitised by Platou *et al.* (1989) for inclusion in the CORINE project (Co-ordination of Information on the Environment). The database was enriched in 1990-1991 from the archive documents of the original EC Soil Map and the resulting database became version 2. The work of the Soil and GIS Support Group of the MARS Project led to version 3 of the database. A slightly updated version (3.2.8) of the Soil Geographical Database at scale 1:1,000,000, covering central and eastern European and Scandinavian countries (Jamagne *et al.*, 1995), forms the core of version 1.0 of the European Soil Database. The aim of the database is to provide a harmonised set of soil parameters, covering Europe (the enlarged EU) and bordering Mediterranean countries, to be used in agro-meteorological and environmental modelling at regional, national, and/or continental levels.

Recently the Soil Geographical Database of Europe (SGDBE) has been extended in version 4.0, to cover *Albania*, *Austria*, *Belgium*, *Bosnia and Herzegovina*, *Bulgaria*, *Croatia*, *Cyprus*, *Czech Republic*, *Denmark*, *Estonia*, *Finland*, *France*, *FYROM* (Former *Yugoslav Republic of Macedonia*), *Germany*, *Greece*, *Hungary*, *Ireland*, *Italy*, *Latvia*, *Lithuania*, *Malta*, *The Netherlands*, *Norway*, *Poland*, *Portugal*, *Romania*, *Serbia*, *Slovakia*, *Slovenia*, *Spain*, *Sweden*, *Switzerland* and the *United Kingdom*.

The most recent extension covers *Iceland* and the New Independent States (NIS) of *Belarus*, *Moldova*, *the Russian Federation* and *Ukraine*. Work is ongoing to incorporate soil data for other Mediterranean countries: Algeria, Egypt, Jordan, Lebanon, Morocco, Palestine, Syria, Tunisia and Turkey.

In addition to these geographical extensions, the database has also experienced important changes during its lifetime. The latest major changes include the introduction of a new extended list of parent materials and, for coding major soil types, the use of the new World Reference Base (WRB) for Soil Resources (FAO, 1998). The database is currently managed using the ArcGIS® Geographical Information System (GIS) software system and associated relational databases.

The database contains a list of Soil Typological Units (STU) characterizing distinct soil types that have been identified and described. The STU are described by attributes (variables) specifying the nature and properties of the soils, for example: texture, moisture regime, stoniness, etc. It is not appropriate to delineate each STU separately thus STUs are grouped into Soil Mapping Units (SMU) to form soil associations. The criteria for soil associations and SMU delineation have taken into account the functioning of pedological relationships within the landscape. A detailed instruction manual for the compilation of data for the Soil Geographical Database of Europe version 4.0 has been published by Lambert *et al.* (2003). An overview per country is given in Table 2.7.

The wealth of soil profile information that is being collected in Europe is well illustrated by Bullock *et al.*, (1999) in Table 2.8. Its availability however is much more problematic.

Table 2.7 National Soil Geographic Databases in Europe

Country	<1:250 000	1:250 000	1:500 000	1:1 000 000	Smaller scale	Year
Albania	ST			ESDB		?
Austria				ESDB		1989
Belarus				ESDB	SOTER	
Belgium	Local			ESDB		-2000
Bosnia-Herzegovina	Local			ESDB		?
Bulgaria			Russian	ESDB	SOTER	1968
Croatia				ESDB		1998
Cyprus	FAO			ESDB		1970
Czech Rep.	Local			ESDB	SOTER	?
Denmark	Local			ESDB		1989
Estonia	Local			ESDB	SOTER	?
Finland				ESDB		
France				ESDB		2003
Germany			German	ESDB		
Greece			Local	ESDB		2003
Hungary	Local			ESDB	SOTER	?
Iceland				ESDB		2003
Ireland		Local		ESDB		1980
Italy		WRB		ESDB		2008?
Latvia			Local	ESDB	SOTER	1976
Lithuania		Local		ESDB	SOTER	
Luxembourg	Local			ESDB		1969
Macedonia FYR				ESDB		
Malta	Local			ESDB		1960
Moldova				ESDB	SOTER	1969
Netherlands	Local			ESDB		
Norway				ESDB		
Poland			Local	ESDB	SOTER	1906!
Portugal				ESDB		
Romania			Local	ESDB	SOTER	1971
Serbia	Local			ESDB		
Slovakia			WRB	ESDB	SOTER	1973
Slovenia	Local			ESDB		1999
Spain				ESDB		
Sweden				ESDB		
Switzerland			German	ESDB		
Turkey				ESDB		
Ukraine				ESDB	SOTER	1977
United Kingdom		Local		ESDB		

ESDB: European Soil Database SOTER:=SOTER for Central and Eastern Europe.
Local=Local soil classification system FAO = FAO Legend. WRB = World Reference Base
German = German soil classification system Russia o Russian soil classification system.

Table 2.8 Details of national soil mapping and monitoring in European countries

Country	1:250,000	1:50,000 to 1:25,000	1:10,000	Number of Sampling (Inventory or Monitoring) sites
Albania	100%		28% (farms) at 1:5K	
Austria		63-98%	10% F, 63% A 20% 1:5K	514 F plots (grid 8.7 x 8.7km), 5,000 F soil profiles, 26,000 analyses BORIS; 432 agri monitoring points; soil assessments data – 32% Environ. Soil survey 5,000 F + 2,500 A
Belgium	100%	100%	100%	15,000 soil profiles =+ analyses
Bosnia Herz		100%		
Bulgaria	100%	100%	90%	50,000 main soil profiles
Croatia		100%		6,000 soil profiles
Cyprus	100%	100%		Nitrate monitoring (1:250,000)
Czech Republic	100%	100%	100% 100%, at 1:5K,	30,000 soil profiles 200 permanent monitoring plots, 500 forest monitoring
Denmark	100%	A	In prep	8,000 soil profiles, 7km x 7km grid survey; 393 HM monitoring
Estonia	100%	100%	100%	10,000 soil profiles; various monitoring programmes
Finland	In prep.	30%		28,000 texture, 80,000-100,000 samples (for farmers) 2,000 monitoring sites (pH, C, Ca, Mg, K, HM)
France	30%	Incomplete	case studies	ICP Ft (16x16 km, 540 plots); some monitoring
Germany	30% (1:200K)	Incomplete	case studies	
Greece			case studies	3,000 sites for fertiliser monitoring
Hungary	100%	100%	70%	1,200 points (800A + 200F + 200 hot spots)
Iceland				75% vegetation maps at 1:40,000 & 1:25,000, soil erosion databases for 1:100,000
Ireland	100%	44% at 1:126K		295 soil points (22% of country)
Italy	100%		case studies	
Latvia	100%		100% of farms	2,547 points (5km x 5km); various monitoring projects
Lithuania	100%		farm level	7,000 profiles (analytical data A + F); various monitoring projects
Luxembourg	100%	100%		
Macedonia				
Malta		100%		MALSIS 280 points (1kmx1km) 1st stage; 240 Malta+60 Gozo 2nd stage 350 profile data, 800 soil samples data
Netherlands	100%	100%	55% groundwater table	various monitoring projects
Norway				9km x 9km grid F
Poland		district level		2,000F, 5,700A, 1,000 mineral soil samples 216 arable soil profiles
Portugal	100%	35%	case studies (irrigation)	800 soil profiles described 100 soil profiles analysed 80 soil profiles for hydraulic properties; soil erosion monitoring
Romania	100%	80% A	20% A	soil survey (A) at scales 1:10,000 & 1:5,000) forest survey at 1:50,000, database of land units soil quality A & F – grid 16x16km (942 profiles=670A + 272F) PROFISOL 4,200 soil profiles (16kmx16km) 1,200 profiles for pedo-geochemical database,
Serbia	100%		Case studies	Agriculture and water research-42,000 sq km; some monitoring
Slovakia	100%		100% 100% at 1:5K,	18,000 soil profiles + analyses 330 monitoring points (A) 280 monitoring points ((F)
Slovenia	100%	100%	1:5K for urban soils & on GIS	1,700 soil profiles+analyses; pollution monitoring (2kmx2km A.; 4kmx4km F), 1kmx1km in polluted areas
Spain	50%	15%		453 soil profiles; 2,000 data (critical loads studies) erosion studies 20,000 points; contamination: 1,200 samples from pastures; +2,600 samples from arable land
Sweden		1% A		ICP Forest soil monitoring (no. of sites not known)
Switzerland		7%		Some monitoring
Turkey		A (for irrigation)		
United Kingdom	100%	30%	case studies	6000 soil profiles + analyses; 9,000 national soil inventory points (5km x 5km); 6,500 analyses, 2,200 monitoring sites

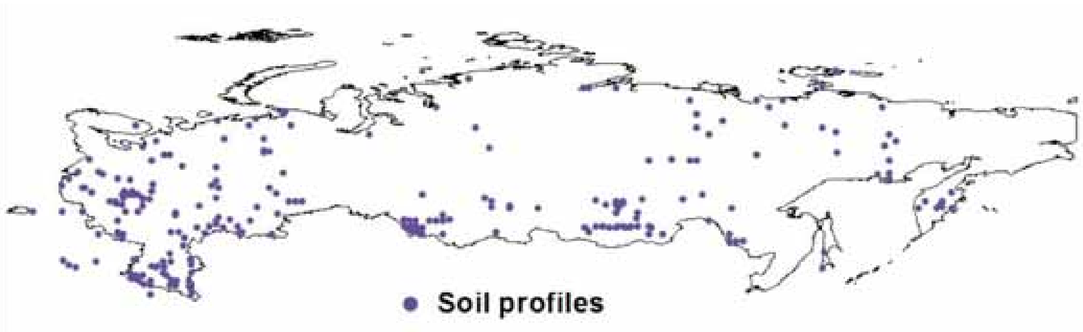
A – agricultural; F – forest ; HM – Heavy Metals; 1:5K – 1:5,000

National soil databases of Russia

Soil geographic database (SGDB) of Russia is archived at the Department of Soil Science, Lomonosov Moscow State University in collaboration with the Soil Institute. The database consists of a soil map of Russia at a scale of 1:2.5 M, representative soil profiles, and soil attributes which are linked to the mapping units of the soil map of Russia. More information about the database can be found at http://db.soil.msu.ru.

A national soil profile collection for Russia is kept at IIASA and consists of 234 soil profiles, which are complete with soil attribute data. The dataset is freely available online and can be accessed from the following website: http://www.iiasa.ac.at/Research/FOR/russia_cd/download.htm. It has two tables: the first provides measured soil data and the second table one provides default values where measured data are lacking in the first table. The reference soil profiles come from numerous literature sources. The extent and practical importance were major reasons for the profile selection. Therefore, agricultural soils received priority in the database elaboration. While the collection aimed to cover all soils of Russia, there were problems with analytical data for some poorly investigated soils in the north, Siberia, and the Far East. The geographical distribution of measured soil referenced profiles is shown in Figure 2.14.

Figure 2.14 Distribution of Russian soil reference profiles at IIASA



Two SOTER products cover Russia: SOTER for Central and Eastern Europe which includes the European part of Russia at 1:2.5 Million scale, including soil profiles for the dominant soils; and SOTER for northern Eurasia which includes the Asian part of Russia at 1:5 M scale without soil profile information.

Australia

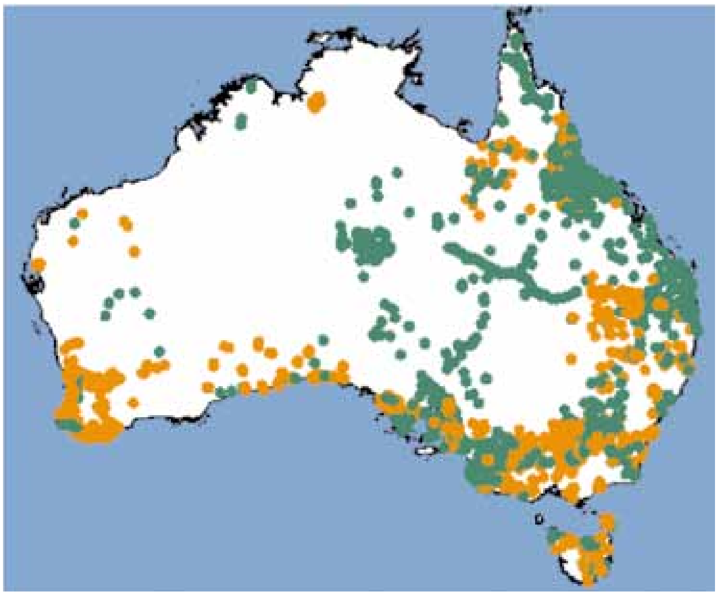
ASRIS (Australian Soil Resource Information System) was formed under the auspices of The Australian Collaborative Land Evaluation Program (ACLEP) to collate and maintain the best available, nationally consistent soil and land resource information for Australia. It provides a scientific information infrastructure for assessing and monitoring the condition of Australia's soil and land resources (http://www.asris.csiro.au/). ASRIS has soil and land resource information from institutions in different regions in Australia (Figure 2.15 and Table 2.9). The level of detail of the data

Table 2.9 Number of ASRIS profiles from each State and Territory

State/Territory	State Agency	CSIRO	Total
New South Wales	23920	499	24419
Northern Territory	4717	108	4825
Queensland	37884	2246	40130
South Australia	20806	1522	22328
Tasmania	5043	275	5318
Victoria	3787	399	4186
Western Australia	60593	775	61368
Australian Capital Territory	0	1456	1456
Total	156750	7280	164030

depends on the survey coverage in each region. More specifically, it provides a hierarchy of mapping units with seven levels of generalization: The upper three levels (L1–L3) provide descriptions of soils and landscapes across the complete continent while the lower levels (L4–L6) provide more detailed information, particularly on soil properties, for areas where field survey have been completed. The lowest level (L7) relates to individual sites in the field. Presently, ASRIS is collaborating with Australian institutions and Government Departments with interest in land and environmental issues (http://www.asris.csiro.au/). In addition to the soil database, ASRIS also archives legacy soil maps and is developing new soil maps as well.

Figure 2.15 Australia soil profile database



(*Source:* http://www.asris.csiro.au/mapping/viewer.htm)

New Zealand

In New Zealand, the S-Map project was created as part of the government-funded Spatial Information programme run by Landcare Research to provide digital soil spatial information system for New Zealand (http://www.landcareresearch.co.nz/). The S-map project houses the national soils database for New Zealand and has its work still in progress. When completed, it will provide seamless digital soil map coverage for the country and at any scale from farm to region to nation.

The National Soil Database (NSD) it houses is a 'point' database containing descriptions of about 1,500 New Zealand soil profiles, together with their chemical, physical, and mineralogical characteristics (Figure 2.16).

Figure 2.16 S-Map soil profile database in New Zealand

(http://www.landcareresearch.co.nz/)

2.5.4 Conclusions

An enormous amount of soil data has been collected up to date. The bulk of this information was gathered at local scale for agricultural (and other) development and monitoring processes.

As soil survey work was driven by local problems, there was initially little harmonization in soil description, soil classification and soil analytical methods used.

In recent years there has been growing agreement on each of these issues. The FAO Guidelines for Soil Profile Description (FAO, 2006) and the Soil Survey Manual of the USDA (USDA, 1993) are very similar and are now recognized as international standards. In soil classification the development of the World Reference Base for Soil Resources, itself largely based on the USDA Soil Taxonomy and the related FAO Legend for the Soil Map of the World, has made many national classifications converge towards a common approach and terminology. Certainly there is still no universal agreement on a unique system, but the large differences that existed in the past are narrowing.

