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Soil Mapping in Africa at the Crossroads: Work to Make up for Lost Ground*

by

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Keywords. — Soil Survey; Soil Databases; Land Resources; Soil Evaluation; Central Africa.

Summary. — While in Western Europe most national soil survey institutes have closed down or been privatized, in Africa there are still relatively strong soil institutes in most countries backed by — albeit insufficiently — government funds. Funds for classical soil surveys are difficult to obtain, although the demand for digital soil information from different sources is increasing. Though many soil institutes all over the world have adopted useful innovations, such as soil and geographic information systems and automated data collection, technology has not, by itself, provided enormous improvements in the way soil information can be used. In fact, the overenthusiastic, uncritical or hasty use of modern electronic tools can lead to inappropriate results and unwise decisions. Soil surveys must keep up with the times and be able to offer up-to-date, quantitative information about soil and how soil changes in both space and time. The quality and quantity of the soil data available in Africa are assessed and the problems for further development of such databases are reviewed and possible solutions given to overcome some of the obstacles. Particular attention is given to the efforts of the recently launched Africa Soil Information Service as well as the digital SOTER map of Central Africa, at scale 1:2M for DR Congo and 1:1M for Rwanda and Burundi.

Trefwoorden. — Bodemkartering; Bodemdatabanken; Bodemrijkdommen; Bodemevaluatie; Centraal-Afrika.

Samenvatting. — *Bodemkartering in Afrika op de tweesprong: inspanningen om het verloren terrein terug te winnen.* — Terwijl in West-Europa de meeste nationale instituten voor bodemkartering opgedoekt of geprivatiseerd werden, zijn er in de meeste landen in Afrika nog relatief sterke bodeminstituten actief met de steun van overheidsfinancie-

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ring, die overigens vaak ontoereikend is. Zelfs al blijft de vraag naar digitale bodeminformatie verkregen vanuit verschillende bronnen stijgen, toch blijft het moeilijk om financiering voor klassieke bodemkartering te verkrijgen. Hoewel vele bodeminstituten over de hele wereld nuttige innovaties ingevoerd hebben, zoals bodem- en geografische informatiesystemen en geautomatiseerde systemen voor dataverzameling, heeft de technologie op zich niet tot enorme verbeteringen geleid in de manier waarop bodeminformatie kan gebruikt worden. Een overenthousiast, niet kritisch of overhaastig gebruik van moderne elektronische instrumenten kan leiden tot onjuiste resultaten en onverstandige beslissingen. Bodemkartering moet evolueren in de tijd en moet ons kwantitatieve up-todate informatie kunnen geven over de bodem en hoe die bodem in tijd en ruimte verandert. De kwaliteit en kwantiteit van de beschikbare bodemgegevens in Afrika worden geëvalueerd en problemen bij de verdere ontwikkeling van dergelijke databanken worden in kaart gebracht zodat naar mogelijke oplossingen kan gezocht worden om bepaalde hindernissen uit de weg te ruimen. In het bijzonder wordt aandacht geschonken aan de inspanningen van de “Africa Soil Information Service” die recent werd opgericht en aan de digitale SOTER map van Centraal-Afrika, op schaal 1:2M voor D.R. Congo en 1:1M voor Rwanda en Burundi.

MOTS-CLES. — Cartographie des sols; Bases de données des sols; Ressources terrestres; Evaluation des sols; Afrique centrale.

RESUME. — *La cartographie des sols en Afrique à la croisée des chemins: efforts pour rattraper le terrain perdu.* — Alors qu’en Europe occidentale la plupart des instituts pédologiques nationaux sont fermés ou privatisés, en Afrique il existe encore sur la quasi-totalité du continent des instituts pédologiques relativement importants bénéficiant, bien que de manière insuffisante, de fonds gouvernementaux. Les fonds destinés aux prospections pédologiques classiques sont difficiles à obtenir, alors que la demande d’informations pédologiques digitales, reçues de différentes sources, est en augmentation. Bien que beaucoup d’instituts pédologiques à travers le monde aient adopté des innovations utiles, notamment les systèmes d’information géographique et la collecte automatisée des données, la technologie n’a pas apporté, par elle-même, d’énormes améliorations quant à la manière de traiter les informations pédologiques. En effet, l’utilisation surintensive, peu critique ou hâtive des outils électroniques modernes peut conduire à des résultats incorrects et à des décisions inopportunes. Les études de sols doivent évoluer avec le temps et être à même d’offrir des informations actualisées et quantitatives et de décrire la manière dont le sol change à la fois dans l’espace et dans le temps. La qualité et la quantité des données pédologiques disponibles en Afrique sont ici évaluées. Les problèmes liés au développement accru de telles bases de données sont passés en revue et des solutions éventuelles pour surmonter certains obstacles sont proposées. Une attention particulière est accordée aux efforts du *Africa Soil Information Service*, récemment créé, ainsi qu’à la carte digitale SOTER d’Afrique centrale, à l’échelle 1:2M pour la RD Congo et 1:1M pour le Rwanda et le Burundi.

