Spatial soil information in South Africa: Situational analysis, limitations and challenges

AUTHORS:
Garry Paterson[1]
Dave Turner[1]
Liesl Wiese[1]
George van Zijl[2]
Cathy Clarke[3]
Johan van Tol[4]

AFFILIATIONS:
[1]Agricultural Research Council – Institute for Soil, Climate and Water, Pretoria, South Africa
[2]Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa
[3]Department of Soil Science, Stellenbosch University, Stellenbosch, South Africa
[4]Faculty of Science and Agriculture, University of Fort Hare, Alice, South Africa

CORRESPONDENCE TO:
Garry Paterson

EMAIL:
garry@arc.agric.za

POSTAL ADDRESS:
ARC – ISCW, Private Bag X79, Pretoria 0001, South Africa

DATES:
Received: 30 May 2014
Revised: 22 July 2014
Accepted: 14 Sep. 2014

KEYWORDS:
soil data; soil survey; digital soil mapping; natural resources; pedotransfer

HOW TO CITE:
Paterson G, Turner D, Wiese L, Van Zijl G, Clarke C, Van Tol J. Spatial soil information in South Africa: Situational analysis, limitations and challenges. S Afr J Sci. 2015;111(5/6), Art. #2014-0178, 7 pages. http://dx.doi.org/10.17159/sajs.2015/20140178

Soil information is vital for a range of purposes; however, soils vary greatly over short distances, making accurate soil data difficult to obtain. Soil surveys were first carried out in the 1920s, and the first national soil map was produced in 1940. Several regional studies were done in the 1960s, with the national Land Type Survey completed in 2002. Subsequently, the transfer of soil data to digital format has allowed a wide range of interpretations, but many data are still not freely available as they are held by a number of different bodies. The need for soil data is rapidly expanding to a range of fields, including health, food security, hydrological modelling and climate change. Fortunately, advances have been made in fields such as digital soil mapping, which enables the soil surveyors to address the need. The South African Soil Science fraternity will have to adapt to the changing environment in order to comply with the growing demands for data. At a recent Soil Information Workshop, soil scientists from government, academia and industry met to concentrate efforts in meeting the current and future soil data needs. The priorities identified included: interdisciplinary collaboration; expansion of the current national soil database with advanced data acquisition, manipulation, interpretation and countrywide dissemination facilities; and policy and human capital development in newly emerging soil science and environmental fields. It is hoped that soil information can play a critical role in the establishment of a national Natural Agricultural Information System.

Introduction

Information about the distribution of the natural resources of a country is vital for a wide range of purposes, including local and regional planning, economic forecasting, food security and environmental protection. The most critical of natural resources, in terms of agricultural production, are terrain, climate and soil.

Information on terrain can easily be obtained from topo-cadastral maps, digital elevation models and other survey information. Climate information is readily accessible from sources such as the Agroclimatology Programme at the Agricultural Research Council's Institute for Soil, Climate and Water (ARC–ISCW) and the South African Weather Service. Direct assessment from near-real-time weather station data and increasing applications from modelled climate surfaces at increasing levels of detail have enabled extrapolations in time and space to be made as required. Soil information, on the other hand, is more difficult to obtain, especially at more refined levels of detail. Substantial financial investment is often necessary to obtain soil data because soils and their properties, and consequently their potential and limitations, change very substantially over short distances, and the skills and expertise necessary to accurately record, measure and map such changes are time and labour extensive.

The situation is likely to become more critical in the foreseeable future, with the continually increasing population of South Africa requiring more food, fibre and energy to be produced, against the background of potentially changing climate patterns across the country and the wider southern African region.

Accurate soil information forms an essential component of environmental baseline characterisation for any country. In this review, we provide an historical background leading to the current state of soil information in South Africa, highlight the soil information requirements of the country and outline a way forward in terms of data capture, storage and interpretation using recent technological advances.

Historical perspective

The first actions concerned with obtaining spatial soil information in South Africa were carried out by the Department of Agriculture, through the then Division of Chemistry, in the 1920s, although the first recorded soil investigation was undertaken as early as 1899.[1] Subsequently, a series of soil surveys was carried out, including areas along rivers where large dams were constructed, mainly to allow cultivation under irrigation in some of the drier parts of the South African interior. As a consequence, the information contained on these early maps is mainly concerned with a very superficial description of the soils, coupled with an irrigation suitability class, sometimes refined with a qualification such as presence of gravel or 'brak' (salts) within the soil profile. Although these surveys were usually extremely detailed in scale (often at 1:5000 to 1:7500), and were often confined to narrow strips on either side of the rivers concerned, they retain some present-day value.

The first steps in the recording of information about soils in South Africa on a wider scale were taken in the late 1930s, culminating in the publication *Soils of South Africa* by CR van der Merwe[2], who attempted to gather all existing knowledge, both first-hand and assumed, so that a national soil pattern map, at a very small scale (approximately 1:2 500 000) was produced.

With this first attempt as a starting point, the expansion and increasing mechanisation and modernisation of agriculture in South Africa during the 1950s began to recognise the need for increasing knowledge about the soils across the more productive zones of the country. The expanding sugar industry in the then Natal Province commissioned soil surveys[3] to characterise and map the distribution of soils along the southeastern seaboard, mainly in terms of their suitability for cultivation with sugarcane. Beater's[3] soil descriptions embraced the concept of 'natural soil bodies'. Shortly thereafter, a second large survey[4] was carried out in Natal, namely the *Soils of* *the Tugela Basin*, in which a wider range of soils, occurring on various parent materials, was studied. The Tugela Basin study deviated from the concepts of soil series as a natural soil body by providing the first concepts of locally based soil classes that were accommodated within a formal hierarchical soil classification system. These classes would eventually become the soil series and forms of the first edition of the South African soil classification system.[5]

At the same time, a wide range of other surveys, mainly for irrigation suitability, but also including a range of selected 1:50 000 map sheets, had been carried out by the Soil and Irrigation Research Institute, further improving and expanding the soil knowledge base of South Africa. The state of spatial soil knowledge, the various scales of surveys and the possibilities and limitations thereof, were summarised for the Silver Jubilee Congress of the Soil Science Society of South Africa in 1978.[6] In addition, a range of studies in different geographical areas was carried out to help quantify the soils occurring, and by implication, naturally occurring soil bodies. These studies included the previous Transvaal[7], Free State[8] and Karoo[9] Agricultural Regions, as well as an extensive series of surveys of the former homeland areas carried out by private consultants, such as Loxton, Venn and Associates.