Standardization of soil laboratory methods has also made good progress, although significant differences remain for such crucial characteristics as texture and organic carbon measurements.

From a policy side, a major reduction in funding by central Governments in most countries of the industrial world starting in the 1980's, resulted in the transfer of responsibility from central soil survey and research organisations to regional groups and/or private sector organisations. This introduces a number of difficulties, particularly a lack of uniformity in approach and methodology used, proliferation of different soil classifications, a lack of availability of the information after surveys have been completed and difficulties in harmonising the information at national and continental levels. (Bullock *et al.*, 1999).

Soil data have not been collected everywhere with the same intensity, sometimes for obvious reasons. For example, where the climate is too dry, too cold or the slope too steep to support human uses soil information often remains scarce as there is little incentive (apart from research) to increase soil knowledge in these areas.

Most, but not all, industrial countries have reasonable to highly detailed soil information available, while the situation in the developing world is more varied, as illustrated by the scale of the national country soil maps. Soil profile information is also very variable from country to country; while even where it is collected it is not always available to researchers or the general public.

At a regional level the SOTER initiative has collected legacy soil maps and legacy soil profiles and organized these with a standardized methodology and soil classification system. This has allowed a certain regional harmonization of information for large parts of Africa, Europe, South America and the Caribbean. Lack of ongoing funding, however, has put the future of the SOTER programme in doubt.

At the global level, the Harmonized World Soil Database brings together the available information from different national and regional soil mapping programs such as DSMW, SOTER, the national soil map of China and the European Geographic Database and is, at present, the only digital global soil product available.

However, it is fundamental to emphasize that the time of collection of most of global and regional soil legacy data available dates back to the 1960s to 1990s. Therefore, currently, the global soil science community is limited in its ability to provide up to date data on the actual status of global and regional soil resources. There has been a considerable gap between the production of the unique world soil map and now, as no alternative up-to date soil information is available at this moment.

This review of existing and available soil maps and databases globally and regionally is as interesting for what is omitted as for what is included. It can be reasonably assumed that past soil investigations, in most countries, have almost certainly resulted in the collection of hundreds of thousands to perhaps millions of field observations and tens to hundreds of thousands of laboratory analysed soil samples per country. The vast majority of these observations and analyzed soil samples have clearly never been collated or made available for inclusion in publically available, open databases. The significant effort required to assemble data for the relatively small number of analysed soil profiles included in the few existing global databases of analysed soil profile information (e.g. ISRIC-WISE) is indicative of how difficult it can be to obtain and collate previously collected soil profile data.

This begs the question as to why historical soil profile observations and associated analytical data are so difficult to locate, obtain and collate into open, shared, international databases. Perhaps the entities that originally collected the historical field observations and conducted the laboratory analyses lacked the resources or mandates to enter these data into digital databases. Perhaps concerns about data ownership and intellectual property rights discouraged organizations from compiling data to share widely. Perhaps the local nature of most previous soil investigations precluded considering how locally collected data could be of interest, and use, in a wider, global context. Perhaps the lack of an available, and easy to access and use, global repository for accepting and curating soil profile data was the reason so much data never got shared. Whatever the reasons, the fact remains that only a very tiny fraction of previously collected field soil observations or previously analysed soil samples have ever been preserved and found their way into open and available global data bases of soil information.

Perhaps it is time to consider how this oversight might be corrected in the future. Perhaps all it might take to encourage the capture and sharing of information about soil field observations and laboratory analysed soil samples is to provide a suitable, open, and easy to use platform to enable entry and sharing of such data for any and all entities that which to contribute their data. Perhaps if the global soil science community were provided with an opportunity to contribute their data on field observations and laboratory analyses to a centralized global facility for holding, harmonizing, curating and sharing soil data globally. It is hoped that the survey of existing soil information sources contained in this document will stimulate discussion of possible mechanisms by which collation and sharing of soil observations and data can be improved in the future.

3. SOIL INFORMATION USERS NEEDS

Quite often, statements such as "...according to soil users' requirements..." or "...targeting soil users' needs..." are common in documents justifying the production of soil spatial information. However, very little information exists in the literature clearly showing what the users' needs are. Although it is generally known that users of soil information attach particular reasons explaining the importance of soil to their applications, their specific concerns are seldom included in the design of soil information systems. Assessment of users' needs should therefore be an integral part of any soil information system and soil mapping activities before their conception, planning and implementation.

There are some attempts, though, in the literature of organizations which have evaluated soil information users' needs prior to launching their soil information systems. The present document reviewed this literature in an attempt to draw lessons for future soil mapping activities. In addition, targeted interviews were also conducted with users to establish their needs and levels of satisfaction with the current supply of soil information.

3.1 Review of previous assessment of users' needs

A limited literature was found on organizations that had carried out users' needs assessment. They include a survey on users of soil maps from British Columbia (Valentine *et al*., 1981), ASRIS user needs assessment (Wood and Auricht, 2011), and Soil Atlas of Africa users' requirements (http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/survey.html).

In the case of users of soil maps from British Columbia, a survey was carried out in 1981 to establish whether or not soil maps and reports for British Columbia were providing the information required in a form that was intelligible to users who were not soil specialists. The survey was conducted on potential users of soil maps identified from such sources as professional association membership lists and the distribution list of the Resource Analysis Branch, Ministry of the Environment, Victoria, British Columbia. Results of the survey showed that:

- Users need site-specific soil information for the areas of their concern and that texture, slope and soil water content were the properties of highest importance
- Users need meta-data and information about mapping procedures and reliability, and simple but standard symbology for maps and legends

Twenty seven years later, the findings of the British Columbia users' needs survey were still echoed in a different setting. ESBN in collaboration with FAO and African Soil Science Society (ASSS) conducted a user needs assessment in 2007 to get insight into the needs and wishes of users about the content of the soil atlas of Africa that they proposed to produce. The respondents were from Africa, Europe, America, Asia and various International Organizations. Although the objectives for this survey were different from those of British Columbia, its assessment results had similar features. It showed that:

- Users want site-specific soil information (preferably given country-wise)
- The descriptions of the soil types must contain information on their attributes/properties and distribution
- Supporting information must be included and incorporate degradation/conservation issues, and information on critical soil parameters (soil depth, soil texture, water-holding capacity)

Recently, ASRIS also carried out soil information users' needs assessment in order to provide direction for the future development of Australian national soil data products that meet specific user requirements and are applicable to a broad range of soil data users (Wood and Auricht, 2011). The results showed that:

- Soil users seemed to have preference for information on key soil attributes such as soil moisture, nutrition, toxicity, biology and carbon.
- Users want an easily accessible source of nationally consistent, authoritative, trusted, and well documented soil attributes available as downloadable data sets.
- Links to comprehensive meta-data, including method descriptions, error and uncertainty and input source data (especially as it relates to any derived data layers) should be provided alongside soil data information. This is important so that users can assess the fitness for purpose of national data and further refine data sets for their specific needs.

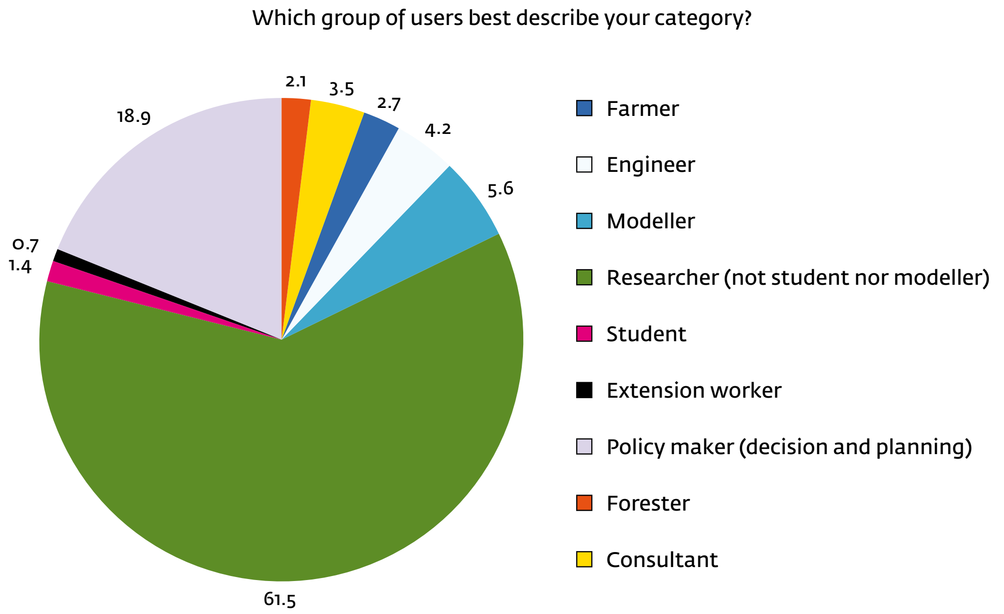
The results of these surveys seem to have a clear message of what users of soil information want irrespective of their geographic locations: need for metadata, importance of certain soil attributes, and preference for site-specific soil information.

3.2 Survey of user needs for soil information

3.2.1 Characteristics of the survey respondents

As part of the GSP framework regarding pillar 4 on enhancing soil information, an online survey was conducted to assess various aspects of users needs with regards to the existing soil information in the public domain. The survey questionnaire (see appendix 1) was sent out to soil information users throughout the world using contacts at international organizations, FAO country networks, representatives, individuals, among others. Altogether, there were 144 respondents who were categorized as farmers, researchers, planners, extension workers, etc. (Figure 3.1). Researchers were the majority of respondents (66%), followed by Policy makers (17%).

Figure 3.1 Categories of respondents during the users' needs survey



It seems the survey did not adequately represent respondents who were farmers, extension workers, and students. Farmers and extension workers are important categories of soil users who are directly involved with soil in food production and environmental conservation. Nonetheless, they are also known to rely greatly on researchers for synthesised soil information. Some of their user needs may still be reflected by the needs expressed by researchers. A large proportion of the respondents (78.3%) said they worked in public organizations, NGOs (12%), and private (5.6%) or parastatal organizations (5.6%). Only a small proportion worked in commercial enterprises (2.1%). 22% used soil information in Europe as the location for application of soil information, 14.7% in LAC, 14.2% in Sub-Saharan Africa, and 9.6% used soil information at a global scale. The majority of the soil information users said they were frequent users (75%), which implies that they gave a promising representation of how trends in soil information dissemination have been affecting them.

3.2.2 Usage of soil information

When asked about the general areas for which they use soil information, the majority of respondents said they use the information for research (17.5%) and for land degradation assessment (16.7%) (Table 3.1). Only 1.5% (named "others" in Table 3.1) used soil information for generation of extrapolation domains of improved technologies, creation of the soil data centre infrastructure, economic aspects/ valuation, climate change emission factors, biodiversity assessment, digital soil mapping, natural hazards zonation, or assessment of ecosystem services (Table 3.1).

Table 3.1 Areas of use of soil information

For which purpose do you use soil data or information?	
Answer	**Response (Percent)**
Land degradation assessment	16.7
Agronomic decisions	11.7
Climate change adaptation/ mitigation	11.3
Hydrology	3.9
Engineering	0.9
Policy development	8.6
Academic	8.3
Research	17.5
Commercial	0.9
Forestry applications	2.1
Planning	6.8
Environmental modelling	9.8
Others	1.5

Generally, most people prefer geo-referenced data (72%) compared to non-georeferenced data (28%). Furthermore, the largest group of soil information users said they often use soil profile data (33%), 23% use measured soil attribute data, 22% use soil-class maps, 21% soil properties maps, and 3% use outputs from soil models (pedo/taxo-transfer functions). The small proportion of respondents (3% ± 2%) who said they use outputs from soil models has some bearing on the relevance and validity of outputs from soil inference systems, which base their outputs on rule-based models to infer soil properties from other soil properties. This survey results portray an image of the majority of soil users not placing a high regard on outputs from inference systems.

Soil physical and soil chemical properties are still the most requested of all the soil attributes (Figure 3.2). Other soil attributes which are needed by a small fraction of other soil users include soil erosion data, soil mineralogical data, and information on management/productivity. The results of this survey tend to mirror what others found in similar previous users' needs surveys (Valentine *et al.*, 1981; Wood and Auricht, 2011); thus, strengthening the need for more emphasis on development of more information on soil physical and chemical properties.

In terms of soil-data type demand, the policy makers and researchers seem to have high variance of the data type demand (Figure 3.3). They equally want all data types. Farmers want more of chemical properties, engineers more on soil profile characteristics, and modellers want more of soil physical properties.

Figure 3.2 User's demand for soil attributes data

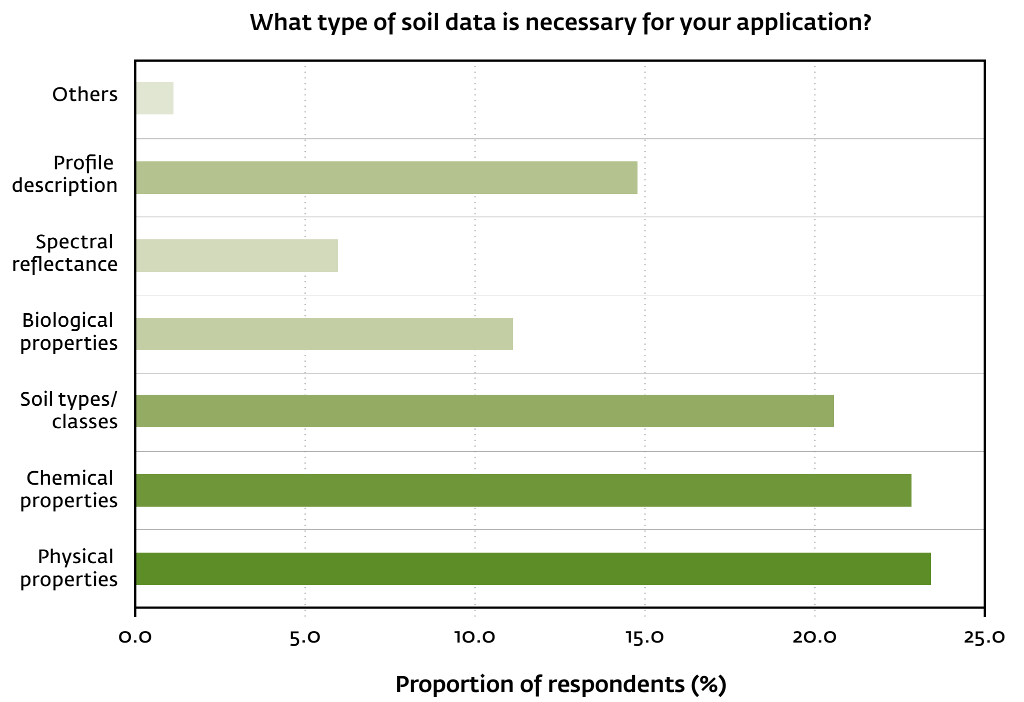
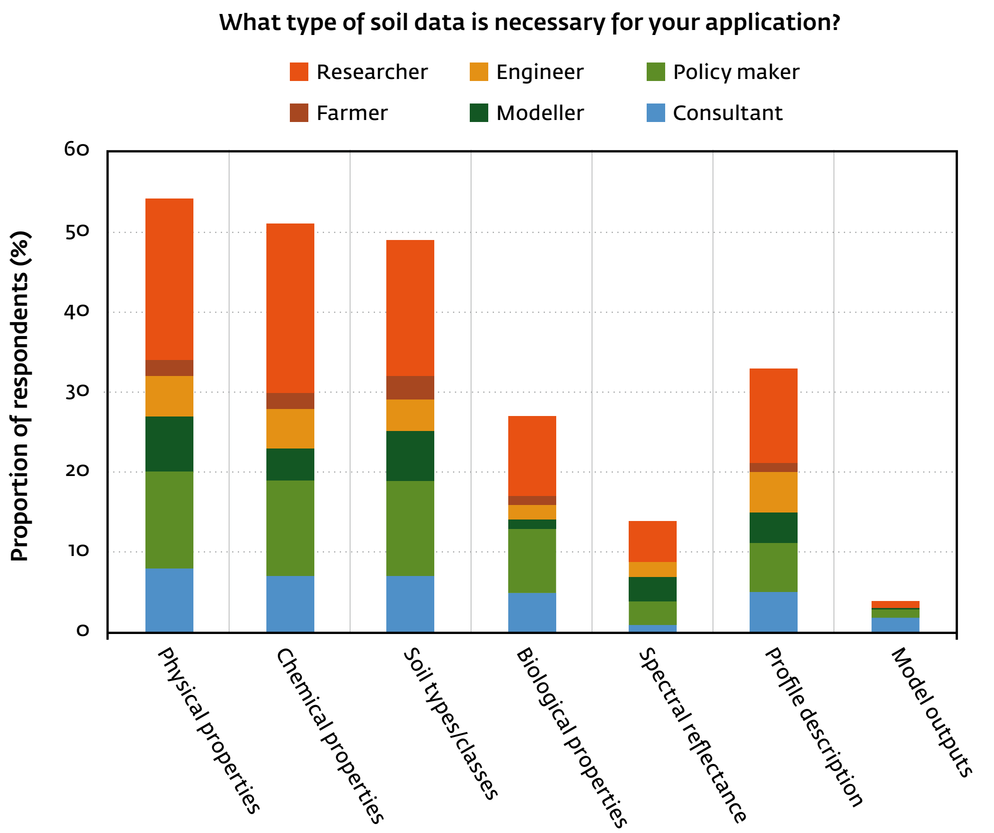