1. A Historical Review of Soil Mapping in Africa

Soil studies in Africa have always made a substantial contribution to the development of concepts concerning soil classification, soil genesis and soil survey techniques. Studies of South Africa's soils started in the early 1890s and from 1897 to 1900; a very important soil survey was conducted in Madagascar (Muntz 1900). Even in the pioneer studies, the red soils of Africa were considered as special, and all classification systems provided a special place for them.

The development of soil classification systems has gone on hand in hand with developments in survey methodology. The soil series concept introduced in 1904 by the US Soil Survey as a basic mapping unit has been adopted for soil mapping in most parts of Africa. The earliest known soil map of Africa at a scale 1:25 M was published in 1923. This map, based on limited observations, intended to show the probable location and trend of the great soil belts of Africa (Shantz & Marbut 1923).

In the period 1930-1945, several notable reconnaissance surveys were undertaken in Africa on limited budgets and with few staff. Among these are the reconnaissance survey of the Belgian Congo (Baeyens 1938) and a map of the central part of Nyasaland (Hornby 1938). The Provisional Soil Map of East Africa (1935-1936) developing the concept of the soil catena is regarded by many as the outstanding survey of this period. The vegetation-soil surveys of Northern Rhodesia (Trapnell & Clothier 1937, Trapnell *et al.* 1948) are classic examples of the ecological approach. In Rhodesia a soil classification based on geological materials was proposed in the late 1940s (Ellis 1948, 1951).

Although the first important contributions to tropical soil science date from the thirties, the 1950s perhaps mark the second renaissance of pedology. The decade of the 1950s saw increasing studies on African soils because some European countries, especially Belgium, France and Portugal founded in their African colonies large research stations with a pedological section. The importance given in the fifties to soil survey in Africa resulted automatically in a special interest in soil classification. In 1954, Leopoldville (Kinshasa) in Congo hosted the 5th World Congress of Soil Science, the first one to be held in a tropical environment.

Within the English-speaking parts of tropical Africa, the system used in Ghana and in parts of Nigeria is perhaps the best known. The Ghana classification is a natural classification based on rainfall and parent material (Brammer 1962, Ahn 1970).

During the colonial period, several of the colonial powers established their own soil classification systems. The INEAC (*Institut National de l'Etude Agronomique au Congo* / National Institute for Agricultural Research in Congo) system (Sys *et al.* 1961), devised for use in the former Belgian Congo, put the emphasis on successive stages of weathering. In the Portuguese colonies, a neat classification was developed for deep, relatively well-drained profiles (Botelho da Costa 1946, Botelho da Costa *et al.* 1953). For the general soil map of Angola (1:1 M), such groupings were used as taxonomic units, with complexes of groupings as cartographic units (Botelho da Costa 1959). The pedologists of ORSTOM (*Office de la Recherche Scientifique et Technique d'Outre-Mer* /

Office of Overseas Scientific and Technical Research) were involved in soil surveys of different areas in Africa (Ruellan 2003, Feller *et al.* 2008) and in the development and revision of soil classification systems (Aubert 1954, Aubert & Duchaufour 1956). Two outstanding contributions serving as a basis for international exchange of pedological and agronomic information include the FAO 'Soil Map of the World (scale 1: 5 M)' Project which started in 1961 (Dudal 1968-1969) and the Soil Map of Africa at scale 1: 5 M (D'Hoore 1964, 2003), published in 1964 in the framework of a joint project by the Inter-African Pedological Service and the CCTA (*Commission de Coopération Technique en Afrique* / Commission for Technical Cooperation in Africa). Legends were developed for these small-scale maps. The CCTA classification reflected a major effort of correlation between the various systems in use in different African countries. It is an outstanding synthesis, and served a particularly valuable purpose in bringing the ORSTOM and INEAC approaches more fully to the attention of English-speaking countries in Africa. The development and application of this system stimulated cooperation and international exchange of pedological information and ideas.