However, despite the increasing body of knowledge, mainly of soils occurring, there was still limited information concerning the soil properties and their distribution within many areas of South Africa. Certain regions of the country, as well as certain soil types, still remained only vaguely surveyed, so a decision was taken to initiate a countrywide soil survey that would remedy this situation.

Land Type Survey

In the early 1970s, the national Land Type Survey[10] commenced in South Africa. This huge undertaking was based on a field survey, using 1:50 000 topo-cadastral sheets as base maps, but with the aim of publishing the finished maps at 1:250 000 scale. A *land type* mapping unit, the basis of the survey, was defined as ‘a homogeneous, unique combination of terrain type, soil pattern and macroclimate zone’ and when the survey was completed around 30 years after its commencement, about 7070 such zones, based on some 400 000 soil observations (equivalent to approximately 1 observation per 300 ha) had been defined. The greatest advantage of the Land Type Survey was the fact that every part of the country, from the highly productive Highveld to the driest parts of the Northern Cape and the mountains of the Drakensberg, had been visited. Furthermore, a supporting database of around 2500 modal soil profiles, as well as a further 10 000 series identification samples (designed to confirm field soil diagnosis) had been created, providing quantitative data about a range of soil properties across the greater part of South Africa. As the field investigation phase of the Land Type Survey progressed, it also led to further advancements in soil classification, culminating in the publication of the second edition of the South African soil classification system.[11] The products of the Land Type Survey were initially a series of 1:250 000 scale overlay maps, printed by the Government Printer using the standard topo-cadastral map sheet framework. Each map sheet, or combination of one or more adjoining map sheets, was accompanied by a printed memoir book, which provided information on all the land types, climate zones and modal soil profiles occurring on that map (or maps).

As the Land Type Survey progressed, the information that was provided enabled several of the agricultural regions to establish systems to help with their environmental inventory and to contribute to improving agricultural production. These regions included the Highveld Region[12] and Natal Region[13].

The soil information system into the digital age

With the advent of digital computing in the early 1990s, soil maps could be digitised and the accompanying legend, text and analytical information stored digitally. Interpretation technology has advanced so that the manual processes of map interpretation have been replaced with the development of geographic information systems technology. This advancement has led to the establishment of the Soil Information System housed at ARC–ISCW. Land type field sheets were digitised and edge matched to produce a continuous coverage for South Africa. Land Type soil inventories have been fully captured in electronic formats, together with an extensive complement of soil profile descriptions and soil analyses. Additional soil map information from a variety of detailed surveys has either been digitised or image-scanned for electronic archiving. Elementary search applications for metadata have been established and a prototype data capture and soil data transfer application developed.

A limited number of soil information interpretation routines were added to the Soil Information System. Examples include:

- The soil profile information collected during the Land Type Survey has been supplemented by other descriptive and analytical data from a variety of sources[14], including soil profile analyses collected during irrigation assessment surveys, a range of ad-hoc soil investigations and two major projects commissioned by the Department of Agriculture[15,16] designed to improve the geographical distribution of soil profile data in South Africa.
- Two regional soil mapping projects at 1:50 000 scale have also been converted to electronic format, namely the Pretoria-Witwatersrand-Vereeniging peri-urban survey[17] and the Western Cape Metropolitan survey[18].
- A range of paper soil maps produced since the early years of the 20th century has been scanned and geo-referenced (but not digitised), in an effort to preserve and make available the information for future generations.
- A database of over 1500 profiles from rehabilitated soils on open-cast coal mines was established as part of a project[19] to study the effects of mining on the valuable agricultural soil resources of the Highveld.

From the 1960s until the late 1990s, the major focus was towards recording and mapping the distribution of soils and their functions. Soil profile descriptions and analyses were collected, representing point information of soil properties at site-specific locations. However, while classification classes provide generalised information on soil properties, concepts of soil property information are generally lacking. Beater[20] used the soil series concept to focus on soil property information. Generalised soil property information was developed for selected sandy soils of the North West Province[21], for textural soil properties of KwaZulu-Natal and Mpumalanga[14], and generally for the KwaZulu-Natal Coastal Belt. Future research should focus on developing innovative soil property information to complement traditional soil survey information that will become essential for future information system applications.

Applications include assessing the land capability of South Africa[22], as well as mapping chemical properties of South African soils, such as organic carbon[23], pH and heavy metals[24]. Recently, various land suitability assessments[25,26] have added to soil interpretation options. The KwaZulu-Natal Department of Agriculture and Environment has developed the BioResources Information System[13] for that province that has a strong fundamental basis in terrain, soil and climate natural resources. Other soil information systems that are operated within the forestry industry, by agricultural cooperatives and private companies, are reported to contain large volumes of soil information. These information systems do not lie in the public domain, so this information is not readily available to the general public. Mechanisms to overcome intellectual property rights so that this information can be accessed could be of mutual benefit to future land users.

There is now much scope for additional map and soil analysis capture operations. In a digital soil information age, a vast array of applications incorporating and developing soil information, together with complementary natural resource information, can be envisaged. In this paper, we set the scene for these developments in examining opportunities and suggesting frameworks where these may now become real possibilities.