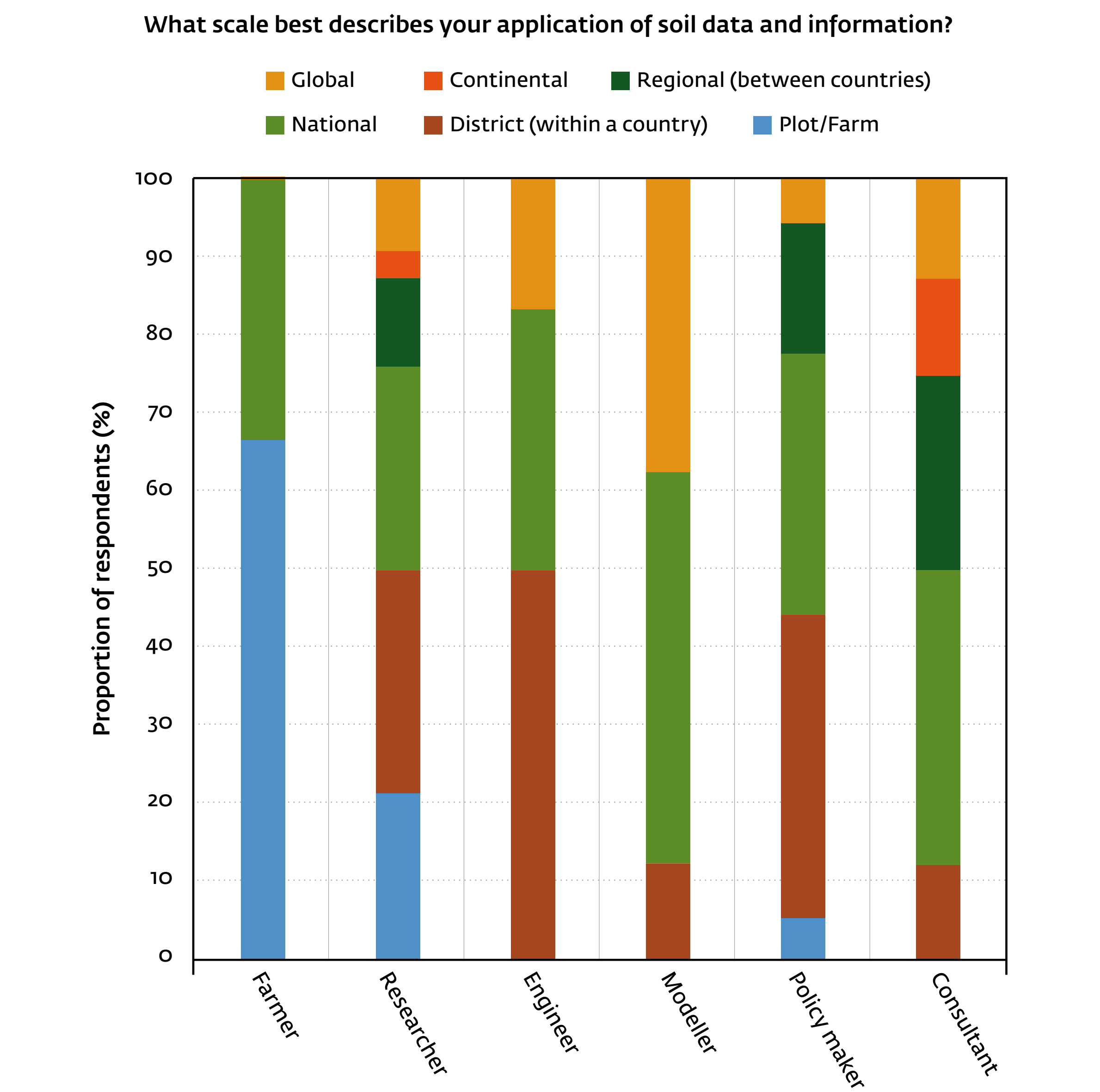
Figure 3.3 Soil data type demand by various user categories



Most of the users surveyed seemed to prefer site-specific soil information. 32% said they have been working at the national scale, 30% at district scale and 16% at the plot level. In general, more than three-quarters of the respondents are working at national and sub-national scales. Only 9% seem interested in global scales (Figure 3.4).

It is interesting to note how policy makers target mainly farmers (at district and national scales), engineers work mostly at district and national levels, and global issues were left for modellers, researchers and consultants (Figure 3.4). Consultants, policy-makers, and researchers also seem to have interest in regional issues, going by the relative proportions of their scales of operation at this level. The latitude of operation seems wide for consultants; they have a thorough mix of scales of operation. These results also show that global soil information can also influence local and regional policies to some extent.

Figure 3.4 Scale of operation by different groups of soil information users surveyed

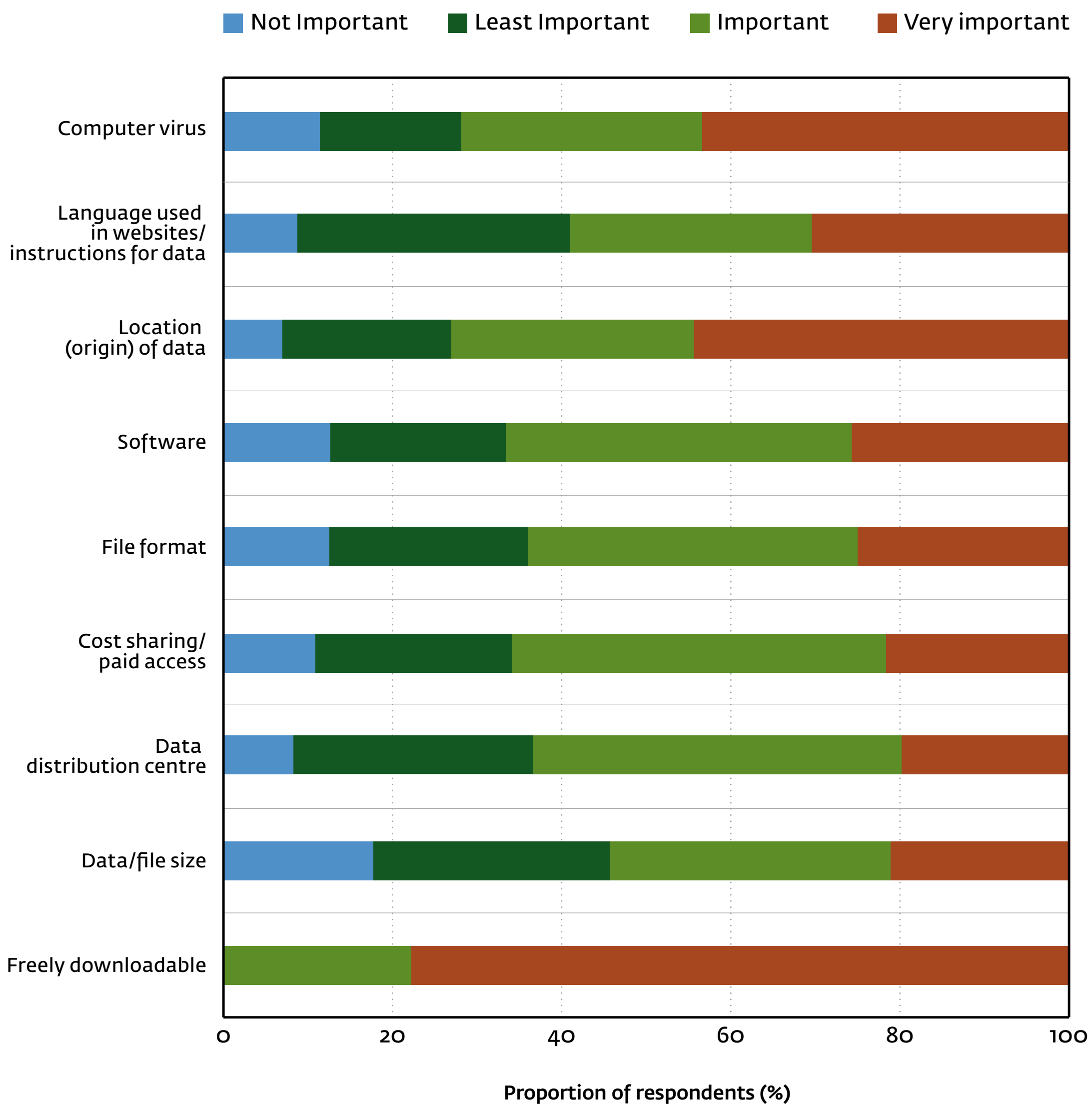


3.2.3 Soil data access

Soil information access is one of the widely quoted problems among data users. In this survey, soil users were asked to name their preferred mode of accessing data. 32% of the respondents chose online tabulated data as their preferred mode of accessing soil data, 29% preferred online GIS layers such as maps, and 19% preferred online reports. In general, data available online seems to be preferred to offline or hard copy data. Modellers are top the list of those who prefer online data followed by engineers and policy makers. Farmers and consultants seem to prefer data available in hard copies.

When accessing data, the issues that are most important for soil information users include whether data is freely downloadable, availability of georeferenced data, and potential transmission of computer virus (Figure 3.5). File sizes and language used in the websites seem not to concern soil information users very much.

Figure 3.5 Data access issues regarded by soil information users



Although almost 30% of the users suppose that soil data information should be cost shared, a large proportion (43%) of soil users seem undecided as to whether the cost should be shared or not. There are also those who are willing to trade data detail/accuracy with cost. Over half of the respondents (53%) felt that they would be comfortable with less accurate but free soil data. Engineers and consultants are the only groups of soil users who would accept to pay for more accurate data (Table 3.2). Policy makers and researchers, however, can make do with less accurate but free soil information. In fact, they are the majority of those who feel that soil data collected at public expense should be freely availed to the public.

Table 3.2 Users response to cost and accuracy issues on data access

In terms of cost and data accuracy, what would be your preference?		
	Proportion of respondents within each category (%)	
User category	**Less accurate but free**	**Accurate but costly**
Farmer	50	50
Researcher	53.4	46.6
Engineer	0	100
Modeller	42.9	57.1
Policy maker	66.7	33.3
Consultant	37.5	62.5

3.2.4 Soil data characteristics

Apart from data access issues, there are various aspects of soil data that users of soil information tend to find inadequately addressed. Issues such as methodology of data generation, reliability of the methods, etc. have been shown to be critical for data users. This survey evaluated the level of importance data users attach to these issues. The results showed that accuracy/reliability, availability of soil attributes, GPS coordinates, methodology for data generation, and scale are the most important aspects that users would like to have (Figure 3.6).

These same issues have also been observed in the previous users' needs survey in the literature (Valentine *et al*., 1981). Interestingly, copyright issues, classification scheme, number of publications, and whether soil maps are pixel-based or polygon-based do not appear as important to users of soil data. This result has implications on the clamour for pixel-based mapping that has been vigorously promoted in the past few years.

The areas that users of soil information think should be strengthened in order to improve soil information use include online data dissemination, measured soil attributes, standardization, and acknowledgements of people involved in data generation (Table 3.3). They also would wish to see charges on data acquisition eliminated or reduced.

Figure 3.6 Soil data issues important to data users

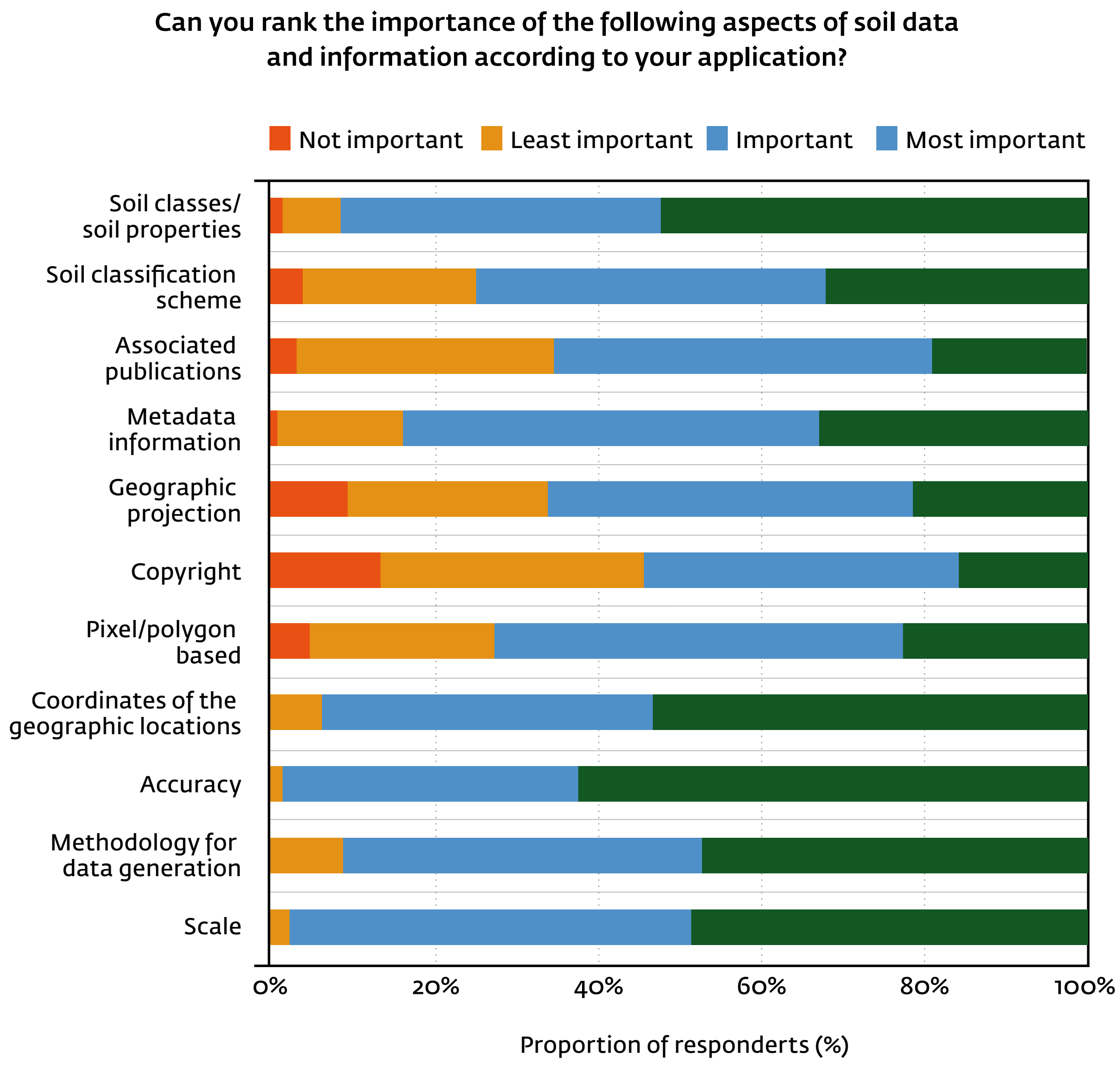


Table 3.3 Users' suggestion on soil information improvement

What kind of improvements would you prefer in future soil data provision?				
Answer	**Most important**	**Important**	**Least important**	**Not important**
Information concerning owner and authorship of data, email contacts, etc	34	78	22	0
Information about laboratory and other data handling methodologies used	51	70	11	1
Guidelines on how to handle different data units and meaning of special characters	53	59	19	1
Standardization of data formats	63	56	13	0
Metadata catalogue	48	63	20	1
Faster access to data	59	57	13	1
Measured soil data	68	52	6	1
Criteria for data evaluation	41	72	14	2
Charges on data acquisition	10	61	44	10
Online data access	93	36	2	2
More detailed soil information	61	58	11	2