Although initially developed as a legend for a specific map, not a soil classification system, the FAO Legend (FAO 1974) found quick acceptance as an international soil correlation system. It has been used on FAO soil surveys in Africa and for international soil classification in many African countries.

During the last decades of the 20th century, new issues — environment, population growth and food security — emerged and information technology took shape. Modern tools specific to soil surveys, such as geographic information systems, were readily becoming available and soil databases evolved quite rapidly. Although the stage was set where information could be delivered to end-users in a timely manner and packaged for their use (Zinck 1995), this technological revolution was no guarantee for enhanced quality of the soil data itself (Nachtergaele & Van Ranst 2003). Soil information was considered less useful to the task of enhancing food production. Though there were increased investments in environment protection and conservation, soil scientists did not make the transition rapidly enough to exploit the funding available in this new field. Investments in pedological research shrank and emphasis shifted to applications (Eswaran *et al.* 2004).

By the end of the 20th century, also FAO had terminated its global programme and primary field data collection was seriously downsized or even stopped. Some of the reasons put forward to explain this crisis are external to soil survey and strongly influenced by the general economic situation. Inappropriate presentation and the poor accuracy of soil information, together with high survey costs, are often to blame. The soil science jargon is often not user-friendly or user-oriented. The crisis in collecting primary field data in general may also partly be blamed by the over-reliance on the use of satellite imagery as the ideal tool to carry out natural resources inventories (Nachtergaele & Van Ranst 2003).

Soil survey arrived at a crossroads and many national soil survey centres closed down or were privatized and abandoned systematic soil mapping. As funds for classical soil surveys are not available anymore or very difficult to obtain, computer techniques, like digital soil mapping, may solve the increasing demand for soil information. Although satellite imagery is an extremely useful tool to assist surveys even at the highest resolution it limits observation to land cover. Measured soil data are usually available for a limited number of locations, and the missing data are estimated through interpolation or extrapolation, or by using geostatistical analysis, transfer functions or all kind of models. The question arises whether all these computer techniques offer an alternative for the field survey.

2. African Soil Databases: An Overview

At continental level the 1:5 M scale FAO-UNESCO Soil Map, as part of the Soil Map of the World (FAO 1971-1981), is still, twenty-five years after its finalization, the only consistent, harmonized soil inventory that is readily available in digital format and comes with a set of estimated soil properties for each mapping unit. Although this map has been utilized in many global studies on climate change, food production, and land degradation, its low resolution is not suitable for land management decisions at field or catchment scales.

Most countries have updated their soil information since the publication of the FAO Soil Map of the World. In fact, several African countries have now produced national soil maps, which in scale and level of information can easily compete with those developed in the industrialized world. Botswana, Kenya, Rwanda, Ghana, Tunisia are but a few examples of countries that have gone to great lengths to fully inventory their soils and document them (Van Ranst *et al.* 2004).

As an example, in Rwanda, a conventional national soil survey (scale 1:50,000) started in 1981 and was completed in 1994. The semi-detailed soil survey was based on extensive use of aerial photographs and fieldwork. As such, forty-three soil maps at scale 1:50,000 were produced, covering the whole of Rwanda and the 1833 georeferenced soil profiles, corresponding to two hundred and seventy-six different soil series, had been described and analysed. Spatial, descriptive and analytical data were discussed and summarized in the explanatory notes developed for each soil map. A reconnaissance soil map at scale 1:250,000 has been produced as well and also a climatic database was compiled. In order to make this huge amount of information more effectively for clients' needs and to facilitate users' access, an automation of the data was carried out using adopted geographic information systems (GIS) and soil information systems (SIS). From 1989 onwards, the soil maps and all observation points with their corresponding data were stored in a master database using GIS and database software (VAN RANST *et al.* 2002). The soil data were digitized as a polygon theme, representing the soil mapping units drawn on the topographical base maps, and as a point theme indicating each observation. Soil analytical data were organized in a relational database which contains the general soil profile data, physical and chemical analysis data of the horizons, and the soil map explanatory reports. The labels of each soil mapping unit, forming the skeleton of the final soil database, were then related to the tabular database containing essential soil properties, to form an integrated soil coverage, comprising both spatial and descriptive data (IMERZOUKENE & VAN RANST 2001). A schematic representation of the integrated natural resources database of Rwanda is shown in figure 1.

