SOIL INFORMATION SYSTEMS

P A BURROUGH

The history of the introduction of automated information systems and GIS in soil survey, from the automation of map production to the quantitative modelling of soil and land resources, is reviewed. The methods used for collecting data from soil profiles and about the spatial distribution of soil are described. Soil profile data and the attributes of soil map units are often stored in relational databases, whereas the spatial distribution of soil mapping units (polygons) is often stored in topological arc-node (vector) form or in grid cell (raster) form depending on the software and application. The use of optimal interpolation methods in soil survey is reviewed, including extensions such as co-kriging and disjunctive kriging. The general principles of a range of applications are discussed and illustrated by examples. GIS are now firmly established in modern soil survey practice and are used for map production, deriving suitability maps to meet users' requests for special-purpose information and for modelling environmental processes.

DEVELOPMENTS IN SOIL INFORMATION SYSTEMS AND IDEAS ABOUT THE NATURE OF SOIL

The first international scientific meeting on soil information systems was held in Wageningen in the Netherlands in September 1975. The meeting was organized by the newly formed Working Group on Soil Information Systems set up under Commission V of the International Society of Soil Science, as had been proposed at the Tenth International Congress of the Society in Moscow in 1974. The 55 scientists from 18 countries who attended the meeting hoped that their activities would be the first steps towards a revolution in soil research methodology and the problems of soil science. Professor Ciric, then Chairman of Commission V of the International Society of Soil Science, wrote in his Foreword to the Proceedings of the meeting (Bie 1975), that the high cost of collecting and analysing soil samples fully justifies the inclusion of all indices (attributes) in a soil information system, and he noted that 'the adaptation of methodology to the requirements of the information system will result in a definitive break with the old descriptive, largely subjective, methods of our field research. The logic of the information system cannot tolerate any vague or undefined notions'.

The first phase of development

The Working Group on Soil Information Systems was extremely active and the Wageningen meeting was followed in rapid succession by others. Meetings were held in Canberra, Australia in 1976 (Moore and Bie 1977), Bulgaria in 1977 (Sadovski and Bie 1978), Canberra again in 1980 (Moore, Cook and Lynch 1981), Paris 1981 (Girard 1981) and Bolkesjø, Norway in 1983 (Burrough and Bie 1984). The papers presented at these meetings represent the first phase in quantifying soil survey data. As might be expected, they concentrate on the problems of recording and storing data from soil profiles in the computer. Brought up on the philosophy of strict hierarchical classification (cf. *Soil Taxonomy* – Soil Survey Staff 1976) and lacking the modern insights of relational database structures, soil scientists first wrestled with the problems of obtaining data that contained both qualitative and quantitative characteristics in

variable length fields into the readily available hierarchical and network database structures of the time (Mackenzie and Smith 1977). Soil profiles are difficult to record because data are usually collected for those naturally occurring horizons which can be seen when the soil is exposed in a pit or cutting. Unfortunately, these horizons are not always clear or easy to see and define unambiguously, with the result that the number of horizons – and hence the number of data items to be recorded – can vary greatly, even between profiles belonging to the same soil landscape unit. The positive benefit of this early work was that soil survey organizations were forced to think very carefully about the way in which soil data should be collected and organized, which brought a considerable amount of standardization and improved the ways in which data were recorded in the field. Standard computer forms were developed for field recording and (somewhat later) portable field computers were used. These developments of national standards were particularly vigorous in Canada, The Netherlands, the United States and France (Bie 1975; Dumanski, Kloosterman and Brandon 1975; Girard 1981; Mausbach and Reybold 1987).

One aim of the early soil information systems was to provide viable alternatives to the rigid, bureaucratic, hierarchical soil classification systems that are still in use. The work in the 1970s on using the methods of numerical taxonomy as an alternative to established soil classification (cf. Webster and Burrough 1972a, 1972b, 1974; de Gruijter 1977; Webster 1977; Lamp 1983) stimulated much academic research but did not lead to general acceptance of the methods in regular soil surveys. This was largely because of the difficulties associated with interpreting the classes that were so constructed and in dealing with the problems of spatial variation.