3.3 Conclusions and implications of users' requirements

3.3.1 Soil mapping

The results of the online survey and the literature review show that the majority of soil information users are keen on georeferenced soil data. Since most users seem to be working at the national and sub-national levels, the soil mapping activities generating soil information should give priority to farm, district, and national scales. The details they would prefer to see included in the soil information database are:

- measured soil attributes (physical, chemical, and biological properties)
- georeferenced locations where the measurements were carried out,
- Metadata describing the methods used in data generation, accuracy/reliability, dates of measurements, etc

Although users were divided on their preference for pixel-based or polygon-based soil maps, they are unanimous that the maps should be of fine resolution and relevant to their areas of interest. Furthermore, the maps should also be enriched with the following information:

- Mapping approach and accuracy/reliability
- Soil attribute data
- Limitations, potential, and soil threats of different soil classes in terms of soil functions
- Coordinates of sampling points

The concepts on which soil inference systems are based are still not well appreciated by many users. The majority of soil information users do not seem to prefer use of model outputs as substitutes for observed or laboratory determined soil information. Although the use of an inference system is inevitable since it is difficult to measure accurate soil information at every meter throughout the whole world, the majority of soil users still have a low opinion about products based on soil inference methods. A lot of work is therefore needed to:

- Develop more rigorous and accurate models for inference systems
- Promote the use of soil inference systems
- Include reliability/uncertainties alongside the soil inference system outputs

3.3.2 Dissemination of soil information

Many soil users would like to have free access to soil information. They think that if soil information is generated at public expense, then the resulting generated information should be freely availed to the public. The preferred mode of disseminating the information is through the internet. Users would like to have the convenience of downloading relevant data rather than having to search widely for the information. This implies that the custodians of soil information systems tasked with data storage and dissemination should consider online repositories as much as is possible.

In addition, the following suggestions were extracted from user suggestions with regard to data dissemination:

- Inclusion of versatile, user-friendly, web-based data storage and retrieval systems
- Acknowledgement of data sources and methodology for data generation
- Data legends, metadata, and relevant documentation of the data should be included in the dissemination approaches used
- Reduction or removal of data access restrictions
- Computer virus-free data access

While it is evident that the number of respondents was not as large as hoped for this survey, bibliographic research and past experiences showed that this is a common trend. The main reasons behind low participation are as follows: a) accessibility to soil information users, b) limited access to internet in some countries, c) willingness to invest time in responding to another survey. However, this survey provides a very general overview of what is expected in terms of soil information. The main message from this exercise is that any soil mapping activity should target surveying their users before starting their activities, as soil mapping should be a demand-driven activity.

4. STATE OF THE ART METHODS AND TOOLS FOR SOIL MAPPING

4.1 Introduction

Soil maps provide descriptions of spatial and temporal attributes of soil and landscape. Soil mapping has traditionally involved the development of an understanding of soil forming processes which is then applied to predict the location of classes of soil types and the likely range of within-class variation of soil properties. Recently, there has been a growing realisation among many soil scientists that spatially extensive and available environmental data layers can be effectively utilized to represent various components of soil forming factors and processes with a view to improving soil mapping. Digital Soil Mapping (DSM) is a new technology soil scientists are now using to map soil properties based on plausible relationships between sparsely available observations of soil properties and extensively available environmental data layers. DSM is the computer-assisted production of soil property maps or the creation and the population of a geographically referenced soil database generated using field and laboratory observation methods coupled with environmental data through quantitative relationships (Lagacherie *et al*. 2007).

DSM is a new approach for improving delivery of soil survey information. It was developed to address problems and limitations associated with traditional soil survey. Traditional soil survey has always had problems with the collection of representative soil data, cost implications in soil mapping, how to spatially represent soil properties in a soil map, and efficient delivery of accurate soil information, among others. These problems have hampered access to, and wide application of, accurate soil information. DSM is a technological advancement that seeks to improve the processing, accuracy, and delivery of soil information at various scales worldwide. These potentials are some of the aspects that users of soil information are seeking. Although DSM offers the promise of improved delivery of soil information and increased coverage of mapped areas, it also has its share of challenges just like any other technology. This document looked at the potential and challenges of DSM with regard to providing soil information that can satisfy soil user requirements.

4.2 Evolution of soil mapping

DSM evolved from the state-factor soil forming paradigm developed by Jenny (1941) for describing the relationship between soil formation and distribution. In this paradigm, the soil profile characteristics are governed by climate, organisms, relief, parent material, and time, which are known as soil forming factors. If the relationship between soil profile characteristics and soil forming factors is known, as well as the distribution of soil forming factors, then the distribution of soil profile characteristics can be inferred (or predicted) from the distribution of soil forming factors. In early soil mapping activities, the emperical relationship between soil profile characteristics and soil forming factors was related to Jenny's equation and was implemented by surveyors/pedologists using conceptual soil-landscape relation models (Hudson, 1992). The soil surveyors/pedologist used this mental model to produce a soil map by relating field observations of classified soil profiles along with less detailed augered soil observations to local information on the spatial distribution of soil forming factors principally extracted from the interpretation of aerial photographs but supplemented with consideration of relevant maps of environmental factors.

Some soil scientists later developed quantitative models to represent initial mental models for the sake of improving the soil mapping process. Equation 4.1 gives a general format for these models in which S_p is the predicted soil property/type.

$$S_p = f(cl, o, r, p, t) \qquad \text{Equation 4.1}$$

where cl is climate component, o is organism (representing vegetation or fauna or human activity), r is topography (representing landscape characteristics), p is the parent material, and t is age or time factor. Examples of models for Equation 4.1 are: Fuzzy Inference, neural network, Bayesian, and regression trees (Cook *et al.*, 1996; Zhu *et al.*, 1997).

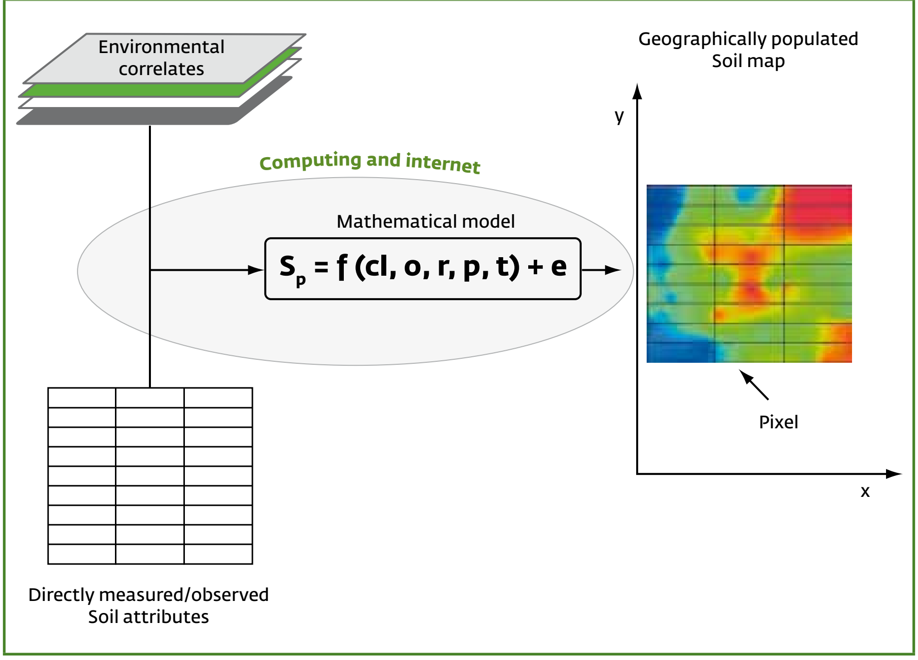
Further developments were made on the structure of Equation 4.1 by splitting it into two: deterministic and stochastic parts. The deterministic part modelled the soil-landscape relationship in a similar manner as Equation 4.1 while the stochastic part modelled the spatial variation of the soil attribute. Equation 4.2 gives the general structure of the improved model.

$$S_p = f(cl, o, r, p, t) + \varepsilon \qquad \text{Equation 4.2}$$

where ε is the stochastic component. Geostatistical methods such as kriging have been used to model the stochastic component (Burgess and Webster, 1980; Yasribi *et al.*, 2009).

Improvements in technology for data capture (e.g. remote sensing and microwave, GPS, spectroscopy, etc.) coupled with computational advances have helped to improve predictive soil mapping. Soil maps and spatial soil information systems can now be created by mathematical models that account for the spatial and temporal variations of soil properties based on soil information and environmental surrogates of soil forming factors. This is the new paradigm in soil mapping (McBratney *et al.*, 2003). It relies on quantitative relationships between easily measured and extensive environmental covariates and more difficult to measure and less extensive observations of soil attributes to predict the soil attributes in locations for which direct measurements/observations were not made. The results of such quantitative prediction eventually help to populate the target geographic area (at a given spatial interval which is known as *pixel size/resolution*) with the soil information (Figure 4.1).

Figure 4.1 Conceptual model of Digital Soil Mapping (DSM)



4.3 Traditional versus digital soil mapping

Soil mapping has traditionally involved the development of a conceptual understanding of soil forming processes which is applied to predict the spatial distribution of classes of soil. Often, descriptive and diagnostic soil profile characteristics are used to classify soil at sampled locations (Hole and Campbell, 1985; Boul *et al*., 1997). For a long time, aerial photography and, to a limited extent, satellite imagery, provided the spatial context for predicting class-type soil maps. These class-type soil maps had *artificial* boundaries and divisions that were utilised to convey spatial and temporal variance in soil types and properties. Since the early 1990's, both the spatial and attribute data have been incorporated into computerised data bases and GIS to improve the utility and accessibility of soil data and information. Most traditional soil maps are still class-type with abrupt boundaries between soil types with the variation of soil properties mostly described as occurring across boundaries. Within the polygons of soil maps, internal variation may be inferred through reference to the presence of different classes of soil but the spatial pattern of this variation is not explicitly described or mapped. Recently, advances in DSM endeavour to produce an alternative means to map soil properties (and also sometimes soil classes), by correlating soil properties to ancillary information derived from digital environmental data layers, and by using spatial statistics to interpolate the soil properties (or classes) between point-observations at known locations. So far DSM has been successful in producing soil property maps and representations of continuous variation of soil properties in the landscape while traditional soil mapping continues to be the more commonly used method for producing conventional class-type soil maps.

In traditional soil mapping, relatively few sites are visited or sampled within the study area landscape, and predictions are made based on conceptual models that relate soil properties at the sampled sites to covariates as observed on aerial photographs or geology maps. The models and rules are often held tacitly in the minds of the soil surveyor and are rarely expressed in detail other than as soil mapping legends. In DSM, conceptual models of conventional soil survey are statistically translated into quantitative rules. At the core of DSM is soil (data from traditional soil mapping) and digital environmental data layers. These are used to construct the quantitative models for mapping. DSM is therefore not so much a replacement for traditional soil mapping, but rather a compliment that extends and qualtifies conventional soil mapping approaches. As with traditional soil survey and mapping, DSM relies on inputs of detailed field and laboratory based soil data, an understanding of soil formation and impact processes, and the availability of spatially explicit and relevant environmental covariate data.

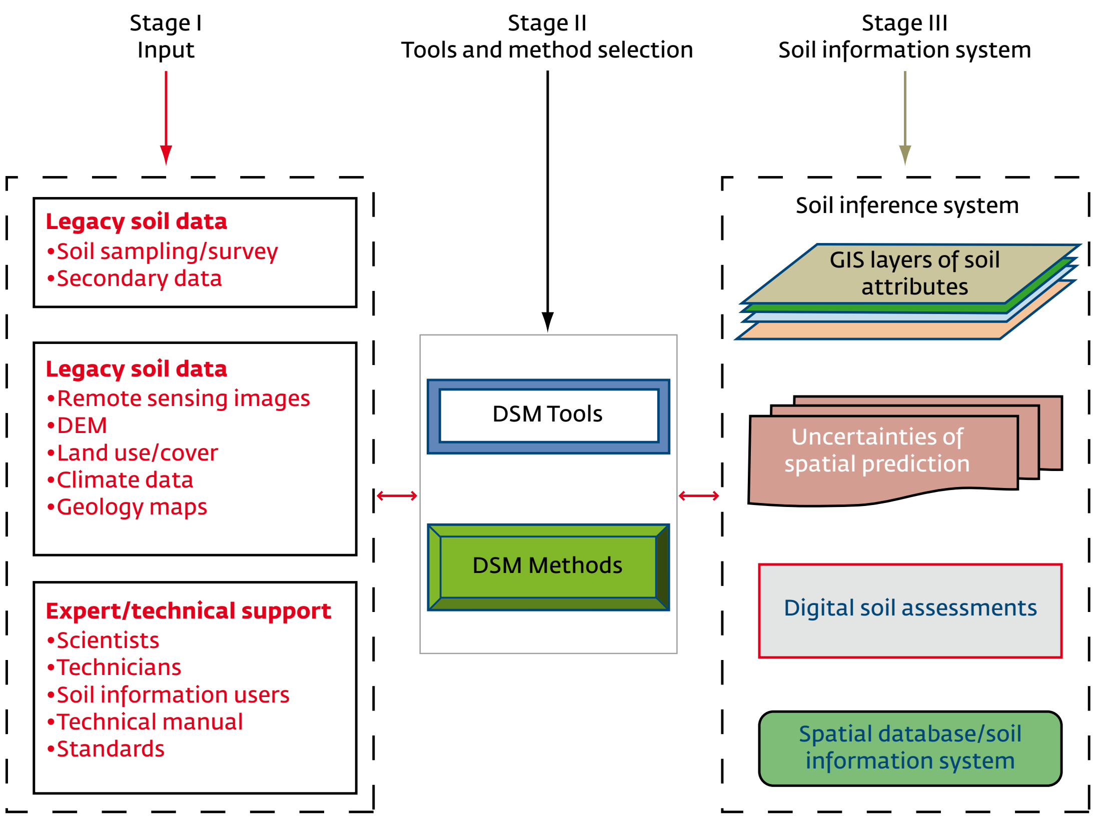
4.4 Characteristics of digital soil mapping

Although DSM aims at producing digital soil maps, it is also a process for producing geographically referenced databases at a given spatial resolution. The digital soil maps form a spatial database of soil attributes (properties), which together with the existing databases of samples of the landscape at known locations contribute to soil information. In addition to building soil database, digital soil maps should also describe the uncertainties associated with spatial predictions.