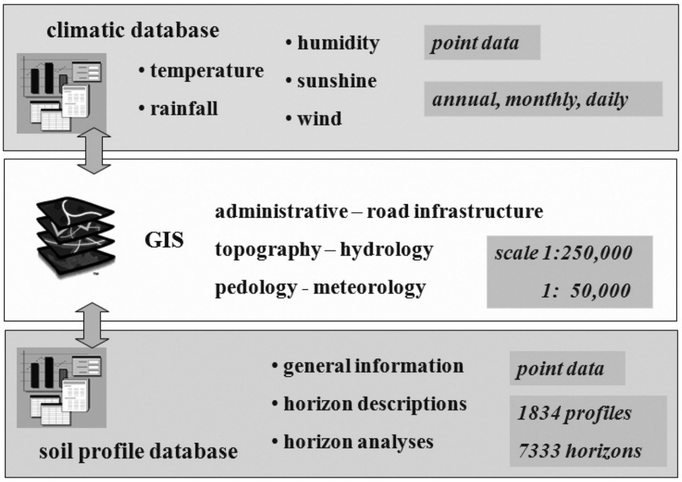

Fig. 1. — Schematic representation of the integrated natural resources database of Rwanda.

The system allows easy updating, modification or reorientation depending on the requirements of the different ministerial departments who are going to use it. As such, the land resources information can be used more efficiently and accurately and will assist the government of Rwanda in investigating specific agricultural and environmental issues in appreciable time limits (VERDOODT & VAN RANST 2006). The maps and the database are available at the Laboratory of Soil Science of Ghent University and at the Ministry of Agriculture in Kigali.

A number of African countries still have large gaps in their information and have hardly gone beyond the 1:5 M scale information contained in the soil map of the world. The Democratic Republic of Congo, Somalia, Algeria, Burma are a few examples. In the DR Congo only 15 % of the territory has been mapped at scale 1:50,000 to 1:500,000 (fig. 2). The existing soil maps produced by INEAC before 1960 and by the Laboratory of Soil Science of Ghent University after

1960 are currently being updated, using a uniform legend, and digitized in the frame of an interuniversity collaboration project between Ghent University and the Universities of Kinshasa and Lubumbashi.

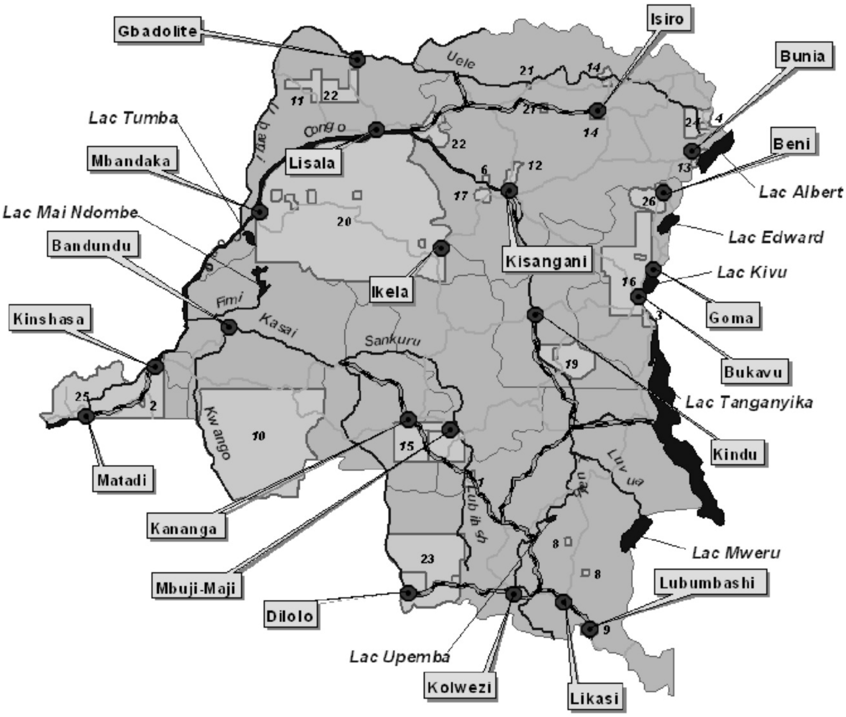

Fig. 2. — Soil map coverage in the Democratic Republic of Congo.