Soil survey applications were among the first uses of GIS. Both the US Department of Agriculture (Johnson 1975) and the Dutch Soil Survey STIBOKA (van Kuilenburg *et al.* 1981) were first to automate the production of soil survey maps. The methods of digital cartography developed by the United States Geological Survey were used for soil mapping and irrigation studies in Kentucky (Loveland and Ramey 1986). In the case of STIBOKA, the technology for producing the 1 : 50 000-scale digital soil survey map base was considerably enhanced by the parallel development of a GIS for landscape mapping (Burrough 1980; Burrough and de Veer 1980, 1984) which dealt not only with point and polygon data, but also with complex line attributes, spatial searches and adjacencies. Burrough (1982) gives a review of these first developments.

The second phase

The second phase in the automated handling of soil information came as soil scientists attempted to bring in rigorous methods for mapping. Before automation, the spatial variation of soils in the landscape had been mapped by interpretation of the relationships between the kind of soil recorded at a soil profile pit or boring and the external features of the landscape in which the profile was situated. In reconnaissance surveys, few observations of the soil were made and maps showing the distribution of different kinds of soil were made almost exclusively by the informed interpretation of external features as seen on aerial photographs. This kind of mapping is a complex, subjective art which resists quantification and it was, therefore, extremely difficult to assess the intrinsic value of the documents produced (Burrough and Beckett 1971a, 1971b; Burrough, Beckett and Jarvis 1971; Beckett and Burrough 1971a, 1971b). The ability to record, store and retrieve data from many soil observations, including their exact location and elevation on the ground (the exact location of a soil profile observation was rarely recorded in many early surveys) paved the way for studies of the spatial variation of soil properties within the subjectively delineated landscape units.

Although the phenomenon of the continuous, but noisy, spatial variation of soil property values had been recognized earlier (Wilding, Jones and Schafer 1965; Beckett and Webster 1971), it was not until the late 1970s and the 1980s that soil scientists began to pay much attention to methods for interpolating soil attribute values directly from point observations. Much work was done both by soil physicists (e.g. Nielsen and Bouma 1985) and field soil scientists (Webster 1985) to apply the methods of geostatistics to interpolation, to the analysis of spatial structures, to the problem of optimizing sampling networks and to simulating the spatial variation of soil properties (McBratney and

Webster 1981, 1983a; McBratney, Webster and Burgess 1981; Webster and Burgess 1984; Burrough 1990). The study of how geostatistical methods can assist soil survey has been a subject of international soil survey meetings since 1983 (e.g. Giltrap 1984; Nielsen and Bouma 1985; Mausbach and Wilding 1991) and remains a theme of current interest even though the basic technology is now available to all (Englund and Sparks 1988).

The third phase

The third phase in the quantification of soil information has taken four largely separate paths:

- consolidation and implementation;
- the use of digital soil information for analysis and modelling;
- the basic data models used in soil survey;
- the use of expert systems.

Consolidation and implementation

The first path represents the consolidation of the research of the 1970s and 1980s in the form of local, national and indeed international soil profile and soil map databases. For the most part, these are standard applications of existing commercial relational database and automated thematic mapping technology. The question facing national and international soil information organizations is no longer how to build original systems nor how to adapt commercial systems to meet specifications, but rather how to choose between the wide range of commercial options that is now available. The problem of building a very large database of soil information has now shifted from the technology to the ways in which data from different areas or lands are modelled, recorded and stored. These problems of data standardization are more acute than any technology problem when building an international database (e.g. van Reeuwijk 1982, 1984; Baumgardner and Oldeman 1986; Pleijsier 1986, 1989; Baumgardner and Van der Weg 1989). There has also been increasing attention paid to the problems of data quality and loss of information when soil data are converted from one format to another (Marsman and de Gruijter 1984; Burrough 1986; Marsman and de Gruijter 1986; Bregt 1989; Bregt and Beemster 1989).