DSM process characteristically involves three stages: stage I is concerned with development and assessment of inputs; stage II is where the choice of methods and tools is made; and stage III is where the spatial inference system is developed and applied (Figure 4.2). In general, DSM can be said to have the following features:

- Use of soil survey outputs (field and profile observations and soil maps) as a key input
- It is oriented towards modelling and computer applications
- Its outputs go beyond the production of soil maps (mostly raster/pixel-based)

Figure 4.2 Digital Soil Mapping (DSM) process



4.5 Input for DSM

4.5.1 Soil legacy data: meaning, characteristics, and types

The term 'legacy data' has been mentioned in hundreds of journal articles and technical documents on soil mapping. In general, legacy data are those that have been stored in an old format or inherited from languages, platforms and techniques earlier than the current technology. They have the following characteristics:

- They were collected using the traditional/conventional technology
- Data documentation is not elaborate in most cases
- Older data may have missing author information or institutional knowledge
- They may require elaborate steps to access, process, and apply with the current technology
- They are very important/mandatory as they form the basis for the current advancements

In soil, legacy data take the form of:

- Class-type or categorical maps (e.g. maps for soil, geology, land use etc)
- Soil survey results and profile descriptions
- Soil sample observations
- Conventional laboratory results for soil attributes
- Contour/interpolated maps (e.g. climate maps)
- Expert knowledge

Legacy data are the foundation (and sometimes building blocks) for DSM. They can be used as calibration/validation samples, as skeletons for developing DSM (where new samples fill the gaps), and for reducing the cost and difficulties in obtaining new samples for DSM. Legacy data are available in many national soil institutes, regional soil information systems, and global initiatives such as ISRIC and HWSD. The previous chapters of this document have described some of these sources of legacy data.

4.5.2 Need for improvement of legacy data

Although legacy data have a key role in DSM, they are inherently problematic to use with the current technology. The following are the main areas where the legacy data pose difficulties for use in DSM:

- Data gaps with large regions lacking any available legacy data
- Inconsistent format/ measurement units or symbols between and sometimes within datasets
- Access and copyright issues
- Bulkiness/storage formats
- Challenges in dealing with the time gap and associated biophysical-geochemical changes that have occurred in representative areas since the collection of the legacy data. These changes are often ignored/over-looked when integrating legacy data with the current DSM data. The need to weight or transform the legacy data in order to conform with the current DSM data is a potential source of inaccuracy.
- Coordination and structures for data sharing are still needed to improve access to the legacy data.

More resources are needed to enrich the legacy data through:

- Additional soil survey/soil sampling
- Data recovery efforts for existing legacy data
- Conversion (digitization) of legacy data into user-friendly formats for the current technology.
- Improved storage and access to legacy data

The following steps are suggested when converting the legacy data into digital formats:

- Harvesting/collection of legacy data
- Extract possible information from the legacy data such as legends, symbols, units, etc
- Identify existing georeferenced points that can be pinned (e.g. hard targets, latitudes and longitude lines on maps, etc)
- Convert extracted information into a digital database
- Scan the hard copy maps and manually trace the maps.
- Use software to clean and to re-assign colour codes on the scanned copies
- Georeference the cleaned outputs to a agreeable/standard projection

Then, the final output can be easily integrated with the new datasets or new techniques in DSM.

4.5.3 Environmental correlates

Environmental correlates represent the Jenny's soil forming factors given in Equation 4.1. They include climate, organisms, topographic relief, parent material, and space. Since they influence different aspects of the soil formation process, they often have some quantifiable relationship with the soil types/properties. Table 4.1 gives a summary of the importance of the environmental correlates and their potential sources.

Table 4.1 Summary of types of environmental correlates for DSM

Factor/correlate	Significance in soil forming process	Examples	Data source
Climate	Affects nature and rate of biophysical and geochemical process/activities	Rainfall	Climate map
		Temperature	TWI
		Wetness	
Organism	Nutrient cycling	Land use	Land use map
	Soil particle breakdown	Land cover	Land cover map
	Soil morphology pattern creation		NDVI
Relief	Position in the landscape	Terrain	Landform
	Weathering and particle movement	attributes	Slope
	Soil morphology pattern creation		Surface curvature
	Soil depth		
Parent material	Soil mineralogy and soil type	Geology	Geology map
	Weathering	Lithology	
	Soil depth		
Time	Weathering	Age	Geology map
	Age of the land surface		

For environmental correlates to satisfy the needs of DSM, they need to have the following characteristics:

- They should be georeferenced so that their spatial coordinates contribute to the DSM model in Equation 4.1
- They should be rasterized (or resolved) into pixels
- They should have uniform geographic projection and pixel resolution in order to be compatible with each other and with the soil legacy data
- They should be easily accessed/readily available
- They should be independent of each other (to avoid collinearity in DSM modelling)

The most common sources of environmental correlates are: Digital Elevation Models (DEM), remote sensing images, land use and land cover maps, climate maps, and geology maps.

4.5.4 Data sources for DSM

Climate

Climate is the meteorological conditions, including temperature, precipitation, and wind, that characteristically prevail in a particular region. Climate data may exist as point data or as raster files. There are some websites which host such datasets at the global scale (see for example http://www.worldclim.org/, http://data.giss.nasa.gov/gistemp/, http://precip.gsfc.nasa.gov/ or the FAOCLIM at http://www.fao.org/nr/climpag/pub/EN1102_en.asp). Individual countries, through the meteorological departments, also have their own climate data.

Land surface elevation

Land surface elevation and the shape and features of the surface form topography. Landscape topography can be obtained from direct survey using levelling instruments or from remote sensing data (such as aerial photographs, LIDAR, radar, etc). Digital Elevation Model (DEM) is one of the forms for representing land surface elevation. It is a general term for digital dataset of topography (Li *et al*., 2005). DEM can be a raster- (a grid of pixels representing elevation) or vector-based dataset (e.g. Triangular Irregular Network, TIN). Freely downloadable DEM data for the whole world are available As GTOPO30 (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info) which has 1 km pixel resolution, SRTM (http://dds.cr.usgs.gov/srtm/) which 90 m pixel resolution, or ASTER GDEM (http://asterweb.jpl.nasa.gov/gdem.asp) which has 30-m pixel resolution. High resolution DEM datasets may also freely available for some countries or sold per scene.

DEM generated from remote sensing data often has problems which must be overcome before they are suitable for soil mapping. Many algorithms and software are available for correcting the DEMs (Lee *et al*., 2003; Xeujun *et al*., 2008). Once corrected, DEMs can be used to derive terrain parameters needed for soil mapping (Table 4.1). To this end, there are also many algorithms and software that have been developed for deriving different terrain parameters (see for example, http://www.saga-gis.org; McMillan *et al*., 2003; Smith and Clark, 2005).

Remote sensing images

Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object. Different remote sensing techniques use different wavelengths of energy (as seen in the electromagnetic spectrum), such as visible, infrared, gamma rays, microwave, etc. Whichever the remote sensing technique, the general principle involves acquisition of the characteristic of an object (known as image of the object) through radiations which have been reflected or emitted by the object. The energy path for the radiations starts from the energy source to the object (which then reflects/emits the radiation) to the detector (or sensor) (Figure 4.3). Examples of sensors include digital camera, satellite sensor, etc. Satellite sensors are onboard aircrafts/satellites which fly above the earth's surface, so that the earth's surface is the object that reflects the energy radiations.

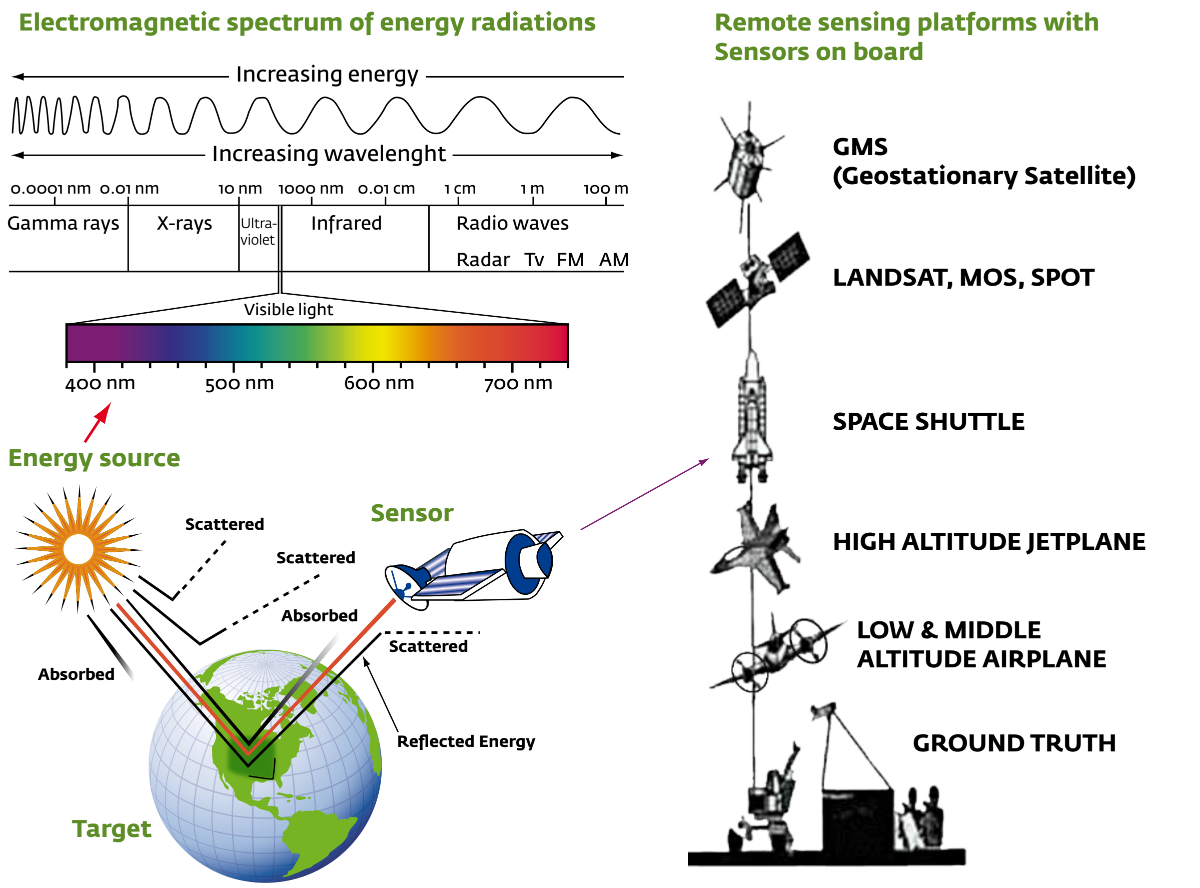
Remote sensing can be generally categorized into four broad groups for soil mapping: optical remote sensing (which relies on solar energy or artificial light (e.g. torch in diffuse reflectance, etc) as source of radiation), remote sensing due radiation from own body temperature (e.g. thermal radiation from the earth's surface), remote sensing using long waves (e.g. microwave, radio, NMR, etc), remote sensing using very short waves (e.g. gamma and x-rays) (Rees, 2001).

Whichever the system used, the emitted or reflected energy in remote sensing is analyzed to produce information about the characteristics of the object. These characteristics include:

- Types and extent of land cover
- Geomorphological features of the landscape
- Types of land use
- Climatic conditions of the atmosphere (and to some extent, the earth's surface)
- Soil and rock properties

Different remote sensing sensors have different abilities to detect various wavelengths of energy. Some sensors can only detect bands of wavelengths while other can distinguish small differences in wavelengths of reflected/emitted radiations. In the scientific field of remote sensing, this ability is known as spectral resolution. The higher the spectral resolution the more the sensor can detect many wavelengths of reflected radiations. Similarly, satellite sensors have different abilities to distinguish adjacent objects reflecting energy radiations. This ability is known as spatial resolution. Sensors with fine spatial resolution can distinguish objects which are separated by only a few metres (or centimetres) while those with coarse spatial resolution can only distinguish objects which are tens/hundreds of metres (or kilometres) apart. Lastly, satellite sensors which go round the earth have the opportunity to take images of a particular spot on the earth's surface many times depending on

Figure 4.3 Theory of remote sensing of the earth



how long they take to revisit the same spot during their revolution. This aspect of satellites is known as temporal resolution. All together, satellites' spectral, spatial and temporal resolutions enable detection of features and changes of the earth's surface with time and space. These features and changes are used by soil scientists to identify possible landscape patterns and associations, which can be related to different soil types/soil properties. Different remote sensing images (due to differences in sensors and satellite missions) such as Landsat, SRTM, MODIS, AVHRR, ASTER, etc have different resolutions which are exploitable in DSM to capture varied aspects of the landscape.

Table 4.2 gives examples of common remote sensing sensors which can be used in DSM. They can be grouped into three classes: satellite-based, airborne, and proximal sensors. Information about availability, cost, and acquisition dates of the remote sensing images can be readily obtained from the internet. Since remote sensing images can infer information about landscape characteristics, they have been used as proxy variables to assess relationships between the landscape characteristics they represent and soil legacy data. Furthermore, their spatially explicit nature (i.e. georeferenced pixels which cover the entire landscape of interest) is often used to support spatial mapping of soil in the landscape. Examples of the landscape characteristics commonly represented by remote sensing images in DSM are: Terrain attributes – from DEM; Land use/cover – using multispectral images such as Landsat, SPOT, Quickbird, etc.; Parent material – from gamma-ray spectrometry. There is plethora of literature on how these landscape characteristics can be obtained from the remote sensing data (see for example Cook *et al.*, 1996; McMillan *et al.*, 2005; Melesse *et al.*, 2007; Xie *et al.*, 2008).

Table 4.2 Examples of common remote sensing sensors and their resolutions

Sensor	website	Spatial resolution (Meters)	Spectral resolution (number of bands)	Temporal resolution (number of days)
Satellite-based				
AVHRR	http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html	1000	4	1
MODIS	http://modis.gsfc.nasa.gov/	250 (500,1000)*	36	1
Landsat	http://landsat7.usgs.gov/	30 (60)	7	16
ASTER	http://asterweb.jpl.nasa.gov/	15 (30, 90)	15	16
ALI	http://eo1.usgs.gov/sensors/ali	30	10	16
SPOT	http://www.spot.com	2 (5-20)	15	3-5
IRS	http://www.nrsa.gov.in/#	23.5	15	16
Hyperion	http://eo1.usgs.gov/hyperion.php	30	196	16
IKONOS	http://www.satimagingcorp.com/about.html	1 - 4	4	5
Quickbird	http://www.satimagingcorp.com/about.html	0.61 - 2.44	4	5
Worldview	http://www.satimagingcorp.com/about.html	0.55	1	2 - 6
GeoEye	http://www.satimagingcorp.com/about.html			
Airborne				
AVIRIS	http://aviris.jpl.nasa.gov/	20	224	
HypMap	http://www.optoknowledge.com	5	128	
Proximal				
EMI	Electromagnetic Induction			
FieldSpec FR	FieldSpec FR Spectroradiometer			
NMR	Nuclear Magnetic Resonance			
Gamma	Gamma-ray spectrometer			
XRD	X-Ray defractometery			

**Different resolutions in the brackets are for different types of that particular sensor*

Parent material

Parent material denotes the underlying geologic material, superficial or drift deposits from which soil is formed. DSM data on soil parent material can be obtained from existing geological maps or through the use of remote sensing data such as gamma rays. Freely downloadable geological map of the world at a scale of 1:35M is available at http://mrdata.usgs.gov/geology/world/. High resolution geological maps of other countries can also be found at http://geology.about.com/od/maps/Geologic_Maps.htm or from websites of individual countries. Parent material can also be obtained through the use of gamma-rays spectrometry, which is a technique for measuring the abundance of radio-nuclides in soils and parent materials (Cook *et al*., 1996; Wilford and Minty, 2007; Herrmann *et al*., 2010).