Table 1 shows the national coverage in twenty-one African countries. As to the soil map status, the following general conclusions can be drawn:

- Many countries have some kind of general map at very small scale, usually substantially smaller than 1:250,000;
- Cartographic coverage for regional master planning of scales between 1:100,000 and 1:250,000 is largely incomplete, making it difficult to identify high-potential areas or, conversely, critical problem areas and their priority for more detailed inventories;
- Soil maps appropriate for project planning at scales around 1:25,000 cover a very small percentage of the countries;
- Soil maps suitable for operational planning, usually at scales larger than 1:25,000 are seldom mentioned.

Table 1
National soil survey coverage in 21 African countries (ZINCK 1995, updated)

	Small scale 1:500,000 - ± 100,000 (%)	**Medium scale 1:100,000 - ± 50,000 (%)**	**Large scale ≤ 1:25,000 (%)**
Algeria	–	5	5
Benin	100	10	2
Botswana	40	5	–
Burkina Faso	100	25	–
Burundi	100	–	–
Cameroon	30	5	1
DR Congo	10	5	–
Egypt	100	10	10
Gabon	30	–	–
Gambia	100	–	100
Ghana	95	–	–
Kenya	100	25	–
Mali	50	–	–
Morocco	–	40	20
Nigeria	70	35	–
Rwanda	100	100	–
South Africa	70	–	–
Swaziland	100	10	5
Tanzania	50	–	–
Togo	80	20	–
Uganda	100	–	–

This shortage results in a demand for medium- and large-scale maps virtually everywhere. These are precisely the scales at which the contribution of soil information to land-use planning and problem solving is most directly effective (ZINCK 1995).

In general, most developing countries have scattered soil surveys only partly correlated with one another and of variable age and quality, but tracking the coverage and quality of the many ad hoc surveys is not easy.

In the early 1990s, FAO recognized that a rapid update of the Soil Map of the World would be a feasible option if the original map scale of 1:5 M was retained. The parallel programmes of ISRIC (International Soil Reference and Information Centre), UNEP (United Nations Environment Programme) and FAO merged together in mid-1995, when at a meeting in Rome the three major partners agreed to join the concerned resources and work towards a common world SOTER (SOil and TERrain) approach covering the globe at 1:5 M scale by the 17th World Congress of 2002 to be held in Thailand. The SOTER methodology is basically a conversion of existing soil maps and their associated information into digital data (VAN ENGELEN & HUTING 2004). SOTER mapping is similar to land systems or physiographic soil mapping but with stronger emphasis on the terrain-soil relationship. A SOTER unit represents a unique combination of terrain and soil characteristics. The methodology focuses on the identification of areas of land with a distinctive pattern of landform, lithology, surface form, slope, parent material and soil.

Since the start of the programme, other international organizations and institutions have shown support and collaborated to develop SOTER databases for specific regions. Table 2 shows the agencies involved in the activities for different regions in Africa. One can notice that SOTER databases of many regions have already been published, and this information has also been used to produce the Soil Map of Africa following the World Reference Base system: (http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/).

Table 2
Progress in SOTER databases in Africa

Region	Main agencies involved	Publ. date
Kenya (version 1)	KSS* – ISRIC	1995
North-Eastern Africa	FAO – IGAD**	1998
Southern Africa	FAO – ISRIC – national institutes	2003
Central Africa	FAO – ISRIC – UGent	2007
Kenya (version 2)	KSS – ISRIC	2007
Senegal	FAO – ISRIC (GLADA*** project)	2008
The Gambia	FAO – ISRIC (GLADA project)	2008
South Africa	FAO – ISRIC (GLADA project)	2008
Tunesia	FAO – ISRIC (GLADA project)	2008

* KSS: Kenya Soil Survey.
** IGAD: Intergovernmental Authority on Development in Eastern Africa.
*** GLADA: Global Assessment of Land Degradation and Improvement.

It should be noted that although the information is collected according to the same SOTER methodology, the specific level of information in each region results in a variable scale of the end products presented. The SOTER database for north-eastern Africa, for instance, contains information at equivalent scales between 1:1 M and 1:2 M, but the soil profile information is not fully georeferenced.

Recent literature reviews all identify important requests for data needed for sustainable development and impact assessments of land use and management on soil functioning (Carter 2002, Tzilivakis *et al.* 2005, Erkossa *et al.* 2007, Lal 2008, Northcliff 2009). This is urgently needed to combat land degradation and mitigate or adapt to climate change. Consequently, there is a great demand for information on rather dynamic soil properties responding to management.

