Digital soil mapping: Towards a multiple-use Soil Information System

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Abstract: In recent years thematic mapping has undergone a revolution as the result of advances in geographic information science and remote sensing. However, mapping of soil types and characteristics has not fully shared in this revolution, because of the complexity of soil geography and the high cost of its direct observation. None the less, the demand for soil information has never been higher, since the soil resource is so important for rural and urban planning, for environmental protection, and to understand water and geochemical cycles. This paper reviews the advances which are leading towards multiple-use soil information systems. These advances include: (1) low-cost, wide-area data, especially elevations and spectral reflectances; (2) direct digital remote sensing of soil properties; (3) geostatistical interpolation and sampling design; (4) terrain modelling; (5) predictive soil mapping; (6) data integration; (7) pedotransfer functions and soil inference systems; (8) powerful desktop computing environments; (9) the Internet. The challenge is to integrate these advances into operational systems that respond to the extensive actual and latent demand for soil information.

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Introduction

In recent years thematic mapping has undergone a revolution as the result of advances in geographic information science and remote sensing. *Soil survey*, or more properly, *soil resource inventory*, is the process of determining the pattern of the soil cover, characterising it, and presenting it in understandable and interpretable form to various users [9]. It is thus a kind of thematic mapping. Despite the increasing demand for interpreted soils information, soil mapping has not fully shared in this revolution. This is mostly due to the complexity of soil geography and the hidden nature of the soil: it is a three-dimensional body, which also varies in time, which we only observe at widely-spaced sampling points, and almost always only at one point in time. An added problem is the high cost of field sampling and laboratory analysis.

This paper reviews the conceptual bases of soil information systems [5], with emphasis on the production of interpreted soil information over large areas and at low cost, to a wide range of users. It is intended as an entry point into this exciting new work, and to encourage its application to the specific requirements and context (both geographic and social) of each soil survey organisation.

Today there is great demand for accurate soil information over large areas from environmental modellers and land use planners (both urban and rural) as well as more traditional agricultural users of soil resource inventories. All these users want *interpreted* information; that is, soil properties or behaviour directly relevant to their application. For example, a catchment hydrologist wants to know the parameters of the infiltration curve, and the saturated and unsaturated hydraulic conductivities with depth. The agronomist wants to know the available nutrient content and the retention capacity for applied nutrients, the quantity and type of salts, and trace metal content. The civil engineer wants to know the bearing capacity, plasticity, and Atterberg limits. The urban planner wants to know areas which are too contaminated to be used for gardens, housing or sports fields without expensive soil remediation. And, they want this information in the form that they can directly use in their models.

There are two major steps: (1) **mapping** the soil cover and (2) **interpreting** it in a form directly accessible to various users. We review these in the two main sections of this paper.

Soil survey

Soil survey has historically been a knowledge– and labour–intensive process, requiring a high degree of skill and even artistry, and of doubtful accuracy in the wrong hands. The question is to what extent new conceptual and technological advances can accelerate this process and make it more reliable and objective. Traditional soil survey presents area-class maps of soil types, which represent the mapper's conceptual model of soil variability, backed up by field observations. Modern soil survey must present digital maps of interpreted soil properties. This trend is well-recognised and has been the impetus for a recent international workshop on digital soil mapping [27], which is to be repeated in Rio de Janeiro in July 2006.

Models of soil variability for soil mapping

Approaches to soil mapping can be divided into two main streams: **knowledge-based**, where the surveyor builds up a mental model of why each soil is where it is, and **data-driven**, where actual observations are observed and interpolated; of course the best features of these two may be combined into a mixed approach.