4.5.5 Technical support

Technical support for DSM is perhaps the most under-developed compared to the other aspects of input process in DSM technology (Figure 4.1). In order to encourage wide and accurate application of DSM technology, there is a need to improve the participation of all stakeholders by stimulating improved technical knowledge (such as training in modelling, pedology, database management, etc), standardization (of methods, tools, and input variables), validation, and sanctity of the user needs. In terms of technical knowledge, there is a big gap between those who have little knowledge and those who do not have any at all. There are very few scientists with adequate and complete knowledge of spatial modelling, pedology, and computer/software applications; all of which are equally needed in DSM. Academic training, hands-on practical training, publication of cook-books, and case-studies are still needed in order to increase the number of technical personnel necessary to propel DSM to the required levels. Presently, there are many publications touching on various aspects of the technical knowledge (such as geostatistics, pedology, etc). However, they need to be assembled into one (or two) volume(s) with specific examples for DSM in order to widen the latitude of DSM applications. Furthermore, standards of practice (for tools and methods) need development to enforce uniformity and professionalism in DSM technology. Coordination, support, and development of infrastructure for data generation, archiving, and exchange (sharing) are also needed. This is particularly important for global soil mapping initiatives.

4.6 Methods for DSM

4.6.1 Spatial prediction methods for DSM

Spatial prediction methods provide the means for estimating the values of a variable (or class) at un-sampled sites using data from point observations. There are two main categories of spatial prediction: interpolation and extrapolation. Interpolation estimates values of a variable at un-sampled sites using data from point observations within the same region while extrapolation predicts the values of a variable at points outside the region covered by existing observations (Burrough and McDonnell, 1998).

There are many spatial prediction methods in the literature. They can be categorized into three broad groups: non-geostatistical, geostatistical, and mixed methods. Geostatistical methods can be further divided into those that use many explanatory variables (known as multivariate) and univariate methods. Table 4.3 gives a summary of these interpolation methods.

Table 4.3 Some of the spatial prediction methods for DSM

Non-Geostatistical	Geostatistical	
	Univariate	Multivariate
Nearest neighbours	Simple kriging	Universal kriging
Inverse distance weighting (IDW)	Ordinary kriging	Kriging with an external drift
Regression models	Block kriging	Cokriging
Natural neighbours	Factorial kriging	Principal component kriging
Triangular Irregular Network (TIN)	Indicator kriging	Multivariate factorial kriging
Trend surface analysis	Disjunctive kriging	Indicator kriging
Splines		
Classification and regression trees		
Kalmer filters		
Bayesian Maximum Entropy		
Mixed methods		
Regression kriging		
Linear mixed model		
Trend surface analysis combined with kriging		
Regression trees combined with kriging		
Classification combined other interpolation methods		
Bayesian Maximum Entropy		

There are three common characteristics often observed with spatial data: (i) slowly varying, large-scale (global) variations in the measured values, (ii) irregular, small-scale variations, and (iii) similarity of measurements at locations close together. While characteristics (i) and (iii) are handled by smoothing methods such as in non-geostatistical methods in Table 4.3, characteristic (ii), the small-scale residual variation in the concentration field, is accounted for by geostatistical methods (Nielsen and Wendroth, 2003).

4.6.2 Remote sensing and GIS

Remote sensing and GIS remain the most exploited tools in DSM for deriving covariates for mapping soil, spatial statistics, and spatial data transfer. Remote sensing can capture soil cover, top soil properties, atmospheric conditions, land surface elevation (DEM), and trend changes. Georeferenced remote sensing images carry these attributes in a spatially explicit manner, which helps DSM to cover large areas efficiently. Furthermore, the increasing development in remote sensing technology and computing is widening the window for seeing various aspects of soil and soil cover, which hitherto was concealed from pedologists (Liang, 2004). However several pre-processing of remote sensing images need to be performed in order to produce more sophisticated covariates that would represent more accurately the soil variations.

Terrain attributes

Terrain is the vertical and horizontal dimension of the land surface. In DSM, terrain is represented in a digital model known as Digital Terrain Model (DTM) or Digital Elevation Model (DEM). The important landscape attributes for DSM are known as terrain attributes. They are normally calculated from DEMs. Terrain attributes can be separated into primary and secondary attributes. Primary terrain attributes are those that are directly calculated from elevation data and include first and second derivatives such as slope, aspect, plan and profile curvature. Secondary attributes are obtained from the primary attributes and included flow accumulation, compound topographic index, flow direction, etc (Zevenbergen and Thorn, 987). Table 4.4 gives a summary of these attributes.

Table 4.4 Some of the spatial prediction methods for DSM

Non-Geostatistical	Geostatistical
Primary terrain attributes	
Slope	Inclination of the earth’s surface
Aspect	direction of slope
Plan curvature	Unclassified demonstration of the earth' surface curvature (bulge) across the direction of aspect
Profile curvature	Classified demonstration of the earth' surface curvature (bulge) in direction of aspect
Secondary terrain attributes	
Upslope area (A)	the area that can potentially produce runoff to the location
Topographic wetness index	Potential supply of soil water
Stream power index	Erosive power of flowing water
Length of slope	Sediment transport capacity

Other remote sensing indices
Image indices are used in DSM to enhance remote sensing images with respect to soil forming factors. They include NDVI, Grain Size Index, Colouration Index, and Hue Index (Xiao *et al*., 2006; Luo *et al*., 2008).

4.7 Tools for DSM

4.7.1 Tools for computing

Processing of DSM input data (e.g. legacy data, remote sensing images, etc.) requires requisite software and good computing abilities in terms of computer capacity and processing speed. As the scale of DSM increases from local to global level (and with increase of spatial resolution), the demand for computing abilities also increase. This implies that high-end computers may be needed for fine resolution (e.g. tens of metres) global mapping.

In addition to computing abilities, DSM also needs software for various applications such as interpolation, processing and analysis of terrain attributes, digitizing legacy data, and statistical analysis of input data (e.g. spectral reflectance).

Software for interpolation and statistical analyses
There are many geostatistical and GIS software for interpolation. Some of them are commercial while others are freely downloadable. The majority of GIS software can handle geostatistical and non-geostatistical interpolation methods. GRASS (http://grass.fbk.eu/), ILWIS (http://52north.org/

downloads/ilwis) and SAGA (http://www.saga-gis.org) are examples of freely downloadable GIS software, which can handle both geostatistical and non-geostatistical interpolation methods. In addition, they are compatible with other software since data can be imported and exported in various file formats.

Numerous freely-downloadable software for geostatistical analysis are also available from the internet. R (http://cran.r-project.org/), Gstat (http://www.gstat.org/) and GSLIB (http://www.gslib.com/), VESPER (http://sydney.edu.au/agriculture/pal/software/vesper.shtml), S-Plus, ISATIS, are some of the versatile software which can handle classical statistical and geostatistical analyses. It utilizes a number of packages to implement geostatistical and classical statistical analysis. These packages are also freely downloadable from R website.

Software for deriving terrain attributes and remote sensing image analysis
The majority of the software for non-geostatistical interpolation can also be used for deriving terrain attributes and remote sensing analysis. SAGA and ILWIS are some of the example which can be freely downloaded. Other freely downloadable software are: LandSerf, TAS, GRASS, TOPAZ, MICRODEM, etc. There are also commercial software available for these applications.

Software for soil database and mapping
A number of software exist (and are still being produced) for various aspects of soil mapping such as profile description, database management, soil classification, and production of soil maps. SDBm is one such software for storing primary soil information and summarizing soil profile data. It was developed by FAO.

SoLIM (Soil Land Inference Model) is software for soil mapping based on recent developments in geographic information science (GISc), artificial intelligence (AI), and information representation theory. It is available at http://solim.geography.wisc.edu/about/index.htm.

4.7.2 Tools for storage and dissemination

Digital database
DSM technique is rapidly evolving throughout the world and maps, databases, and literature about DSM are increasingly being produced. It is important that a digital database of these pieces of information be constructed. The digital database, which is a seamless compilation of all DSM data and outputs, should have a way of storing the data, enabling query facilities on the data, and allowing for visualization of data and products. There are a number of existing organizations with such systems, which can provide technical support for the construction of DSM digital database (see for example http://www.add.scar.org/).

Visualization and dissemination tools
The increasing development of spatial data infrastructures over the world can be utilized to improve dissemination of soil information. Online software (e.g. Google Earth, Aquila, etc.) can be exploited and linked to the digital database to enable worldwide visualization of the DSM database and products. These software can also be used to import the associated legends, generate 3D surfaces, contours from isometric maps, wind barbs and 3D vector objects in a user-friendly way. ISRIC and ESBN are already implementing similar versions of digital databases with opportunities for online access, web-map generation, data/map visualization etc. (http://library.wur.nl/isric/ for ISRIC and http://eusoils.jrc.ec.europa.eu/library/jrc_soil/index.html for ESBN).

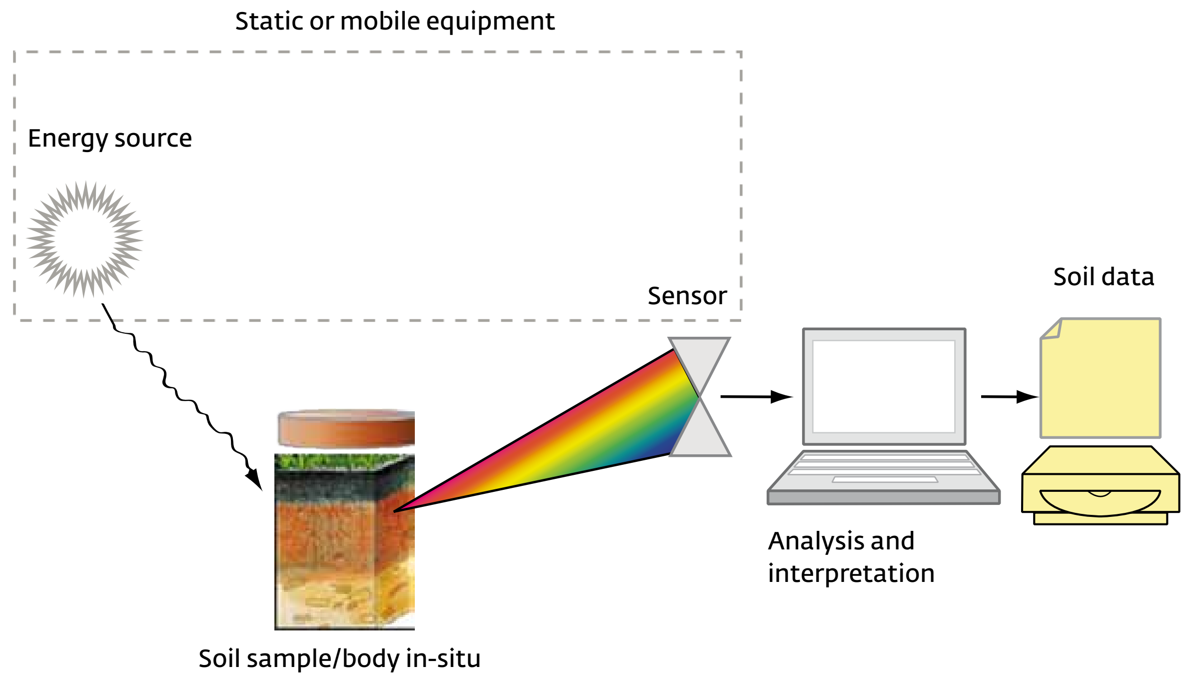
Other innovative applications with intended to reach soil information users have also been developed through the use of mobile phones (Beaudette and O'Geen, 2010), ready-made maps for use in mobile phones, GPS receivers, etc. which have been developed by ESRI (http://www.arcgis.com/home/group.html?owner=mdangermond&title=esri%20soil%20mobile%20and%20web%20maps).

4.7.3 Proximal soil sensing

Collection of soil data is one of the age-old limiting factors in soil mapping because it involves time-consuming, costly, cumbersome, and (sometimes) less accurate methods. The traditional methods that have been applied in soil data collection include: field methods (such as Munsell colour chart, soil texture by feel, visual inspection, samplers, direct measurement with field equipment such as infiltrometer, tensiometer, moisture probes, etc.); laboratory methods for tests on soil samples collected from the field (such as physical, chemical, and biological equipments and reagents); and archived soil data (maps, reports, and published articles). Soil scientists are now turning a new page in soil data collection. Technologies which were initially used in other disciplines are finding their way into soil science to improve data collection and analysis. Techniques such as infrared spectroscopy, x-ray diffraction, Global Position Recorder, mobile laboratories, Nuclear Magnetic Resonance, etc. are increasingly being used in-situ or in the field to collect soil data (Viscarra-Rossel *et al*., 2010). Proximal soil sensing, a new word for static or mobile soil data collection, is gaining acceptance as the way to improve soil data collection.

The principle of soil proximal sensing is much the same as remote sensing save for the proximity of the sensor to the object, relative position of sensor with respect to the object (invasive or intrusive), and whether the sensor is static (on a soil sample) or carried/dragged along in soil body (McBratney *et al*., 2010). Figure 4.4 gives a simple illustration of how proximal soil sensing is used to collect soil data.

Figure 4.4 Concept of soil data collection using proximal soil sensing



Equipment and sensors for proximal soil sensing are being tested in many places around the world. Some of them are given in Table 4.5.

Table 4.5 Some of the proximal soil sensing applications

Organization	Website	Equipment used
ICRAF (World Agroforestry Centry)	http://worldagroforestry.org/research/land-health/spectral-diagnostics-laboratory	Inclination of the earth's surface
CSIRO	http://www.clw.csiro.au/services/mir/	direction of slope
Cranfield University	http://www.cranfield.ac.uk/sas/nsri/research/projects/rapidsoilanalysis.html	Unclassified demonstration of the earth' surface curvature (bulge) across the direction of aspect

4.8 Soil information systems

DSM products cover the landscape at varying resolutions depending of the scale of maps produced. Therefore, it makes it possible to get soil information on every location in the landscape. Furthermore, given that soil properties often exhibit relationships between themselves, other soil properties/characteristics not included in the DSM database can be inferred from properties in the database. All together, the mapped and inferred soil properties and soil database contribute to the DSM information system. The information system can be used to deduce/monitor varied aspects of soil such as soil functions (e.g. quality/health) and soil threats (e.g. degradation, pollution, etc.) as well as feed into policy-decisions for environmental sustainability.