3. African Soils at the Crossroads

African soils nowadays are really at the focus of a lot of international attention. With a very ambitious project (GlobalSoilMap.net), a group of internationally known soil scientists will produce a global digital soil map providing necessary information to solve major issues such as arresting soil degradation and improving soil fertility and food security (Sanchez *et al.* 2009). The project activities started on the sub-Saharan sub-continent with the launch of the Africa

Soil Information Service. Information on this project is provided on the following websites http://globalsoilmap.net/ and http://www.africasoils.net/, a must for those interested to follow the recent progress made.

The GlobalSoilMap.net project aims to provide a global soil information system consisting of the primary functional soil properties at a grid resolution of ninety by ninety metres within the next five years. The new digital soil map will be created using state-of-the-art and emerging technologies for soil mapping and predicting soil properties at fine resolution. The data and tools will be freely available, web-accessible, and widely distributed and used. The project is an initiative of the Digital Soil Mapping Working Group of the International Union of Soil Sciences (IUSS) and is led by academic and research centres in all continents. Designed around nodes in every continent, it allows for the exchange of information and dissemination of data, fostering the south-to-south and north-to-south technology exchange and testing.

The project took off in sub-Saharan Africa (SSA) in November 2008, after obtaining an $18 million grant from the Bill and Melinda Gates foundation and the Alliance for a Green Revolution in Africa (AGRA). The Africa Soil Information Service (AfSIS) is led by Pedro Sánchez of the Tropical Soil Biology and Fertility Institute (TSBF-CIAT). AfSIS will develop a practical, timely, cost-effective, soil health surveillance service to map soil conditions, set a baseline for monitoring changes, and provide options for improved soil and land management. This will be realized making full use of the latest advances in digital soil mapping, remote sensing, infrared spectroscopy and statistics (Sanchez *et al.* 2009).

One of the primary activities in the project is to set standards for soil data and evaluation criteria. Generally, previous soil survey efforts were not designed to cover large areas using statistical sampling criteria and randomization procedures, and are thus not representative of the overall condition of soils in SSA. To address these problems, the AfricaSoils.net project will conduct field surveys and establish soil health baselines in sixty sentinel sites covering a wide range of environmental conditions in SSA (fig. 3).

The establishment of sentinel sites and field survey locations is done using a spatially stratified random sampling approach, which will provide an unbiased sample of the sub-continent. Within each sentinel site, sixteen spatially stratified clusters of 100 ha are identified within which ten plots of 0.1 ha are randomly selected. These plots are further subdivided into four sub-plots of 0.01 ha that will be characterized by taking 0-20 cm composite soil samples. This hierarchical sampling strategy can be directly translated into a multilevel statistical framework that accounts for scale-specific spatial variation. In addition to the soil mapping and soil health surveillance efforts, the project will also develop a decision framework for soil and land management that will build on past experimental data, *i.e.* fertilizer response trials, integrated soil fertility management (ISFM) field trials and new ISFM experimental trials in selected sentinel sites.

Although the proposed approach has many advantages and avoids the limitations of traditional soil surveys, an important disadvantage is that characterization seems to be limited to the topsoil. The question is also whether the proposed approach is representative for all environments in SSA as there is not one sentinel site located in Central Africa.

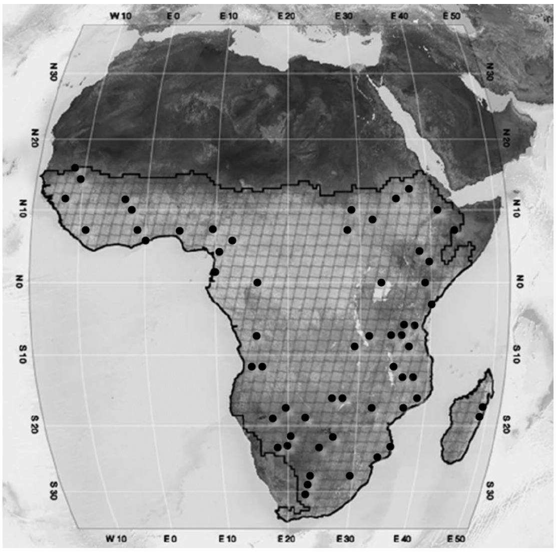

Fig. 3. — AfSIS study area and location of sentinel sites (http://www.africasoils.net/about/map.html).