The knowledge-based model of soil variability In 1941, Jenny [20] published his monograph "Factors of soil formation – a system of quantitative pedology", in which he presented evidence that soils do not occur randomly on the landscape; rather, they are the product of specific soil-forming factors, traditionally known as the **clorpt** model: **cl**imate, **o**rganisms (plant, animal, and microbiological), **r**elief, **p**arent material, and the **t**ime in which these act. He further elaborated these in his 1983 text [21]. Some authors have added **h**umans to this list, because of the obvious influence of land use on soils; others [e.g. 28] take a less homo-centric view and include humans as just another organism. In any case, the basic idea is that *each soil is in its place for a reason*, and if we can determine the (often very complex) history of the soil's environment, we can predict the soil itself. This is the idea behind *knowledge-based* approaches to digital soil mapping advocated by Bui [4] and Hewitt [15].

This approach is related to the idea of the *soil as a natural body*, not simply a list of its characteristics. Another way to say this is that soil characteristics co-vary in feature space: not all combinations of characteristics are equally likely.

When applied to digital soil mapping, this model has concentrated on collecting digital data to represent each of the soil-forming factors, and then combining them according to expert judgement [52, 6, 1]. It simply uses the GIS to overlay existing data to predict soils, just as the pre-GIS mapper does intuitively; the difference is that the relations must be formalised. For example, the expert mapper knows that the boundary between a karstic limestone and an emerged marine plain represents a boundary between soils with different grain size distribution, soil reaction, salinity, etc. and uses the geologic map accordingly; the GIS mapper makes this stratification in the GIS.

The data-driven model of soil variability Another approach is to look only at the data, and develop (geo-)statistical models which can then be applied to predict soil properties at unsampled locations. This has been developed into a comprehensive proposal, with some preliminary examples, by McBratney *et al.* [28]. These authors largely discard the concept of soil as a natural body for purposes of mapping, although they acknowledge its essential correctness; indeed they extend the Jenny **clorpt** model to the so-called **scorpan** model, where the additional factors are **s**oil properties observed at a site or at nearby sites and **n**eighbourhood, i.e. spatial position[1]. The key point is that observations (factor 's') and their spatial positions (factor 'n') are explicitly incorporated into the model; thus the knowledge-based model is merged with the data, which may be analysed by geostatistical approaches.

They define a seven-stage procedure to directly produce a predictive map of soil properties:

1. Define soil attribute(s) of interest, along with the desired resolution and block size – these are the user requirements;
2. Assemble data layers related to these attributes;
3. Spatial analysis of existing data according to the resolution and block size;
4. Analysis of assembled data to determine a field sampling plan;
5. GPS field sampling and laboratory analysis of selected properties;
6. Fit parsimonious quantitative relationships, taking into account spatial structure;
7. Make a predictive digital map according to user requirements.

Combining knowledge-based and data-driven approaches Many practitioners have observed that soil variability can be divided into two parts: the more regional factors can be explained by knowledge-based models derived from the Jenny equation, and then the *residuals* from these models can be modelled with geostatistics. These can roughly be termed the *explained* and *unexplained* variability; however, some of the 'unexplained' might just result from our inability to explain it with current models, whereas some may be inherently random. So a mixed approach is to explain what can be explained by knowledge of soil-forming factors (as expressed in the GIS), and then see if the remaining unexplained variability has any (geo)statistical relation which can be used to improve the prediction.

[1]They also change **cl**imate to **c**limate and **t**time to **a**ge to obtain their acronym

Technological advances for soil mapping

This section reviews some of the technological advances in geographic information science and remote sensing that promise to substantially improve soil mapping. Some are coming into more-or-less routine use in certain soil survey organisations, but most are still in the exploratory, rather than the operational, stage.

Low-cost, wide-area data In the past few years there has been a tremendous increase in the quantity of wide-area data of various resolutions that is available either for free or at low cost per unit area. ITC's satellite and sensor database[2] provides an easy portal to this data.

Especially relevant to soil mapping is the Shuttle Radar Topography Mission (SRTM) digital elevation data, now freely-available at 90 m horizontal resolution, and under certain agreements at 30 m. Jarvis *et al.* [19], working at CIAT, have shown that in general this data is superior to previously-available elevation data for most of South America, although there are some problems in mountainous terrain in certain aspects. The ASTER sensor also provides elevation models from stereo-views which combine nadir and off-nadir scenes.