4.8.1 Soil inference systems

The demand for soil information over varying spatial and temporal extents differs with intended applications. Soil aspects needed for modelling are different from those needed for planning as well as for reporting. Although DSM is versatile for producing soil maps and soil formation at varying spatial scales, not all soil properties should/can be produced. The soil properties which have not been mapped by DSM can as well be inferred using knowledge based rules that can relate information from existing DSM database to other soil properties that have not been included in the DSM database (Minasny and Hartemink, 2011). A system that allows for these processes as well as for managing the evolution of digital soil mapping products including spatially continuous or classified soil properties in a logical and ordered manner is known as a soil inference system. The term "soil inference system" was first proposed by McBratney *et al*. (2002) as a knowledge base to infer soil properties and populate the digital soil databases. However, it is gaining much wider meaning among soil scientists than its prior meaning (Robinson *et al*., 2010). It is now used to encompass GIS layers of DSM products and the development of knowledge rules (or functions) for inferring soil properties at all locations in the landscape.

4.8.2 Digital soil assessment

Soil has varied uses for which its ability (functions) needs to be periodically assessed at all locations in the landscape. Soil functions are general capabilities of soils that are important for various agricultural, environmental, nature protection, landscape architecture and urban applications. Digital soil maps can depict soil properties and functions in the context of specific soil functions such as agricultural food production, environmental protection, civil engineering, etc. These maps can be used to calculate critical nutrient levels, heavy-metal levels or for interpretation of multiple properties such as a map of erosion risk index (see for example Omuto and Vargas, 2009). This aspect of DSM is the most important for policy-decisions and land management (Carre *et al*., 2007).

4.9 Challenges with DSM

DSM has the potential to generate and deliver much new and needed soil information. However, it suffers from a number of challenges which can hinder its total success. The technology has to overcome the scepticism associated with any new technology. Some proponents of the technology have suggested that it can totally replace traditional soil survey and that it can facilitate generation of soil maps/data without the need for field (or even laboratory) testing. These suggestions have greeted DSM with outright rejection from among many soil scientists. Furthermore, the potential tools used in DSM such as remote sensing have also added to the scepticism about DSM. Traditional soil scientists used remote sensing/aerial photographs to aid spatial understanding of soil distribution. They object the exclusive application of remote sensing to map soil properties, which they suppose is what DSM is promoting. This misunderstanding contributes to their apprehension about DSM. There is also a section of users of soil information who are deeply familiar with the traditional soil products (polygon maps, profile descriptions, and laboratory chemical and physical results). They are yet to be convinced of the relevance and applicability of DSM maps and data that appear different from the more familiar traditional products.

Other than perception, DSM also faces challenges in use of its technologies. Many tools used in DSM were developed in other disciplines (such as mathematics, chemistry, geography, computing, remote sensing, etc) and soil scientists have yet to understand their potential and limitations. Some DSM applications with these technologies are bound to be abused and inaccurate soil mapping results disseminated. Training on the fundamentals of these tools is needed among soil scientists.

Lack of coordination in DSM activities is also another challenge. Although there are many initiatives using DSM approaches to produce soil information, there are no standards for use. Traditional soil mapping had standards (manuals, nomenclature, etc) for use. Whether they were adhered to or not is something else, but at least there were standards. DSM is facing the challenge of producing standards and rules of thumb, producing quality control, and disseminating soil information to various users.

5. GLOBAL SOIL MAPPING INITIATIVES

The trans-boundary nature of the threats facing humanity today is increasingly forcing governments to come together to devise common and sustainable solutions. Hence, it is now possible to see various departments/divisions of neighbouring countries working together more than before to advice regional policy decisions on financial matters, security, trade, environment, food security, etc. On land and water matters, there are a number of regional and global groupings which have been formed to collect and organize existing relevant information, harmonize the data and methods, collect new information, produce new products, disseminate data/products, etc. The present document looks at soil mapping activities of these groups. Global soil mapping initiatives aim at developing soil maps, harmonizing and coordinating global soil information systems, and archiving and disseminating world soil databases.

5.1 Globalsoilmap.net

Globalsoilmap.net (www.globalsoilmap.net) is a global consortium that has been formed to make a new digital soil map of the world using state-of-the-art and emerging technologies. This effort originated in 2006 (Sanchez *et al*, 2009) in response to policy-makers' frustrations at being unable to get quantitative answers to questions such as: How much carbon is sequestered or emitted by soils in a particular region? What is its impact on biomass production and human health? How do such estimates change over time?

The GSM consortium's overall approach consists of three main components: digital soil mapping, soil management recommendations, and serving the end users—all of them backed by a robust cyber-infrastructure. A digital soil map is essentially a spatial database of soil properties, based on a statistical sample of landscapes.

This new global soil map will predict soil properties at fine spatial resolution (~100 m). These maps will be supplemented by interpretation and functionality options to support improved decisions for a range of global issues such as food production and hunger eradication, climate change, and environmental degradation. This is an initiative of the Digital Soil Mapping Working Group of the International Union of Soil Sciences (IUSS).

The Globalsoilmap.net consortium was granted funding from the Bill and Mellinda Gates foundation in order to establish this consortium and implement its soil mapping activities in Sub-Saharan Africa. The Africa Soil Information Service (AfSIS) is developing continent-wide digital soil maps for sub-Saharan Africa using new types of soil analysis and statistical methods, and conducting agronomic field trials in selected sentinel sites. These efforts include the compilation and rescue of legacy soil profile data, new data collection and analysis, and system development for large-scale soil mapping using remote sensing imagery and crowd sourced ground observations. (http://www.africasoils.net).

The project area includes ~17.5 million km2 of continental sub-Saharan Africa (SSA). This area encompasses more than 90% of Africa's human population living in 42 countries. The project area excludes hot and cold desert regions based on the recently revised Köppen-Geiger climate classification, as well as the non-desert areas of Northern Africa. This project started in 2009 and is currently the main soil mapping funded regional activity that is under implementation.

The Globalsoilmap.net consortium has developed technical specifications (http://www.globalsoilmap.net/system/files/GlobalSoilMap_net_specifications_v2_0_edited_draft_Sept_2011_RAM_V12.pdf) to guide their global and regional actions.

Exact dates for the delivery of this revolutionary product is not specified, but it is presumed that will require major efforts for its implementation as it is very demanding in terms of financial resources as well as commitment by national institutions.

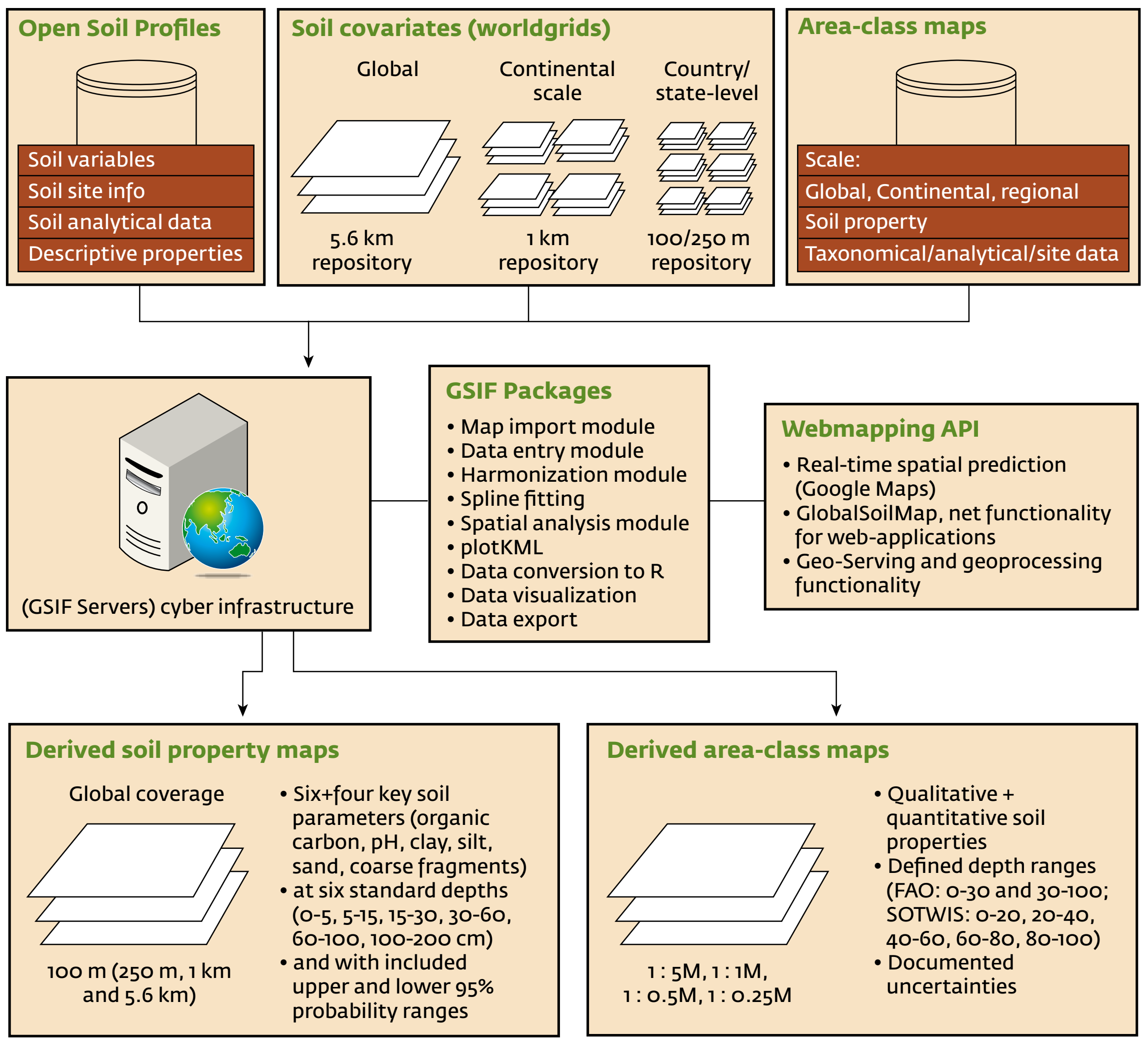
5.2 Global Soil Information Facilities

ISRIC- World Soil Information is an independent foundation that was established in 1964 with the mandate of serving the international community with information about the world's soils resources to help addressing major global issues. GSIF (Global Soil Information Facilities) is ISRIC's framework for production of world soil data. It has been inspired by global environmental data initiatives such as Global Biodiversity Information Facilities, Global Land Cover mapping, OneGeology and similar. The main practical reason for GSIF is to build cyber-infrastructure to collate and use legacy (i.e., historic) soil data currently under threat of being lost forever. Seven key principles explain the design of GSIF:

- Data collection in GSIF is based on crowd-sourcing - everyone collecting soil data or working with soil information is invited to contribute to some of the databases via data portals and to GSIF tools via GSIF software development portals. As such, GSIF follows the Wikipedia approach to building information systems.
- Data entered through GSIF data portals remain the property of the original contributors (copyright holders and/or authors). The original contributors have live access to their entries and full read/write rights.
- GSIF is mainly based on Free and Open Source Software (Linux, PHP, LaTeX, R, GDAL, GRASS, SAGA GIS, PostgreSQL, PostGIS, Python, Google Earth and similar), but other software packages may also be used.
- GSIF has been designed mainly to serve global soil mapping initiatives and not local, isolated (regional and national) projects. Internationally accepted standards (International System of Units, international soil classifications systems, FAO soil field description guides, World Geodetic System 1984, and similar) are recommended. National and local datasets in different languages are also supported, which requires further harmonization.
- GSIF is based on automated procedures for mapping, pattern recognition and report/plots generation. All maps and reports produced as a part of GSIF are reproducible, i.e. they are based on compliable scripts that contain all processing steps. Derived maps can be updated by re-running the scripts with no or little human intervention when new data sets become available.
- All shared soil data used to generate maps will be made available in near real-time in accordance with ISRIC data policy.
- GSIF data processing services and databases (maps and reports), produced as a part of GSIF, will constantly be adjusted based on usage statistics and web-traffic. Complexity (statistical data processing steps, coordinate systems, scale, uncertainty in the maps) is either hidden from the users or communicated using efficient solutions. This follows the Google approach to indexing and browsing geo-data.

The GSIF structure is presented below under figure 5.

Figure 5 GSIF structure for global soil mapping



5.3 Harmonized World Soil Database

Although the HWSD has been fully described in the second chapter, it is important to mention it here as it is still an ongoing initiative. Its main aim is to update this database with missing soil legacy national maps and soil profile data from the industrialized countries (USA, Australia and Canada) as well as developing countries in which soil information exists at national level but was never included in regional and global initiatives. Under the framework of the Global Soil Partnership, FAO is funding the initial phase for the development of the following regional soil information systems: Asian Soil Information System (ASIS), Sistema Latinoamericano de Información de Suelos (SISLAC) and Middle East-North Africa Soil Information System (MESIS). These databases will then constitute the main source of soil legacy data and information to feed and update the global HWSD system and then move forward towards joining the DSM community to make an evolution in terms of soil information.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Legacy data

1. Under the current challenges of food security, climate change adaptation and mitigation, further provision of ecosystem services and sustainable intensification of agriculture, soil information becomes fundamental to guide wise policies and decisions. With the current global and regional soil information available, the soil science community is limited in its capacity to provide accurate and updated information to the different soil users.
2. Soil legacy data and information are a crucial asset for future soil mapping activities and even more important for monitoring purposes. Although legacy data are important, the current available legacy data have a number of problems. The problems include data gaps, storage, compatibility with DSM technology, and copyright issues.
3. HWSD is the most comprehensive global soil database with soil profile, attribute data, and soil map currently available. The database has direct website links and is freely downloadable in formats which are compatible with most software.
4. Rich soil information is available in various national and regional soil mapping/information systems organizations. Some have their data freely accessible, while others impose copyright restrictions on their data. Coordination or understanding are the only ways to associate them with a global mapping initiative
5. Some global datasets/maps are derivations of derivations, yet they are widely used in various fields. This inadequacy is possibly due to lack of information about existing soil data or inadequate and accessible soil information.

6.1.2 Users needs

1. The needs of soil information users and present trends of soil information generation seem to be increasingly divergent.
2. The majority of soil information users are keen on georeferenced soil data, and especially measured soil attributes.
3. Since most direct users of soil information seem to be working at the national and sub-national levels, the soil mapping activities generating soil information should give priority to farm, district, and national scales.
4. Policy making seems to be influenced by soil information at various scales: farm, national, regional, and global.
5. The conceptual underpinnings of soil inference systems are still not well appreciated by many users. The majority of soil information users do not seem to prefer use of model outputs as substitutes for observed or conventionally produced soil information.
6. Many soil users would like to have free access to soil information. They think that if the soil data collection is done at public expense, then the resultant generated information should be freely available to the public.
7. The preferred mode of disseminating the information is through the internet. Users would like to have the convenience of downloading relevant data rather than moving around searching for the information. This implies that the areas of soil information systems tasked with data storage and dissemination should consider online repositories as much as is possible.

6.1.3 DSM

1. There are many freely available DSM tools which can be harnessed to improve production of digital maps
2. DSM does not only produce maps, but it also produces methods for soil mapping, digital soil database/information system, and assessment of soil threats. It is a three-stage process, which can satisfy soil information users needs if well implemented
3. Most DSM processes are not very well implemented. There is still lack of standardization on input data and tools, expertise and training manuals, and coordination of many organizations involved in DSM
4. HWSD, GSIF, GSM, and GSP are some of the main active global soil mapping activities. They have varied strengths which when joined, can help improve global awareness, soil information generation and use, update existing soil information.