The use of digital soil information for analysis and modelling

The second path concerns the use of digital soil information. The problems when using the earlier, non-digital, databases to answer queries about land evaluation were twofold. In the first instance, the data were only held in a generalized, classified form, under the assumption that the class model was a sufficient carrier of information for all applications that could be envisaged. In the second case, it cost much time and money to redraw a reclassified soil map every time a different interpretation map was made. Standard GIS software, with its ability to reclassify soil polygons or pixels according to the attributes held in order to make a new map, has solved the latter problem. The costs of producing derived maps have been replaced by the challenge of working out how the information on the new maps should be derived in a logical, systematic way from the original data.

The largely qualitative land evaluation wisdom developed during the 1970s (FAO 1976) is still being used in many countries for deriving maps showing complex land qualities or land suitabilities but, in recent years, there have been very strong moves towards quantifying the land evaluation process (Bouma *et al.* 1986; Burrough 1986, 1989a, 1990; Beek, Burrough and McCormack 1987; Bouma and Bregt 1989; Driessen 1989). This quantification involves linking the soil information base (profiles and map polygons) to models of crop yield (van Diepen *et al.* 1989; Dumanski and Onofrei 1989), simulating regional and local soil moisture regimes (Bouma *et al.* 1980; Busoni, Sanesi and Torri 1986; King *et al.* 1986), nitrate leaching, pesticide redistribution, erosion and runoff (Herndon and Schertz 1989; de Roo, Hazelhoff and Burrough 1989), to remote sensing of soil moisture regimes (Olsson 1989) and assessing woody biomass (Helldén 1987). Associated with this trend towards linking of the largely static soil database to process models has come an awareness of the problems of change in soil resources (Bouma 1989a, 1989b). One important result of this phase was the decision at the 13th International Congress in Hamburg in 1986 to terminate the purely technically-oriented International Soil Science Society (ISSS) Working Group on Soil Information

Systems and to replace it by a new ISSS Working Group on Quantitative Land Evaluation. The role of the ISSS Working Group in soil variability studies was taken over by the Commission I Working Group on Soil Moisture Variability, and a new Working Group was set up to concentrate activities on the problems of creating a world soil map database at a scale of 1 : 1 000 000 (Baumgardner and Oldeman 1986; Baumgardner and van der Weg 1989).

Data models for soil survey

The third path in the latest phase of work in soil information systems, which has to do with the nature of the basic data models used for recording data, is the least followed. None the less, it is beginning to attract attention, largely through the work on spatial variation and modelling. Much work on modelling, for example of crop yields, has ignored the spatial component entirely. The modellers have often implicitly assumed that the results of their calculations can be directly applied to the spatial units identified in the field, that is to whole soil polygons – irrespective of the scale of mapping. It is now being realized that, as with many soil properties, the results of models can (and very possibly should) be interpolated from the fixed data points in order to describe better the spatial variation within the major landscape units (Stein, Hoogerwert and Bouma 1988). This work is challenging the old ideas that the landscape is built from basic, homogeneous entities – the units of the choropleth (or at least chorochromatic) map model that can be characterized completely in terms of a small number of 'representative profiles' (cf. Bregt 1989; Bregt and Beemster 1989). In its place is coming a realization that all soil information and all interpretations of that information need to be related to the resolution of the survey and to the uses to which that information is being put (Wösten, Bannink and Bouma 1989). Although it now seems clear that the original concepts of fractals as put forward by Mandelbrot (1982) are not completely applicable to soil, the ideas of scaling and multiple-scale variation that they imply are seen as being important aspects of the soil data model (Miller 1980; Burrough 1983a, 1983b, Burrough 1989b; Hopmans and Stricker 1989).