The current state of soil knowledge

At a Soil Information Workshop held at Stellenbosch in February 2014, in which the participants included researchers, academics, government officials, private consultants and industry representatives, the participants produced a resolution calling for improved availability of soil data and better interaction between role players, data users and decision-makers. The call was made for a national task force on soils information, representing the interests of various government departments, industry, the research community and land users/managers to convene regularly to develop new strategies and policy for soil information collection, storage and dissemination:

- to identify current and future soil information requirements at all spheres of government, within industry, the research community and land users and managers,
- to identify soil information gaps and opportunities for further research and collaboration,
- to prioritise activities on soil data and information depending on user needs, and
- to determine impact pathways for realising the required resources.

We further discuss the current situation with regard to these resolution points in the remainder of this paper.

Soil information requirements

There is a well-known saying, 'Knowledge is power'. While the benefits of increased knowledge may not be related to physical or political power, the increased spread and detail of soil information will have substantial benefits over a wide range of disciplines and development opportunities. In the area of future planning for agricultural production and food security in South Africa, one of the larger challenges is the threat of changing climate patterns, which may lead to altered levels of agricultural suitability under natural climate conditions. If various possible scenarios are considered and compared, the spatial distribution of soil types within any area, which can be coupled to crop production and eventually to yield, will help to quantify these possible scenarios, so that informed decisions can be taken.

Virtually every organ of state, as well as parastatal bodies, will benefit from soil information. For example, the Integrated Energy Policy that the Department of Energy is formulating has an agricultural sub-committee tasked with estimating present and future energy demand within the agricultural sector. Accurate, detailed soil information will enable a much better assessment of where soils that are able to be cultivated are located. From there, the approximate number of tractors and other implements, along with the fuel necessary to power them, can be determined.

The area of health is also related to soils. New and existing diseases related to human or livestock health are encountered, and the study of their distribution involves a range of potential factors, one of which may be soil type, usually as a potential host to organisms. Planning of virtually all types of infrastructure will benefit from soil information, whether it refers to high potential soils that should preferably not be disturbed, or swelling vertic clays that will pose a serious building hazard. The amount of knowledge, as well as the level of detail, about soils occurring, will make a difference to almost all decisions that are taken.

In light of the ever-increasing pressures on the high potential soils in South Africa, the Department of Agriculture, Forestry and Fisheries, with assistance from ARC, has prepared a draft policy for the *Protection and Development of Agricultural Land Framework Act* (PDALFA). For it to have maximum relevance, the Bill, when enacted into legislation, will require high levels of detail of soil information across large portions of South Africa. These levels of soil information are currently lacking and must be developed through existing detailed and semi-detailed information sources, and through future soil modelling technology and advanced new data capture operations. Digital soil evaluation technology offers considerable potential in this regard.

The national and international demand for data on soil organic carbon (SOC) distribution, existing stocks and potential changes is rapidly increasing as a result of the crucial role of SOC in soil fertility, food security, nutrient and water retention, biodiversity and ecosystem services. In addition, soil represents the largest store of terrestrial organic carbon, indicating that SOC could also contribute to climate change mitigation.[27] To improve decision-making towards improved soil management and a reduction in soil degradation, sufficiently detailed quantitative data sets and methodologies that enable spatial and temporal quantification of SOC levels and dynamics in soils, are required. Knowledge of the effect of changes in land use on SOC is vital to maintain the critical balance in carbon stocks.

Several global and regional initiatives are now aimed at increasing the level of soil carbon data and information available to support the harmonisation of methods, measurements and indicators for sustainable soil carbon management. At global level, these include the Global Soil Partnership, established under the custodianship of the Food and Agriculture Organization of the United Nations and the Global Soil Map.[28] At regional level, the Africa Soil Information Service (AfSIS) aims to develop continent-wide digital soil maps for sub-Saharan Africa using new types of soil analyses and statistical methods.[29] In addition, South Africa is a signatory to both the United Nations Convention to Combat Desertification[30] and the United Nations Framework Convention on Climate Change[31], under which we are obliged to report on various indicators, including changes in soil carbon. Updated national level SOC maps must therefore urgently be developed and regularly updated to contribute to existing soil carbon mapping initiatives, as well as to comply with international reporting obligations.

Soil information is important in hydrological modelling because soils act as a first-order control on the partitioning of hydrological flow paths, residence time distributions and water storage.[32,33] Soils play a major role in catchment hydrology by facilitating infiltration, controlling overland flow, redistributing water through the root zone, storing water for evapotranspiration and recharging groundwater aquifers.[34] Water is a primary agent in soil genesis, resulting in the development of soil properties containing unique signatures of the way they were formed. Interpretation of soil properties can therefore serve as an indicator of the dominant hydrological processes[35,36] and assist in the structuring and configuration of hydrological models.[37]

Hydrologists agree that soil properties and their spatial variation should be captured in hydrological models for accurate water quantity and quality predictions and estimation of the hydrologic sensitivity of the land to change[38,39], but they generally lack the skill to gather and interpret soil information[40,41]. New generation soil information could alter this perception. Soil inputs in hydrological models vary greatly between different models, but typically include water retention characteristics, hydraulic conductivities, storage ability (depth and porosity) and infiltration rates. In distributed models, the spatial distribution of these parameters is essential to ensure the efficiency of hydrological simulations. The soil hydrological parameters are often indirectly determined using pedotransfer functions. These functions exploit mathematical relations between easily measured properties, e.g. texture, and properties that are tedious and expensive to measure, e.g. water retention curves.

Soil information gaps

South African soil science has been well served through the first and second editions of the South African classification system.[5,11] The state of available soil knowledge has been excellently summarised in a recent publication[42] which combines information from the Land Type Survey with other existing knowledge to look at the distribution and properties of the major soil groups in South Africa. Discussions towards a revision of the classification system[43] including potential adaptation to the nature of diagnostic soil horizons and the structure and content of the classification system[44,45] are proceeding. The discipline now has the important advantage of access to numerous known soil profile locations, profile descriptions and analyses that, together with tacit knowledge, will certainly aid in the formulation of hypotheses.