The new generation of multi-spectral sensors (e.g. ASTER, SPOT-5 HRG, Landsat-7 ETM) have ever finer spatial and spectral resolution, and the increasingly-competitive market is lowering the price even for the most recent data. For soil mapping, archived data is often sufficient, and this is available at low cost. These sensors are mostly useful for vegetation and land-cover mapping, but also can be easily georeferenced over wide areas with a small number of GPS readings to provide a reliable base map and background for soil survey.

Weather satellites such as NOAA, Terra, and Aqua provide free daily data (e.g. from the AVHRR and MODIS sensors) at coarse spectral and spatial resolution. Despite their resolution, they have been used successfully as secondary data sources, especially to characterise vegetation intensity [10] and phenology [11], both of which can be related to soil processes.

Finally, sub-meter pan and multi-spectral sensors (e.g. Quickbird, IKONOS) can be cost-effective solutions for high-precision base maps in areas of intense soil use, such as urban zones and irrigation districts.

Digital remote sensing of soil properties Despite the fact that the soil is usually covered by vegetation, and that in any case only the soil surface is visible, some soil properties may be assessed directly by digital remote sensing. Most efforts have been to predict single properties that have a clear surface expression such

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[2] `http://www.itc.nl/research/products/sensordb/searchsen.aspx`

as soil moisture [18], salts [33], surface crusts and vegetative cover as they influence erosion [22]. Geostatistical techniques can be used to integrate the sensor measurement over the entire study area with point data taken in the field [46].

An especially exciting development is the work of Shepherd & Walsh [45], at ICRAF, who have developed strong correlative relations between soil properties (exchangeable bases, CEC, P, organic C, clay and sand content) and hyper-spectral signatures under laboratory conditions; this work is being extended to field conditions, with airborne and satellite sensors with lower spectral resolution.

Proximal sensors For small areas and detailed investigations, proximal sensors such as ground-penetrating radar and electromagnetic induction [17, 42, 48] can provide direct measurements at very close spacings; these must however be interpreted in terms of soil properties. They are not used in routine survey.

Geostatistical interpolation and sampling design Geostatistics is now firmly established in soil science as a key tool for making the most of existing (generally sparse) data [13, 50]. Numerous studies have demonstrated that much local and even regional soil variability can be modelled as the result of random field (the somewhat disturbing theory behind geostatistical interpolation), and its use is almost universal for field-scale studies. It also provides a sound basis for designing optimal sampling plans [30, 35, 23, 47] based on the structure of spatial dependence.

Terrain modelling A promising approach is the prediction of soil properties by digital terrain mapping [31, 49, 3]. It is a logical outgrowth of the strong relation between soil distribution and geomorphology [12, 7] and advances in automatic terrain classification from elevation models [e.g. 43].

Data integration In a GIS all data is geo-referenced, which provides an implicit relation between them. This is the simplest form of data integration: the collection of multiple themes covering the same area. In soil survey applications, secondary data (e.g. geology and land use), data from sensors (orthophotos, satellite images) and historical information (e.g. existing soil maps) can be collected in a GIS, but the challenge is to make them compatible. The problem begins with the very definition of data elements and spatial objects, their so-called *ontology*. This has been addressed in a soil survey context by Krol *et al.* [26], but much work remains to be done.

Existing analogue soil survey data is often converted to digital form and integrated into a GIS. This presents two challenges. First, the geometry of the analogue product is often poor and can not be converted to digital form without recompilation on a reliable base [8]. Secondly, the thematic information (legend, classification, attributes) may be difficult to translate to current standards; this may require extensive communication between the map maker and the database designer.