6.2 Recommendations

- Considering the challenges of food security, climate change adaptation and mitigation, and further provision of ecosystem services, the soil science community should clearly respond to the natural needs for improved, up-to-date, quantitative and applied soil data and information. This global effort should take into account the ongoing developments in terms of methods and tools currently available, especially those related to Digital Soil Mapping and should not neglect the core of soil mapping that is based on understanding of soil-landscape relationships revealed through field studies undertaken by soil surveys. Ongoing efforts such as Globalsoilmap.net, GSFI, HWSD, etc, should be strengthened by making them part of a unified global effort in which all the global, regional and national institutions participate fully and together plan feasible activities in the short, medium and long-term, in order to respond to their needs in terms of global and regional soil information.
- While it is common to hear that there is an increased need for detailed soil information, it is fundamental to develop a multi-scale / multi-resolution approach in which the global efforts could address the demands coming from the different users. It is true that global and regional information systems are intended to address global activities such as modelling scenarios, status assessment, trends, etc, however some concerns have been raised by users pointing out that soil information should be addressing the needs coming from the field. While this is a very valid request, the soil information community should develop a multiuser system in which the global soil information system could respond to the needs at all levels. This could be a challenging recommendation, but learning from the past it is wise to make soil information a positive cost/benefit asset showing its value at all levels. This will promote its continuous self-development as its direct contribution to all the different fields will showcase a visible impact. This of course should be linked to a training program for soil information users in order to train different users on how soil data and information should be used and linking reliability or accuracy to their decisions.
- There is a fundamental need that traditional soil survey/mapping and DSM communities join forces to fill in the evident gap in terms of soil information. This can be done by recognizing the value of both approaches, overcoming weaknesses through recognized strengths of both approaches and by an inclusive neutral framework that could have a neutral goal. On this, the Global Soil Partnership plays a crucial role as is linked to a UN organization with a global mandate on soils in which 193 countries are members and fight for common global mutual goals.
- Soil legacy data and information constitutes a precious asset, not only for its potential use for soil mapping under DSM, but also for on-going monitoring purposes. Besides, it is the only plausible result of huge investments done by international and national organizations. Its collection, harmonization and storing in a common global database that is open to all the different communities under proper IP rights should be an immediate global effort and activity.

- The copyrights and intellectual property rights are a sensitive issue that should be clearly studied and jointly defined by a global neutral institution or framework representing all possible interests and concerns. The collaborative example of the FAO-UNESCO World Soil Map should be used as a proper working example.
- Capacity development in digital soil mapping should be the main vehicle for generation of up to date, demand driven soil information. A joint global capacity development program should be urgently developed to be implemented at regional level with different modalities. Short and medium term on-the job training programs and also long term BSc, MSc and PhD programs should be developed. This activity demands immediate implementation.
- In an era of financial crisis and increasingly limited financial resources, it is of prime importance that the soil science community join together with a common voice and message in order to request donors to support an integrated plan of action in terms of soil data and information. In this regard, the Global Soil Partnership, through its pillar of action on soil information, is aiming to develop a joint plan of action that is very inclusive and represents all the region's interests and priorities for soil data and information. This indeed becomes a fundamental opportunity and challenge for including all the necessary elements for responding the needs of a growing population in terms of soil knowledge. This plan will then be presented to donors to fund a unique joint endeavour producing improved and much needed soil information.

REFERENCES

AFSIS. 2012. AFSIS Newsletter: January – March 2012. Issue 1. www.africasoils.net

Bahrim N, Bernoux M, Blavet D and Gallali T. 2010. Tunisia soil carbon stocks. International Journal of Soil Science 5:34-40.

Batjes NH, Bridges EM and Nachtergaele FO. 1995. World Inventory of Soil Emission Potentials: development of a global soil data base of process-controlling factors. In: Peng S, KT Ingram, HU Neue and LH Ziska (editors), Climate Change and Rice. Springer-Verlag, Heidelberg, pp 102-115.

Batjes NH. 2002. Soil parameter estimates for the soil types of the world for use in global and regional modelling (Version 2.1). ISRIC Report 2002/02c, International Food Policy Research Institute (IFPRI) and International Soil Reference and Information Centre (ISRIC), Wageningen.

Batjes NH. 2003. A taxotransfer rule-based approach for filling gaps in measured soil data in primary SOTER databases (GEFSOC Project). Report 2003/03, ISRIC - World Soil Information, Wageningen.

Batjes NH. 2005. ISRIC-WISE global dataset of derived soil properties on a 0.5 by 0.5 degree grid (version 3.0). Report 2005/08. ISRIC-World Soil Information, Wageningen (With datset)

Batjes NH. 2006. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.1). Report 2006/02, ISRIC -World Soil Information, Wageningen.

Batjes NH, Fischer G, Nachtergaele FO, Stolbovoy VS and van Velthuizen HT, 1997. Soil data derived from WISE for use in global and regional AEZ studies (ver. 1.0). Interim Report IR-97-025, FAO/ IIASA/ ISRIC, Laxenburg (http://www.iiasa.ac.at/Admin/PUB/Documents/IR-97-025.pdf)

Beaudette DE and O'Geen AT. 2010. An iphone application for on-demand access to digital soil survey information. Soil Science Society of America Journal 74: 1-3.

Bockheim JG, Gennadiyev AN, Hammer RD, Tandarich JP. 2005. Historical development of key concepts in pedology. Geoderma 124: 23-36.

Boul SW, Hole FD and McCracken RW. 1997. Soil Genesis and Classification, 4th ed. Iowa State Univ. Press

Brady NC. 1984. The Nature and Properties of Soils. 9th Edition. Macmillan Publishing Company. New York. 750 p

Bullock P, Jones RJA, Houšková, B and Montanarella L., 1999 Soil Resources of Europe: An Overview. European Soil Research Report #9 JRC, Ispra Italy.

Carré F, McBratney AB, Mayr T, and Montanarella L. 2007. Digital soil assessments: beyond DSM. Geoderma, 142, 69-79

Eswaran H, Reich P. 2005. Global Soil Regions.

European Commission DG Joint Research Centre, 2004 Soil Atlas of Europe.

European Commission DG Joint Research Centre, 2006.Soil Atlas of the northern circumpolar region.

FAO/Unesco. 1971-1980. Soil Map of the World Legend and 9 volumes. UNESCO, Paris.

FAO/Unesco. 1974. Legend of the Soil Map of the World, Unesco, Paris.

FAO/Unesco/ISRIC. 1988, 1990. Revised Legend of the Soil Map of the World. FAO World Soil Resources Reports # 60

FAO. 1995. Digital Soil Map of the World and Derived Soil Properties (Version 3.5). FAO, Rome, Italy.

FAO /IGADD/ Italian Cooperation 1998. Soil and terrain database for northeastern Africa and Crop production zones. Land and Water Digital Media Series # 2. FAO, Rome.

FAO/UNEP/ISRIC/CIP. 1998. Soil and terrain digital database for Latin America and the Caribbean at 1:5 Million scale. FAO Land and Water Digital Media series # 5. FAO, Rome.

FAO/IIASA/Dokuchaiev Institute/Academia Sinica. 1999: Soil and Terrain Database for north and central Eurasia at 1:5 million scale. FAO Land and Water Digital Media series #7. FAO, Rome.

FAO/ISRIC. 2000. Soil and Terrain Database, Land Degradation Status and Soil Vulnerability Assessment for Central and Eastern Europe Version 1.0 (1:2.5 million scale) . Land and Water Digital Media Series # 10. FAO, Rome.

FAO/EC/ISRIC. 2003. World Soil Resources Map. ftp://ftp.fao.org/agl/agll/faomwsr/wsavcl.jpg

FAO/ISRIC. 2003. Soil and Terrain Database for Southern Africa. Land and Water Digital Media Series # 26. FAO, Rome.

FAO. 2004. Carbon sequestration in dryland soils. World Soils Resources Reports 102. FAO, Rome.

FAO. 2006. Guidelines for soil profile description. Fourth edition. Rome, Italy.

FAO/IIASA/ISRIC/JRC/CAS. 2008. Harmonized World Soil Database v1.2.

Fischer G, Nachtergaele F, Prieler S, van Velthuizen HT, Verelst L, Wiberg D. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy (http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/SoilQuality.html?sb=10).

Fischer G, Nachtergaele F, Prieler S, van Velthuizen HT, Verelst L, Wiberg D. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy).

Foth HD and Ellis BG. 1997. Soil Fertility. 2nd Ed. CRC Press. Boca Raton, Florida. 290p.

Geze, B. 1956. Carte de Reconnaissances Des Sols du Liban au 1:200,000. Ministere de l'Agriculture. Beyrouth. Note, 54pp.

Graham MP. 1989. Adobe and Rammed Earth Buildings: Design and Construction. University of Arizona Press.

Hiederer R, Jones RJA, and Daroussin J. 2006. Soil Profile Analytical Database for Europe (SPADE): Reconstruction and Validation of the Measured Data (SPADE/M). Geografisk Tidsskrift, Danish Journal of Geography 106(1). p. 71-85.

Hole FD and Campbell JB. 1985. Soil landscape analysis. Totowa Rowman & Allanheld

Hollis JM, Jones RJA, Marshall CJ, Holden A, Van de Veen JR, and Montanarella L. 2006.SPADE-2: The soil profile analytical database for Europe, version 1.0. European Soil Bureau Research Report No.19, EUR 22127 EN, Office Off. Publ. Eur.Comm., Luxembourg,

Hudson BD. 1992. The soil survey as a paradigm-based science. Soil Science Society of America 56, 836-841

Indraratna B and Nutalaya P. 1991. Some engineering characteristics of a compacted lateritic residual soil. Geotechnical and Geological Engineering 9:125-137.

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, and Schuman GE. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Lagacherie P, McBratney AB, and Voltz M. 2007. Digital Soil Mapping: An Introductory Perspective. Developments in Soil Science 31. Elsevier: Amsterdam.

Leenaars JGB. 2012. A compilation of georeferenced and standardized legacy soil profile data for sub-Saharan Africa (with dataset). ISRIC Report 2012/03. ISRIC. Wageningen.

Leenaars JGB. 2012. Africa Soil Profiles Database, Version 1.0. A compilation of geo-referenced and standardized legacy soil profile data for Sub Saharan Africa (with dataset). ISRIC report 2012/03. Africa Soil Information Service (AfSIS) project and ISRIC – World Soil Information, Wageningen, the Netherlands.

Liang S. 2004. Quantitative Remote Sensing of Land Surfaces. John Wiley and Sons: New Jersey

Luo Z, Yaolin L, Jian W and Jing W. 2008. Quantitative mapping of soil organic material using field spectrometer and hyperspectral remote sensing. Proceedings in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVII. Part B8. Beijing.

McBratney, AB, Minasny B, Cattle SR, Vervoort, RW. 2002. From pedotransfer functions to soil inference systems. Geoderma 109, 41-73

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

Melesse MA, Weng Q, Thenkabail PS and Senay GB. 2007. Remote sensing sensors and applications in environmental resources mapping and modelling. Sensors 7:3209-3241.

Minasny B and Hartemink A. 2011. Predicting soil properties in the tropics. Earth-Science Reviews, 106: 52-62.

Nachtergaele FOF. 2003. The Future of the FAO Legend and the FAO/UNESCO Soil Map of the World. In: Thomas Rice *et al* (Eds). "Soil Classification: A Global Desk Reference", CRC Press, Boca Raton, FL.

Nachtergaele F. and Van Ranst E. 2003. Qualitative and Quantitative Aspects of Soil Databases in Tropical Countries.in Evaluation of Tropical Soil Science: past and future. Koninklijke Academie voor overzeese wetenschappen. Brussels.

Nachtergaele, F, Van Velthuyzen H, Verelst L and Wiberg D. 2012. Manual Harmonized World Soil Database v1.2 February 2012.

Oldeman LR, Hakkeling RTA and Sombroek WG. 1991. Global Assessment of Soil Degradation: An explanatory note. ISRIC-UNEP, Wageningen.

Omuto CT and Vargas RR. 2009. Combining pedometrics, remote sensing and field observations for assessing soil loss in challenging Drylands: a case study of northwestern Somalia. Land Degradation Development 20: 101-115

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

Post WM and Zobler L. 2000. Global Soil Types, 0.5-Degree Grid (Modified Zobler). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/540.

Raich JW and Schlesinger WH. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44 B: 81-99

Raich JW and Schlesinger WH. 2001. Global Annual Soil Respiration Data (Raich and Schlesinger 1992). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Centre, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/622.

Robinson A, Williams S and MacEwan R. 2010. A conceptual framework for a Victorian soil-landscape inference system. In Proceedings of "19th World Congress of Soil Science, Soil Solutions for a Changing World", 1 – 6 August 2010, Brisbane, Australia.

Sanchez P *et al*. 2009. Digital soil map of the world. Science 325: 680-681.

Shi XZ. 2012. Soil database of China and carbon dynamics at regional scale. Presentation at Asian Soil Partnership Program Nanjing Communiqué, February 8-11, 2012, Nanjing. China

Tarnocai C, Kimble JM, Swanson D, Goryachkin S, Naumov YM, Stolbovoi V, Jakobsen B, Broll G, Montanarella L, Arnoldussen A, Arnalds O, and Yli-Halla M. 2002. Northern Circumpolar Soils. 1:10,000,000 scale map. Ottawa, Canada: Research Branch, Agriculture and Agri-Food Canada. Distributed by the National Snow and Ice Data Center, Boulder, CO, USA.

USDA. 1993. Soil Survey Manual. Soil Survey Division Staff. Handbook 18.

Van Engelen V. 2012: e-SOTER. Proceedings GSP meeting March 2012. Rome, FAO.

Van Engelen V and Wen T. 1995 Global and National Soil and Terrain Databases (SOTER). FAO World Soil Reosurces Reports # 74. FAO, Rome.

Venables WN and Ripley BD. 2002. Modern Applied Statistics with S, Springer-Verlag, New York.

Wood BG and Auricht CM. 2011. ASRIS/ACLEP User Needs Analysis. ACLEP-CSIRO.

Xiao J, Shen Y, Tateishi R and Bayaer W. 2006. Development of topsoil grain size index for monitoring desertification in arid land using remote sensing. International Journal of Remote Sensing 27:2411-2422.

Xie Y, Sha Z and Yu M. 2008. Remote sensing imagery in vegetation mapping: a review. Journal of Plant Ecology, 1:9-23.

Zinke PJ, Stangenberger AG, Post WM, Emanuel WR and Olson JS. 1986. Worldwide Organic Soil Carbon and Nitrogen Data, NDP-018. Available on-line [http://cdiac.esd.ornl.gov/home.html] from Carbon Dioxide Information Analysis Centre (CDIAC), Oak Ridge National Laboratory, Oak Ridge, Tennessee U.S.A.

Zurayk R, El-Awara F, Hamadeha S, Talhouka S, Sayegha C, Chehabb AG and al Shabc K. 2001. Using indigenous knowledge in land use investigations: a participatory study in a semi-arid mountainous region of Lebanon. Agriculture Ecosystems and Environment 86: 247-262.

State of the Art Report on Global and Regional Soil Information: Where are we? Where to go?

Under the current challenges of food security, climate change adaptation and mitigation, further provision of ecosystem services and sustainable intensification of agriculture, soil information becomes fundamental to guide wise policies and decisions. This document reviews the present availability of soil information from legacy maps and reports and from ongoing Digital Soil Mapping efforts.

Currently, the soil science community is limited in its capacity to provide accurate and updated information to the different soil users. It concludes that there is an urgent need for traditional soil survey/mapping and Digital Soil Mapping (DSM) communities to join forces and fill the gap with the user's expectations for soil information in space and time.

ISBN 978-92-5-107449-7

9 789251 074497

I3161E/1/12.12

Cover photos: © R. Vargas; © JRC, FAO.