The problems of how to fit the 'messy' data units of soil survey into exactly defined classes has engaged the minds of soil scientists for decades. As noted by Professor Cirić in 1975, the logic of the information system cannot tolerate any vague or undefined notions. Unfortunately, the soil itself has not become more susceptible to exact description as a result of nearly 20 years of applied computer science; it is a phenomenon for which the provision of exact, crisp data models is bedevilled by overlap, complexity, ambiguity and uncertainty. The implications of these complicating factors for soil classification had been foreseen in the 1960s (Webster 1968) and the 1970s (Webster and Burrough 1974) but these problems have received little attention until recently. The importance of these complicating factors has been clearly revealed by retrospective, objective tests of soil map quality. In these, it has often been found that very few soil profiles in a soil mapping unit actually meet all the specifications of the classification unit or mapping unit in which they occur (cf. Marsman and de Gruijter 1984, 1986). The consequences of this dichotomy are that standard Boolean retrieval (SQL) sequences may fail to retrieve soil data adequately, thereby losing information (cf. Burrough 1987, 1989c), and that soil information systems, including soil maps, may appear to outsiders to be less valuable than they really are. The solution to this problem appears to lie in adopting either the geostatistical approach to mapping data quantitatively (which requires large numbers of observations) or in using the methods of fuzzy set theory in order to handle the conundrums of class overlap, complexity and ambiguity (Burrough 1989c).

Expert systems

To date, there seems to have been little concerted effort by soil survey agencies to incorporate their expertise in knowledge-based systems that could be used with GIS. Exploratory work on expert systems and soil classification has been done by Dale, McBratney and Russell (1989), and on land evaluation by Maes, Vereecken and Darius (1987). The most practical expert system to date is probably the ALES system (Rossiter 1989). This is an independent personal computer program that allows farmers to explore the effects of price changes and variations in inputs on expected yields and gross returns in the context of the soil–climatic ecosystem of their farm or region.

RECORDING DATA ABOUT SOIL AND STORING THEM IN THE COMPUTER

Data about soil profiles are recorded from auger borings and soil pits (Hodgson 1978). Field data are usually recorded directly on prepared forms for computer input or may be collected directly using portable field computers. The data collected include qualitative and quantitative descriptions of the location (X,Y,Z coordinates if possible) including the general and local landform, the geological formation, land use and vegetation data. The morphological aspects of the soil profile, including thickness, colour (Munsell Hue, Value and Chroma), texture (per cent sand, silt and clay), structure, consistence, porosity, organic matter and roots, and other attributes of interest such as the presence of indurated material, will be recorded for each soil horizon. The nature of the transition from one horizon to the next will also be recorded. Soil samples weighing between 1 and 2 kilograms may be taken from each horizon for chemical analysis. By using stainless steel cylinders pushed into the soil, undisturbed samples can be collected for determining physical characteristics of the soil such as bulk density, porosity and its hydrological properties. For special-purpose surveys in agricultural experimental stations and for surveying particular problems such as soil pollution, the samples may be taken at fixed depth intervals and not according to any perceived horizonation. When it is known that short-range spatial variation is large, this can be compensated for by taking bulk samples made up of many sub-samples drawn from within a given radius (say 5 metres) from the chosen location.

Standard soil maps are made by drawing boundaries around areas of land that appear to contain similar soil. The boundaries are usually interpreted from the external aspects of the landscape as seen in the field or on stereo aerial photographs. Remote sensing has not proved to be sufficiently useful for directly delineating different kinds of soil but may be valuable for providing information about time-dependent aspects of the soil such as moisture status and erosion. Only rarely are soil boundaries mapped directly by 'eyeball interpolation' between field observations of the soil profile. When field observations are made to locate boundaries, they are almost always quick auger borings that are not fully recorded. The smaller the map scale, the fewer the field observations and the less often that the position of boundaries is checked in the field.

The data from the detailed pit and profile observations are used to create a central concept (a sort of average or 'representative') soil profile with which each delineated map unit can be characterized. A set of central concepts can become formalized in a hierarchical classification system (cf. Soil Survey Staff 1976). According to this concept, the classification unit becomes the sole carrier of information about all soil profiles that are identified as being of that type. The soil map unit shows the spatial distribution of single types or sets of spatially related types of soil.