Powerful desktop computing environments Underlying all these advances is the tremendous increase in computing power available to institutions and even individual researchers or consultants. Procedures that once required high-cost or specialised computers, such as orthophoto rectification [40], geostatistical interpolation [39], generalised linear models [41], and spatial analysis, can now be performed on a standard desktop computer with low-cost (e.g. ILWIS) or free (e.g. GRASS [34], R [16]) programs.

This is supported by the explosive growth of the Internet. Computer programs, technical reference works, and digital data are available from anywhere on earth. Search technology and portals make it fairly easy to find what is needed. This is truly a revolution in the democratization of information, also for soil survey.

Predictive soil mapping These advances can be combined into the modern approach generally called *predictive soil mapping* [44] or (in Germany) *concept mapping* [25]. Most thematic mapping is predictive, of course, since not every location has been visited; but in this context it refers to a map made before field visits, using secondary data related to soil distribution to predict what soil type or characteristics should be found in each location; this can then be verified by efficient field sampling. A related approach is *environmental correlation*, where terrain units [14] or soil properties [32] are predicted by multiple regression, using calibration samples.

Soil survey interpretation

New mapping techniques are only important in so far as they meet user needs. Traditionally, soil surveys have been presented as area-class ("polygon") maps with accompanying tabular information on soil properties in each class; these can easily be turned into GIS coverages with accompanying relational tables. Some surveys go one step further and provide *soil survey interpretations* for a range of anticipated uses, also as relational tables. This development has been particularly strong in the US Cooperative Soil Survey [24, 37, 36], where close relations with a range of consumers of soil information (not just agricultural) was encouraged since the 1960's, finally resulting in the STATSGO (regional) and SSURGO (local) soil geographic databases; a similar level has been achieved in Canada and Australia.

This has mostly been a *supply-driven* approach: the presented data and interpretations are what the supplier (i.e. soil survey organisation) *thinks* the clients want. This may be based on previous requests, but more commonly on anectdotal information collected by the supplier. When there are new needs (e.g. parameters for environmental models), there is rarely a demand expressed to the supplier, since the consumer may not be aware of the supplier's existence, or may assume (correctly at times) that the supplier only provides agricultural interpretations. On the other hand, the supplier may not be up-to-date with the many uses of soil information, and may not be in condition to provide them, although the methods may have been developed by researchers.

Very few soil survey organisations make grid ("raster") maps of soil properties, yet these are increasingly the form used by environmental modellers and researchers on soil processes. Area-class maps are unable to express continuous variation, and can not use geostatistical techniques for interpolation.

Pedotransfer functions and soil inference systems The most common method to provide interpreted soils information from soil survey data is still expert judgement, either by the survey or a consultant. A wide variety of *pedotransfer functions* have been developed for more objective interpretation, most notably for soil-water relations [51]. Recently, McBratney *et al.* [29] have proposed placing pedotransfer functions in the context of a *soil inference system*, which suggests the appropriate function based on user requirements (parameter, scale, precision). This places soil survey as a *demand-driven* process within the wider issue of land-use negotiation and research on soil behaviour [2].

Dissemination of soils data Rossiter [38] reviewed the current status of digital soil resource inventories, with special attention to distribution on the Internet. This is an ideal medium for encouraging wide use of soils data, yet with a few exceptions soil survey organisations have not used this. CD-ROMs can be reproduced very cheaply; this is another distribution channel. Major problems remain with data ownership and the need for organisations to provide their own finance; these work against the wide use of soils data, which can provide political support for the survey organisation.

Conclusion

Providing interpreted soil information for the many consumers who need it (whether they realise it or not) is an ongoing challenge. The soil survey community must take steps to:

1. Establish close relations with users of soils information, to find out what they really want, and in what form;

2. Develop systematic methodologies ("work flows") to provide this data, with appropriate quality control and assurance procedures;

3. Apply modern techniques to accelerate survey and make it more reliable.

Fortunately, the technical possibilities have never been greater, and are increasing. The conceptual frameworks to direct the technology are also fairly well-developed in the research community. The challenge is to make them operational and cost-effective, and respond to the extensive actual and latent demand.

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