However, despite the large volume of available knowledge on the soils occurring within South Africa, there is almost as much untapped information from commercial and semi-commercial sources that is not freely available. Information from academic sources, although in the public domain, has generally not been incorporated into comprehensive soil information systems. These sources include:

- Agricultural support organisations, such as cooperatives, fertiliser and seed companies for which thousands of hectares of detailed soil surveys have been carried out for (mainly) commercial farmers. Much of this information has been interpreted for general or crop-specific suitability, including yield determinations.
- Commercial forestry companies, which have likewise carried out extensive soil surveys in specific areas, mainly to establish suitability for establishing forestry plantations.
- Mining companies that extract mainly coal, platinum and other heavy metals, for which the legal requirements for any potential mining activity include an environmental impact assessment, which must include a soil survey.
- Various governmental departments, both at national and provincial level. This data source applies mainly to soil surveys carried out in the pre-digital age. The storage and preservation of this information was not always effectively done, and was further adversely affected by the major changes within many government departments during the 1990s.
- Academic institutions such as universities and colleges, which could have produced spatial soil data, either in map or profile form. The same problems exist here as for some of the governmental departments. For example, we are aware of instances in which, through ignorance, valuable soil maps have been mislaid or destroyed to the detriment of the soil science discipline.
- Many and varied soil investigations have been carried out for a variety of purposes, including for agricultural potential determinations prior to construction of transport, power, residential or supply infrastructure. These maps are generally not kept in a central archive and are very difficult to trace.

The amount of soil information listed above is vast. For example, from the Land Cover database[46] it has been estimated that an area of approximately 6.62 million ha is under some form of cultivation in the three largest maize producing provinces of South Africa – the Free State, North West and Mpumalanga. This cultivation covers 5.4% of the land area of the country. If one takes a conservative estimate that half of this area might have some sort of detailed soil survey information available, that still equates to over 3 million ha. In addition, there is an estimated 1.96 million ha (1.6% of the land area) of commercial forestry plantations in South Africa[46] and it is reasonable to assume that at least 80% or more of this area will have been surveyed at some point by the forestry companies concerned.

Regarding the coal mining industry, it is a well-known, if unfortunate, fact that a large portion of the coal resources of South Africa lie under extremely productive agricultural soils on the Mpumalanga Highveld. Figures concerning the areas that have been, or are planned to be, affected by coal extraction are difficult to obtain, but a map provided by the Mpumalanga Provincial Department of Agriculture, Rural Development and Land Administration shows the widespread distribution of farms for which mining rights exist, and it is comfortably more than 75% of the arable portion of the province.

Reasons for the unavailability of soil data are varied. Mostly they concern the commercial nature of the data, the fact that it has been paid for by the landowner concerned, as well as a perceived fear that state authorities will misuse any such data to expropriate commercial farmland. While the right of private individuals to protect information needs to be understood and respected, the fact remains that any reasonably competent soil scientist will be able to use the existing available land type data, along with freely available ancillary remote sensing background information such as satellite imagery and even Google Earth. From these sources, a very plausible assessment of the areas cultivated on any particular farm can be made, and a very good indication can be derived of the soils occurring, and consequently, of the general potential of the farm.

ARC–ISCW embarked on a project to collect existing soil maps from provinces known to have soil maps and information. It is expected that much (although not all) of the provincial soil information has been archived. Certain private institutions and persons were also willing to provide soil information that has also been archived. However, soil information in numerous university theses and reports, while in the public domain, remains isolated from a central information system. The solution probably lies in the creation of efficient technology applications to directly capture and evaluate the quality of these essentially new data sources and here, cell phone and GPRS (general packet radio service) technology could prove effective. The Natural Resources Council of the UK has recently launched the *mySoil* smartphone application which allows users to download soil maps of the UK as well as upload photographs and basic soil descriptions at their location. In doing so, a database of basic soil information is being created across the UK and parts of Europe.[47]

Soil survey information held by agricultural cooperatives, private soil consultants, forestry companies and mines is subject to limitations on intellectual property rights. Innovative ways to archive these data such that they are accessible to both the private and public sectors must be established. Lastly, efficient web-based platforms to capture new soil information from public and private sources, and a culture to contribute to a recognised natural resources information system, must be strongly encouraged.

Advanced technologies for data collection and interpretation

Digital soil mapping

The explosion of new advances in the fields of information technology, satellite imagery, digital elevation models and geostatistics has enabled the establishment of various new soil survey techniques, which today is collectively known as digital soil mapping (DSM). The concept of DSM emerged in the 1970s and accelerated in the 1980s. Today, research on different DSM technologies is converging and reaching a stage at which operational systems are being implemented.[28] The industrious Global Digital Soil Map[28] project best showcases the theoretical potential of DSM. The aim of this project is to use both legacy and specifically collected soil data to create a soil map of the world's soil properties to a depth of 1 m and at a resolution of 90 m.[48] Digital soil mapping produces predictions of soil classes or continuous soil properties in a raster format at various resolutions.[49]

The foundation on which DSM rests is that soils are not distributed randomly in the landscape, but are rather the product of the environment in which they are formed.[50] If one could therefore decipher the soil–environment relationship, one could begin to predict the soil distribution from the environmental factors, which may be easier to measure than soil itself. Equation 1 shows this relationship mathematically:

$$S = f(E), \qquad \text{Equation 1}$$

where S is the soil class or property to be mapped, f is the relationship between S and E and E is the environmental factors used to map S.

McBratney et al.[51] formalised Equation 1 in the Scorpan approach as:

$$S = f\,(s, c, o, r, p, a, n), \qquad \text{Equation 2}$$

where S is the soil class or property to be mapped, s is the soil, or other properties of soil at a point, c is the climate or climatic properties at a point, o is the organisms, such as vegetation, fauna or human activity at a point, r is the relief, topography and landscape attributes, p is the parent material, a is the age, the time factor, and n is the spatial variability.

To create a digital soil map, one requires sufficient soil (point data, soil map, land type inventory) and environmental (digital elevation models, satellite images, geological map) information to decipher the soil–environment relationship.