In recent years, it has become clear that it is not sensible to work only in terms of the central class concepts and their expression on choropleth thematic maps. The main reason for reducing all soil observations to central class concepts was because humans could not handle all the detail provided by large numbers of soil profile descriptions and analyses. Today, however, it is realized that classification is but one use of the expensively collected soil data and that it is also worth storing all data collected in the soil information system. A data model for soil survey is given in Fig. 46.1. Each soil mapping unit (legend unit) will be supported by a single set of records containing general information about the kinds of soil found therein, their relative abundances and position in the landscape, and the central concepts underlying their definition together with attribute values that describe them. Because a single mapping unit may consist of many separate delineations (polygons) all carrying the same soil information, the relational data structure for the soil will have the form shown in Fig. 46.2. The polygon boundary data will be held as vectors in an arc-node structure or as compact rasters depending on the type of GIS used.

The data from the soil profiles will also be held in a series of tables. For example, there may be tables for the classification name, the field site and the morphological, chemical and physical properties, all of which can be retrieved without reference to the soil map. In order to facilitate the use of the profile data to support crop modelling, spatial interpolation and computations of means and standard deviations of important soil properties for each separate delineation, it is also sensible to

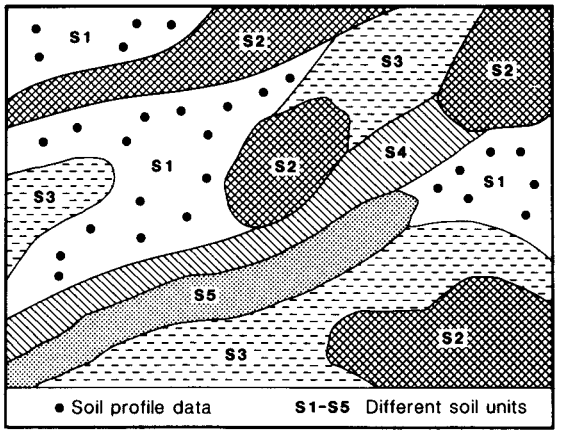

Fig. 46.1 Mapped soil units, polygons and soil profiles are the basic elements of a soil information system.

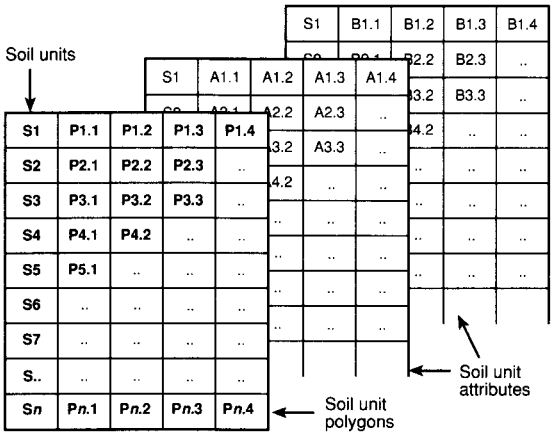

Fig. 46.2 Relational structure of a soil polygon map: S1–S*n* refer to the kinds of soil (mapping units); P1.1 . . . refer to the polygons representing the location of each kind of soil; the property values held by each kind of soil for all polygons are given by the attribute tables A1.1 . . ., B1.1 . . . .

cross-link each profile with the polygon in which it falls (Fig. 46.3). This could be done 'on the fly' by point-in-polygon search but it is probably quicker to do it once as a batch process and store the results in the database. It is also possible to make the reverse linkages and, for each polygon, to store a list of all profiles occurring within its boundaries. In this way, access to either the spatial data or the profile data can be made quickly and easily either directly or through the other.