4. Can We Offer the Information Needed to Maintain or Improve the Sustainability of the Central-African Soil Resources?

Until now, the major source of georeferenced soil data for Central Africa was the FAO soil map of the world at scale 1:5 M. More detailed natural resources information was not easily accessible, sometimes missing and often not in a standard format. However, since the production of the *Carte des Sols du Congo belge et du Ruanda-Urundi* in 1959, new soil information has become available at national level in each of these three countries. The ongoing checking of existing natural resources data of DR Congo and the recent finalization of a digital natural resources database for Rwanda enabled us to develop a scientifically sound Great Lakes Area SOTER database from the detailed, semi-detailed and reconnaissance soil maps and the abundant morphological and analytical soil profile data. During the design of the SOTER database of Central Africa, a physiographic map has been derived after analysis of SRTM satellite data of the region. Geological maps at different scales were translated into lithological maps. These thematic maps were combined to give the SOTER unit maps at scale 1:1 M for Rwanda and Burundi and at scale 1:2 M for the Democratic Republic of Congo, hereafter referred to as Central Africa (FAO/ISRIC/UGENT 2007). Much more additional information characterizing the non-mappable terrain and soil components has been selected, harmonized and inserted in a large relational database containing a wealth of descriptive and analytical soil profile data (Goyens *et al.* 2007). The diversity in input data is also reflected in the soil profile density of the SOTER database (tab. 3). The profile density in the DR Congo is somewhat too low for the scale of 1:2 M.

Table 3
Characteristics of the SOTER databases of Burundi, Rwanda and DR Congo

Country	Scale	# SOTER units	# Soil components	# Profiles	Profile density (per 1,000 km²)
Rwanda	1:1M	41	91	51	2
Burundi	1:1 M	56	187	20	0.7
DR Congo	1:2 M	147	322	96	0.04

#: number.

Little is known about the soil carbon stocks of Central Africa although such baseline data are needed for research and policy development on soil carbon changes. Despite the spatial, temporal and parameter gaps in the original databases, the SOTER database has been used to estimate the Central-African organic carbon stocks up to 1 m depth. Gaps in the measured soil analytical data were filled using consistent, taxonomy-based pedotransfer procedures. Natural variation in individual soil components was simulated to put bounds on regional-scale carbon stocks rather than a single figure (Batjes 2008). Considering the scale and quality of the original soil survey data, the produced organic carbon (O.C.) stocks' map has to be considered as a preliminary, rough estimate of the baseline stocks.

5. Can Traditional Soil Survey Databases Be Exploited More Optimally Using Digital Soil Mapping Tools?

As an example, the available digital soil inventory and three-dimensional digital terrain model of Rwanda allow to produce and to plot automatically digital thematic maps not only for traditional agricultural purposes, but also for settlement planning, disaster-preparedness planning, high-input agriculture, and so on.

Rwanda has a considerable diversity of soils, ranging from Andosols in the volcanic highlands, over Cambisols, Luvisols, Alisols and Acrisols in the subhumid, hilly western highlands, to strongly weathered Ferralsols in the semi-arid eastern lowlands. Socio-economic drivers within this largely rural region foster inappropriate land management, and threaten soil quality and food security. For the identification of sustainable land-use strategies, decision-makers need good soil baseline information. We have analysed the nationwide soil profile database, retained 1,463 soil profiles distributed across the country for statistical analysis, and determined to what extent independent site variables explain the recorded variation in topsoil (0-30 cm, mineral layer) organic carbon content (O.C.). A CHAID (Chi-squared Automatic Interaction Detector) classification tree analysis with cross validation retained altitude as the variable explaining most of the variation in O.C. content. In the low and middle altitude zones respectively, texture and population density were retained at the second level in the classification tree. In high altitude zones, the variation in O.C. content was affected by texture, slope gradient, as well as land use. Overall, this regression tree explained 53 % of the variation in O.C. A stepwise linear regression (tab. 4) involving all continuous variables, retained the altitude (alt), clay + fine silt content (cfs), and population density (pd), and explained 48 % of the variation in O.C. at national level with a mean absolute error of 1.6 %:

$$\ln(SOC) = -1.748 + 0.001 * alt + 0.015 * cfs - 0.001 * pd$$

Table 4

Stepwise linear regression model results with topsoil O.C. content as the dependent variable

Parameter	**Step**	**F stat**	**R^2**
altitude (alt)	1*	494.8	0.276
clay + fine silt (cfs)	2*	273.2	0.402
population density (pd)	3*	83.1	0.437

* Significant at 95 % confidence interval.