Theoretically, with the current amount of data (soil and environmental) already in the public domain, we can potentially create very good baseline soil maps for the entire country. ISRIC created soil class and property maps for sub-Saharan Africa at a 1-km resolution using around 12 000 observation points.[52] However, the accuracy achieved was low, between 18% and 45% for different soil properties. Using all the already available data, we should be able to improve on this map for South Africa. New data (both newly acquired legacy data and newly collected data) added to the database are necessary to periodically update and improve the baseline soil maps. The spatial estimation of error which is associated with DSM-produced maps will easily identify areas where focused projects can be launched to improve specific areas of the maps. A local DSM challenge which soil scientists in South Africa face is the often unreliable soil–landscape relationships as a result of the added complexity of ancient landscapes. Overcoming this challenge calls for the development of site-specific DSM methods which can be used with a degree of confidence.

Unfortunately, DSM in South Africa is still in the developmental stage, with few researchers and little or no commercial work being done in the field. At ARC-ISCW, two studies[53,54] have used remote sensing and the land type soil profile database to produce soil maps for areas of KwaZulu-Natal. Van Zijl et al.[55] disaggregated two land type inventories into soil association maps, also in KwaZulu-Natal. In the Free State, Zerizghy et al.[56] used expert knowledge-based DSM techniques to delineate land suitable for rainwater harvesting. Van Zijl and Le Roux[57] also used an expert knowledge approach to create a hydrological soil map in the Kruger National Park. Both Stalz[58] and Mashimbye et al.[59] mapped salt-affected soils using remote sensing. Van Zijl[60] developed a digital soil mapping protocol for large areas (1000 – 50 000 ha) with no soils data. For the soil survey fraternity in South Africa to fulfill the growing need for spatial soil data, there must be a thrust to create the human capacity with regard to DSM. This thrust may potentially be realised through projects to implement the PDALFA concepts and legislative demands.

Spectroscopic soil analysis

Traditional soil analysis is a costly and time-consuming exercise, which often limits the density of observations made as well as the number of properties that can be measured for a specific site. Near-infrared (NIR) and mid-infrared (MIR) spectroscopy is gaining popularity as a tool for soil analysis because of the ease and speed with which data can be collected both in the field and in the laboratory.[61] A recent review[62] has shown that NIR analysis can be reliably used to measure a number of soil properties, especially soil organic matter, mineralogy, texture and water content. Cation exchange capacity, nutrient content, soil colour and pH have also been measured using NIR analysis.[63-65] In Australia, NIR spectroscopy has been used to discriminate among soils of different classification orders.[66]

In South Africa, NIR spectroscopy has been used for many years in the sugarcane industry to measure soil characteristics such as texture, SOM and nitrogen[67] and to supply the data-hungry requirements of precision agriculture.[68] The Soil Fertility and Analytical Services laboratories of the KwaZulu-Natal Department of Agriculture and Environmental Affairs have set up confident MIR calibrations for organic carbon, total nitrogen and clay content, while calibrations for extractable acidity, acid saturation, pH and extractable calcium and magnesium are used for quality-control purposes.[69] Despite these localised uses, research into infrared techniques in South Africa is lagging far behind the international surge in soil spectroscopic research. Recently, handheld and portable NIR spectrometers have come onto the market and allow in-situ soil measurements. The ability to conduct in-field analyses significantly increases the spatial resolution of soil information that can be captured. With the increasing need for soil information, particularly soil carbon data, NIR spectroscopy may provide a cost-effective tool for obtaining soil information. Collaborative research efforts are required to build up soil spectral libraries for South African soils. The sample collection with associated laboratory analyses at ARC–ISCW may serve as the ideal starting point to standardise NIR measurements against traditional chemical analyses.

Natural resource information system

Using the national Land Type Survey and Agroclimatology databases as a starting point, ARC–ISCW offers a unique information source, which can supply data to increase the knowledge base on natural resources in South Africa. Such a database is a critical step towards assessing, and therefore protecting, our natural resources. However, with much information not available because of the reasons given previously, there will always be the potential to improve this information system by incorporating other data (even if some restrictions might be placed on its use in certain situations) to make the system as comprehensive as possible.

There are three groups of potential soil data which could be used to help with the establishment of a national soil database.

The first group is the already available data collected with public money. The bulk of these data lie with the ISCW and form an excellent basis for a national database. Other sources of this first group of data are the National and Provincial Departments of Agriculture and universities. Most of the soil data which these entities possess was collected with public money and an additional effort should be made to gather this information into the national database.

The second group of soil data which can be included into the database is the data held by private entities. These entities include agricultural cooperatives, soil consultancies, mines and forestry companies which have done soil surveys. It is trickier to include these data into the national database, as there are client confidentiality clauses and intellectual rights which currently prohibit the sharing of most of the data. Methods should be explored to gain access to such data which benefits all parties involved.

Lastly, there is data which are still to be collected. Private and public entities within the soil science field should be asked to contribute to the national soil database. All data collected for public entities and as much data as possible, within legal limits, collected for private entities, should be included. Innovative means, such as the soil application (‘app’) mentioned previously, should be used when possible. During an informal survey conducted at the recent Soil Information Workshop, all the respondents said they would use such an app if it was available. Other means of collecting data could include an online platform onto which data could be submitted and some form of incentive for data added, such as acknowledgement in a manner similar to the way that scientific articles are acknowledged.

Regarding the data recorded, a set of minimum criteria (including at least a soil classification, a location and some sort of analytical data) would need to be established, and different levels of data, depending on completeness and comprehensiveness, could be defined, so that users could obtain information about data confidence.

Impact pathways

Soil scientists will need to take the following actions to fulfill the growing need for soils data:

- Make an effort to regularly interact with other disciplines from a vast array of fields, to be able to assess the need for soils data in these fields.
- Create pathways which allow free sharing of soils data and the creation of a national soils database.
- Develop human capital in emerging soil fields such as digital soil mapping and spectroscopic soil analysis, so that soils data can effectively be turned into functional spatial soil information which fulfills the emerging soil data needs.

Conclusions

The considerable investment and existing development of the ARC–ISCW Soil and AgroClimate Information Systems provides the obvious framework for the operation of nationwide natural resource systems. These systems must become readily accessible to the South

African public and be recognised by government and the private sector as the authoritative information hub. The challenges faced in creating a new generation 'Natural Agricultural Resources Information System' are numerous and emerge from the full spectrum of disciplines in society. The challenges begin with the need for recognition of the future central role to be played by the Natural Agricultural Resources Information System towards food security, environmental sustainability and ultimately the nation's social well-being. At the technological level, the challenges begin with recognition, branding and association of the information system to an institution of scientific integrity held responsible for its creation and maintenance. The ARC–ISCW is the obvious choice as the institution to house this repository, because of its distinguished record of scientific work over more than a century of its existence.

Other technological challenges remain, mainly in further developing data capture, dissemination and model interpretation methodologies. These must be addressed through the acquisition and training of skilled scientific human capacity that is now urgently necessary to sustain the new generation of natural agricultural resource information demands. A positive approach must be devised towards structuring legal solutions to the challenging issues of intellectual property that will arise from collectively merging information residing in the public and private domains.

These issues, coupled to a substantial paradigm shift in funding models, could see the reality of a publically accepted and advanced functioning national Natural Agricultural Resource Information System for South Africa. The question remains: will there be sufficient moral fibre shown by scientists, decision-makers in the public and private sectors and politicians to structure new and innovative advances to meet these challenges for the benefit of the public at large? We believe that, with a concerted effort, the research visions described in this paper are desirable and attainable.

Acknowledgements

We thank the Mondi Wetland Programme for funding this research and Dr Boyd Escott (Ezemvelo KZN Wildlife) and the Agricultural Research Council: Institute for Soil, Climate and Water for providing spatial data relating to wetlands in KwaZulu-Natal.

Authors' contributions

G.P. produced the concept article and collated all contributions; D.T. made contributions regarding soil information systems; L.W. made contributions regarding soil carbon; G.v.Z. made contributions regarding spectroscopic soil analysis; C.C. made contributions regarding soil information; and J.v.T. made contributions regarding digital soil mapping.

References

1. De Villiers MC. Centenary report of the ARC-Institute for Soil, Climate and Water (1902-2002). Pretoria: ARC-Institute for Soil, Climate and Water; 2002.
2. Van der Merwe CR. Soil groups and sub-groups of South Africa. Science Bulletin 231. Pretoria: Department of Agriculture and Forestry; 1940.
3. Beater BE. Soils of the Sugar Belt, Part 1: Natal North Coast. Cape Town: Oxford University Press; 1957.
4. Van der Eyk JJ, MacVicar CN, De Villiers JM. Soils of the Tugela Basin. A study in subtropical Africa. Volume 15. Pietermaritzburg: Natal Town and Planning Regional Commission; 1969.
5. MacVicar CN, De Villiers JM, Loxton RF, Verster E, Lambrechts JJN, Merryweather FR, et al. Soil classification – A binomial system for South Africa. Pretoria: Department of Agricultural Technical Services; 1977.
6. Loxton RF, Thompson JG. Advances in soil science in Southern Africa 1953–1978: Soil survey and land use. In: Proceedings of the 8th Congress of SSSSA; 1978 July 11–14; Pietermaritzburg, South Africa. Technical Communication 165. Pretoria: Department of Agricultural Technical Services; 1980.
7. Verster E. Die gronde van die Transvaalstreek [The soils of the Transvaal region] [PhD thesis]. Bloemfontein: University of the Orange Free State; 1974. Afrikaans.
8. Eloff JF. Die grondhulpbronne van die Vrystaatstreek [The soil resources of the Free State region] [PhD thesis]. Stellenbosch: Stellenbosch University; 1984. Afrikaans.
9. Ellis F. Die gronde van die Karoo [The soils of the Karoo] [PhD thesis]. Stellenbosch: Stellenbosch University; 1984. Afrikaans.
10. Land Type Survey staff. 1:250 000 scale Land Type Survey of South Africa. Pretoria: ARC Institute for Soil, Climate and Water; 1972–2002.
11. Soil Classification Working Group. Soil classification – A taxonomic system for South Africa. Memoirs on the South African Natural Resources No. 15. Pretoria: ARC Institute for Soil, Climate and Water; 1991.
12. Ludick BP, Joubert J. An evaluation of the agricultural potential of the magisterial districts in the Highveld Region in terms of dryland cropping and livestock production. Technical Communication No. 203. Pretoria: Department of Agriculture and Water Supply; 1986.
13. Camp KGT. The bioresource units of KwaZulu-Natal. Cedara Report N/A/95/32. Pietermaritzburg: KZN Department of Agriculture; 1995.
14. Turner DP. Soils of KwaZulu-Natal and Mpumalanga [PhD thesis]. Pretoria: University of Pretoria; 2000.
15. Jacobs EO, Schoeman JL, Potgieter LJC, Nell JP, Oosthuizen AB, Smith HJC, et al. An agricultural resource fixed site monitoring system for South Africa: Soils (DAFF Project No: 21.1.1/07LUSM-10/ISCW). ARC-ISCW Report No. GW/A/2010/01. Pretoria: ARC Institute for Soil, Climate and Water; 2010.
16. Paterson DG, Jacobs EO, Van der Walt M. Soil point data collection project (report for DAFF). ARC-ISCW Report No. GW/A/2012/18. Pretoria: ARC Institute for Soil, Climate and Water; 2012.
17. Yager TU, Kaempffer LC, Coetzee CJ. 1:50 000 scale PWV peri-urban soil map. Pretoria: ARC Institute for Soil, Climate and Water; 1990.
18. Jacobs EO, Oosthuizen AB, Stehr BI. Soils of the Cape Metropolitan area. ARC-ISCW Report No. GW/A/99/83. Pretoria: ARC Institute for Soil, Climate and Water; 1999.
19. Nell JP, Steenekamp PI. Final report: Establishing a soil profile database for rehabilitated opencast coal mined land. ARC-ISCW Report No. GW/A/98/78. Pretoria: ARC Institute for Soil, Climate and Water; 1998.
20. Beater BE. Soil series of the Natal Sugar Belt. Durban: South African Sugar Association; 1970.
21. Schoeman JL. Natural soil bodies of the Lichtenburg, Bothaville, Viljoenskroon and Wesselsbron areas and estimates of their water-holding characteristics as derived from land type data. Technical Communication No. 129. Pretoria: Department of Agriculture and Water Supply; 1989.
22. Schoeman JL, Van der Walt M, Monnik KA, Thackrah A, Malherbe J, Le Roux RE. Development and application of a land capability classification system for South Africa. ARC-ISCW Report GW/A/2000/57. Pretoria: ARC Institute for Soil, Climate and Water; 2002.
23. Stronkhorst LD, Venter A. Investigating the soil organic carbon status in South African soils and the relationship between soil organic carbon and other soil chemical properties. ARC-ISCW Report No. GW/A/2008/24. Pretoria: ARC Institute for Soil, Climate and Water; 2008.
24. Herselman JE, Steyn CE. Predicted concentration of trace elements in South African soils. ARC-ISCW Report No. GW/A/2001/14. Pretoria: ARC Institute for Soil, Climate and Water; 2001.
25. Schoeman JL, Carstens JP, Van der Walt M. DRDLR-ARC Horticultural project: Establishment of fruit and vegetable enterprises and development of mini- and macro-agriparks in different provinces of South Africa. ARC-ISCW Report GW/A/2013/17. Pretoria: ARC Institute for Soil, Climate and Water; 2013.
26. Turner DP, Chirima JG, Paterson DG, Carstens JP, Seabi FT, Mushia N, et al. Integrated food and nutrition security initiative: Mapping of crop producing areas in the Eastern Cape Province. ARC-ISCW Report No: GW/A/2014/23. Pretoria: ARC Institute for Soil, Climate and Water; 2014.
27. Stockman U. Managing the soil-plant system to mitigate atmospheric CO2. Discussion paper for the Soil Carbon Sequestration Summit; 2011 January 31 – February 02; Sydney, Australia.
28. Sanchez PA, Ahamed S, Carré F, Hartemink AE, Hempel J, Huising J, et al. Digital soil map of the world. Science, 2009;325:680–681. http://dx.doi.org/10.1126/science.1175084
29. Africa Soil Information Service [homepage on the Internet]. c2013 [cited 2014 May 09]. Available from: http://africasoils.net
30. PRAIS. Reporting guidelines for strategic indicators (SOs 1, 2 and 3) and performance indicators. Version 1. UNCCD Reporting and review process 2012–2013. Rome: FAO; 2012.