Altitude and clay + fine silt content were positively correlated to the O.C. content, population density was negatively correlated. The regression equation was used to draw a topsoil O.C. map of Rwanda (fig. 4).

In the future, a multilevel approach will be adopted to exploit differences in relative importance of the site variables within specific agro-ecological zones. The analysis provides insight in the O.C. pool present in the Rwandan topsoils and highlights challenges faced when characterizing the spatial distribution of O.C. in environmentally very diverse tropical regions with high population densities (Verdoodt *et al.* 2008).

As such, digital soil mapping, if supported by sufficient soil data collected in the field, has the capability to design much more consistent thematic maps, using a transparent and repeatable approach and providing more information on the accuracy of the presented data. Yet, the current demands for soil data are real challenges and among the soil formation factors, anthropogenic disturbance starts to play an increasingly important role, influencing the intensity of soil processes and as such, changing soil functioning.

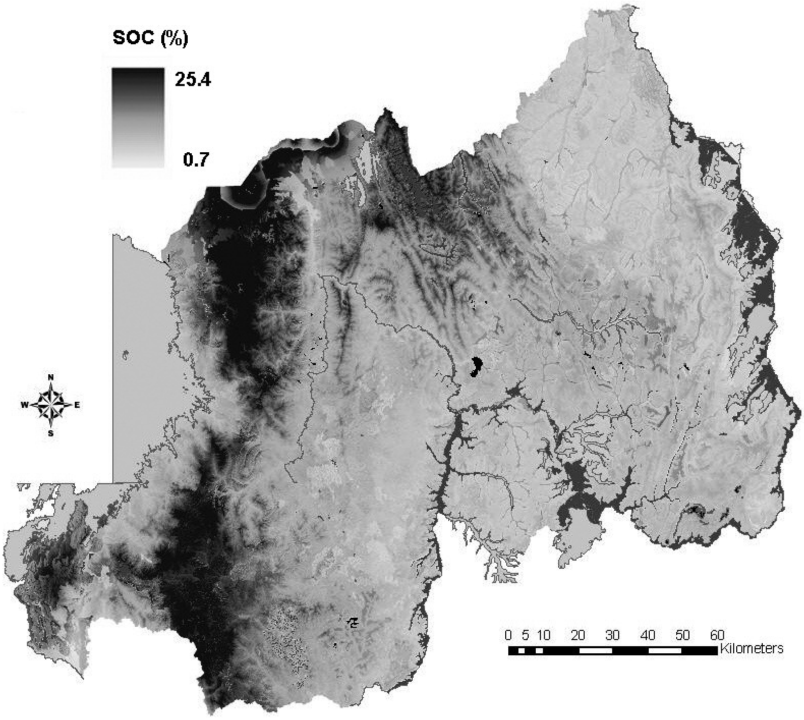

Fig. 4. — Estimated topsoil (0-30 cm) organic carbon content in Rwanda, using a linear regression equation based on altitude, clay + fine silt content and population density. The equation is not valid for the soils developing on volcanic soil material of the Birunga national park in the northeast.

6. Conclusions and Recommendations

The most important conclusions are:

— The status of many regional soil databases is still unsatisfactory given the relatively limited quantity of up-to-date and relevant dynamic soil properties.
— Soil maps can provide inputs to models predicting land-cover changes in response to climatic and human disturbances.
— New innovative techniques in soil survey will be very helpful in addressing main challenges of our time like food security, water scarcity, environmental degradation, *i.e.* there is nothing fundamentally wrong with the soil survey process or the products that have been delivered. The process should be cost-effective and economic, and the product more precise and accurate, less cumbersome for manipulations, and more amenable for use by a variety of disciplines.

Other important recommendations:

- Consolidate and integrate the soil information already available (store it in databases);
- Quality-controlled, georeferenced soil profile information collection should be vastly expanded;
- Problems of data access should be tackled by international political agreements;
- Be aware of current limitations;
- Logical, empirical and mathematical models must be adapted to available data and not the other way round;
- More resources should be made available for required field-based soil investigations to exploit fully the enormous progress made in computer technology.

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