31. UNFCC. Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11. Note by the secretariat, FCCC/SBSTA/2006/9. Rome: FAO; 2006.

32. Park SJ, McSweeney K, Lowery B. Identification of the spatial distribution of soils using a process-based terrain characterization. Geoderma. 2001;103:249–272. http://dx.doi.org/10.1016/S0016-7061(01)00042-8

33. Soulsby C, Tetzlaff D. Towards simple approaches for mean residence time estimation in ungauged basins using tracers and soil distributions. J Hydrol. 2008;363:60–74. http://dx.doi.org/10.1016/j.jhydrol.2008.10.001

34. Schulze RE. Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system. WRC Report No 63/2/84. Pretoria: Water Research Commission; 1995.

35. Ticehurst JL, Cresswell HP, McKenzie NJ, Clover MR. Interpreting soil and topographic properties to conceptualize hillslope hydrology. Geoderma. 2007;137:279–292. http://dx.doi.org/10.1016/j.geoderma.2006.06.016

36. Van Tol JJ, Le Roux PAL, Hensley M, Lorentz SA. Soil as indicator of hillslope hydrological behaviour in the Weatherley Catchment, Eastern Cape, South Africa. Water SA. 2010;36:513–520. http://dx.doi.org/10.4314/wsa.v36i5.61985

37. Van Tol JJ, Le Roux PAL, Lorentz SA, Hensley M. Hydropedological classification of South African hillslopes. Vadose Zone J. 2013;12(4), 10 pages. http://dx.doi.org/10.2136/vzj2013.01.0007

38. Lorentz SA, Bursey K, Idowu O, Pretorius C Ngeleka K. Definition and upscaling of key hydrological processes for application in models. WRC Report No. K5/1320. Pretoria: Water Research Commission; 2007.

39. Wenninger J, Uhlenbrook S, Lorentz SA, Leibundgut C. Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa. Hydrol Sci J. 2008;53:65–80. http://dx.doi.org/10.1623/hysj.53.1.65

40. Lilly A, Boorman DB, Hollis JM. The development of a hydrological classification of UK soils and the inherent scale changes. Nutr Cycl Agroecosyt. 1998;50:299–302. http://dx.doi.org/10.1023/A:1009765000837

41. Chirico GB, Medina H, Romano N. Uncertainty in predicting soil hydraulic properties at the hillslope scale with indirect methods. J Hydrol. 2007;334:405–422. http://dx.doi.org/10.1016/j.jhydrol.2006.10.024

42. Fey MV. Soils of South Africa. Cape Town: Cambridge University Press; 2010.

43. Soil Classification Working Group. Collected documentation towards a revised third edition of the South African soil classification system. ARC-ISCW Report No. GW/A/2013/19. Pretoria: ARC Institute for Soil, Climate and Water; 2013.

44. Turner DP. A revised perspective on the principles of soil classification in South Africa. S Afr J Plant Soil. 2013;30:119–120. http://dx.doi.org/10.1080/02571862.2013.804602

45. Turner DP. Perspectives on the principles and structure of the soil classification in South Africa: Discussion and practical examples. S Afr J Plant Soil. 2013;30:61–68. http://dx.doi.org/10.1080/02571862.2013.789130

46. Schoeman F, Newby TS, Thompson MW, Van den Berg EC. South African national land cover change map. ARC-ISCW Report No. GW/A/2010/47. Pretoria: ARC Institute for Soil, Climate and Water; 2010.

47. Shelley W, Lawley R, Robinson DA. Technology: Crowd-sourced soil data for Europe. Nature. 2013;496:300–310. http://dx.doi.org/10.1038/496300d

48. Minasny B, McBratney AB. Methodologies for global soil mapping. In: Boettinger JL, Howell DW, Moore AC, Hartemink AE, Kienast-Brown S, editors. Digital soil mapping: Bridging research, environmental application and operation. Dordrecht: Springer; 2010. p. 429–436. http://dx.doi.org/10.1007/978-90-481-8863-5_34

49. Thompson JA, Prescott T, Moore AC, Bell JS, Kautz D, Hempel J, et al. Regional approach to soil property mapping using legacy data and spatial disaggregation techniques. Paper presented at: 19th World Congress of Soil Science; 2010 August 1–6; Brisbane, Australia.

50. Jenny H. Factors of soil formation, a system of quantitative pedology. New York: McGraw-Hill; 1941.

51. McBratney AB, Mendoça Santos ML, Minasny B. On digital soil mapping. Geoderma. 2003;117:3–52. http://dx.doi.org/10.1016/S0016-7061(03)00223-4

52. ISRIC – World Soil Information. Soil property maps of Africa at 1 km resolution [homepage on the Internet]. c2013 [cited 2014 July 16]. Available from: http://www.isric.org/content/new-generation-soil-property-maps-africa

53. Van den Berg HM, Weepener HL. Development of spatial modelling methodologies for semi-detailed soil mapping, primarily in support of curbing soil degradation and the zoning of high potential land. ARC-ISCW Report No: GW/A/2009/01. Pretoria: ARC Institute for Soil, Climate and Water; 2009.

54. Van den Berg HM, Weepener HL, Metz M. Spatial modelling for semi detailed soil mapping in Kwazulu-Natal. Report No: GW/A/2009/33. Pretoria: ARC Institute for Soil, Climate and Water; 2009.

55. Van Zijl GM, Le Roux PAL, Turner DP. Disaggregation of land types Ea34 and Ca11 by terrain analysis, expert knowledge and GIS methods. S Afr J Plant Soil. 2013;30:123–129. http://dx.doi.org/10.1080/02571862.2013.806679

56. Zerizghy MG, Le Roux PAL, Hensley M, Van Rensburg LD. Prediction of soil distribution on two soilscapes in land type Dc17 east of Bloemfontein, South Africa. S Afr J Sci. 2013;109(11/12), Art. #2012-0021, 5 pages.

57. Van Zijl GM, Le Roux PAL. Creating a hydrological soil map for the Stevenson-Hamilton Supersite, Kruger National Park. Water SA. 2014;40:331–336. http://dx.doi.org/10.4314/wsa.v40i2.15

58. Stalz JB. Mapping potential soil salinization using rule based object-oriented image analysis [MSc thesis]. Stellenbosch: Stellenbosch University; 2007.

59. Mashimbye ZE, Cho MA, Nell JP, De Clercq WP, Van Niekerk A, Turner DP. Model-based integrated methods for quantitative estimation of soil salinity from hyperspectral remote sensing data: A case study of selected South African soils. Pedosphere. 2012;22(5):640–649. http://dx.doi.org/10.1016/S1002-0160(12)60049-6

60. Van Zijl GM. Creating a digital soil mapping protocol for southern Africa using case studies [PhD thesis]. Bloemfontein: University of the Free State; 2013.

61. Viscarra Rossel RA, Walvoort DJJ, McBratney AB, Janik LJ, Skjemstad JO. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma. 2006;131:59–75. http://dx.doi.org/10.1016/j.geoderma.2005.03.007

62. Stenberg B, Viscarra Rossel RA, Mouazen AM, Wetterlind J, Donald LS. Chapter five – Visible and near infrared spectroscopy in soil science. Adv Agron. 2010;107:163–215. http://dx.doi.org/10.1016/S0065-2113(10)07005-7

63. Dunn BW, Batten GD, Beecher HG, Ciavarella S. The potential of near-infrared reflectance spectroscopy for soil analysis: A case study from the Riverine Plain of south-eastern Australia. Austr J Exp Agric. 2002;42:607–614. http://dx.doi.org/10.1071/EA01172

64. Shepherd KD, Walsh MG. Development of reflectance spectral libraries for characterization of soil properties. Soil Sci Soc Am J. 2002;66:988–998. http://dx.doi.org/10.2136/sssaj2002.9880

65. Viscarra Rossel RA, Cattle SR, Ortega A, Fouad Y. In situ measurements of soil colour, mineral composition and clay content by NIR spectroscopy. Geoderma. 2009;150:253–266. http://dx.doi.org/10.1016/j.geoderma.2009.01.025

66. Viscarra Rossel RA, Webster R. Discrimination of Australian soil horizons and classes from their visible–near infrared spectra. Eur J Soil Sci. 2011;62:637–647. http://dx.doi.org/10.1111/j.1365-2389.2011.01356.x

67. Meyer JH. Rapid simultaneous rating of soil texture, organic matter, total nitrogen and nitrogen mineralization potential by near infra-red reflectance. S Afr J Plant Soil. 1989;6:59–63. http://dx.doi.org/10.1080/02571862.1989.10634481

68. Van Vuuren JAJ, Meyer JH, Claassens AS. Potential use of near infrared reflectance monitoring in precision agriculture. Comm Soil Sci Plant Anal. 2006;37:2171–2184. http://dx.doi.org/10.1080/00103620600817382

69. Bainbridge SH, Manson AD. The use of mid-infrared spectroscopy for the routine prediction of various constituents in soil samples submitted for fertility analysis. In: Proceedings of the Combined Congress; 2009 Jan 20–22; Stellenbosch, South Africa. p. 19.