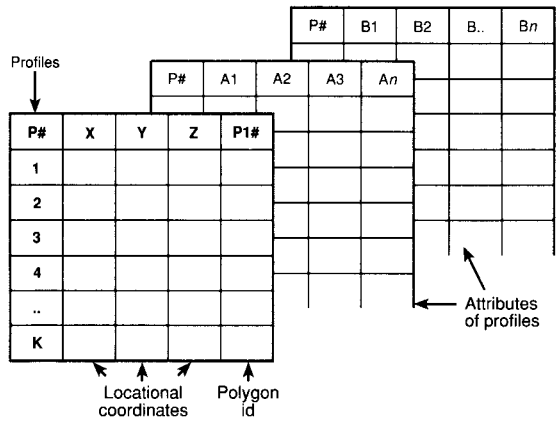

Fig. 46.3 Relational structure for the soil profiles. Profiles are identified by a serial number (P); the tables contain data on location (*X*,*Y* and *Z* coordinates), the soil polygon in which they occur and attribute values (A1 . . ., A*n*, B1 . . ., B*n*).

TREATING SOIL VARIATION AS CONTINUOUS VARIATION: OPTIMAL INTERPOLATION

When soil profile data have been stored in a relational database they can be used in several ways. One is to use them simply to characterize the mapping units in which they occur, by performing either logical, numerical or statistical analysis (see the next section on page 163). Although spatial data on soil are most frequently stored in a form linked to clearly delineated soil map units (polygons), there are many instances where the simple choropleth (or chorochromatic) map model is inadequate. This may be the case when the soil boundaries are vague and diffuse (see Burrough 1986:121 for a discussion of the different kinds of lateral change in soil that may occur at 'boundaries') or when the properties of interest show strong spatial variation within the polygons.

Therefore, an alternative to using profile data merely to characterize the soil polygons is to use the data from the profiles to interpolate single-attribute surfaces that can be displayed individually or used as separate layers in a GIS. There are many interpolation methods that can be used (see Burrough 1986 for a review) but, when sufficient data are available, it is sensible to consider using geostatistical methods to aid interpolation. This is because soil properties only rarely vary in a smooth

and continuous way over space. Besides the abrupt changes (usually called soil boundaries), there is often much short-range variation in the values of soil attributes that cannot be modelled by a smoothly changing function such as a trend surface. The short-range variations can be split into two components: a spatially correlated but irregularly varying component; and a random component (or 'noise') that arises from measurement and sampling errors and very short-range variations that cannot be detected with the resolution of the chosen sample spacing. The spatially correlated but irregular variation can be characterized in terms of a spatial correlation function known as the variogram. The variogram contains information that can be used for optimal interpolation, for optimizing sample spacing and for simulating the spatial variation of soil. This interpolation method is known as 'kriging', after the South African mining engineer D G Krige who first used it. The methodology has been put on a firm theoretical foundation by the French geomathematician Georges Matheron (1971) and, in recent years, it has found many applications in soil science.

A brief introduction to kriging and regionalized variable theory

The kriging technique assumes that the spatial variation of the soil attribute under study can be modelled by a stochastic surface. Attributes that vary in this way are called *regionalized variables* and they satisfy the intrinsic hypothesis (Journel and Huijbregts 1978).

The theory of regionalized variables is now well known, so only the most important aspects will be summarized here (see Journel and Huijbregts 1978; Burgess and Webster 1980a, 1980b; Webster 1985; Burrough 1986; Webster and Oliver 1990). Regionalized variable theory assumes that the spatial variation of any variable can be expressed as the sum of three major components. These are:

- a structural component, associated with a constant mean value or a polynomial trend;
- a spatially correlated random component; and
- a 'white noise' or residual error term that is spatially uncorrelated.

Let x be a position in one, two or three dimensions. Then the spatial variable Z_i at x is given by

$$Z_i(x) = m(x) + \epsilon'(x) + \epsilon'' \qquad [46.1]$$

where $m(x)$ is a deterministic function describing the structural component of Z_i *at* x, $\epsilon'(x)$ is the term denoting the stochastic, locally varying spatially dependent residuals from $m(x)$ and ϵ'' is a residual, spatially independent noise term having zero mean and variance σ^2. To simplify matters, it is assumed here that $m(x)$ is constant. The variation of the random function $\epsilon'(x)$ over space is summarized by the semivariance which, for a lag (sample separation) of h, is given by:

$$\gamma(h) = \tfrac{1}{2}E[Z_{x+h} - Z_x]^2 \qquad [46.2]$$

For a one-dimensional transect, the semivariance at lag h is estimated by

$$\gamma(h) = \frac{1}{2(n-h)} \cdot \sum_{i=1}^{n-h} [Z_{xi+h} - Z_{xi}]^2 \qquad [46.3]$$

where h is the distance between $(n - h)$ pairs of sample sites Z_i, Z_{i+h}. The function can also be estimated for sample sites in two and three dimensions and for different directions to determine possible anisotropy. A plot of $\gamma(h)$ versus h is called an experimental variogram. Various theoretical models (spherical, linear, exponential, Gaussian, De Wijssian, Bessel functions – see Journel and Huijbregts 1978 or Webster 1985 for details) can be fitted through the experimental variogram in order to describe how the semivariance attribute values vary with sample spacing.

Features of the variogram

The variogram summarizes the way in which the values of the attribute being sampled covary in space. Variograms may take many forms but they can be summarized in the terms of non-transitional and transitional variograms.

With non-transitional variograms, the semivariance increases monotonically with increasing sample spacing (Fig. 46.4(a)). With transitional variograms (Fig. 46.4(b)), the semivariance increases with sample spacing up to a critical distance called the *range* at which it levels out. The value of semivariance beyond the range is termed the *sill*. Beyond the range, there is no spatial covariance between sample sites. Up to the range,

the semivariance increases with sample spacing as in the non-transitional case. Both kinds of variogram may show a positive intersection with the Y-axis, which estimates the *nugget* variance. This nugget estimates the non-spatially correlated noise term ϵ'' in eq [46.1] which is caused by measurement errors and very short-range spatial variation below the resolution of the sampling net. Transitional variograms can be modelled by spherical, circular, exponential, Bessel functions or Gaussian models (Journel and Huijbregts 1978).

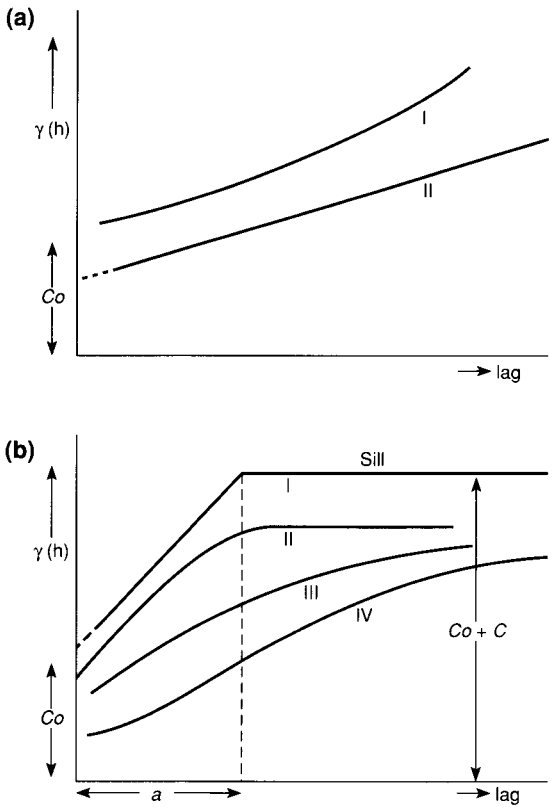

Fig. 46.4 (a) Non-transitional variogram models. Curve I is indicative of a trend in the data. Curve II indicates that spatial dependence occurs for all scales covered by the variogram. (b) Transitional variogram models. I. Linear with sill; II Spherical model; III Exponential model; IV Gaussian model. All models indicate that once the sample spacing exceeds a certain value, then there is no spatial dependence between the sample sites.

Besides these simple models, variograms may show a variety of more complex forms. Anisotropy in the underlying spatial pattern will be revealed by the experimental variograms having different slopes, ranges and possibly sills and nuggets when determined from samples laid out in different directions. When several spatial patterns have been superimposed upon each other (cf. Journel and Huijbregts 1978; Burrough 1983a, 1983b), the variogram will be a composite embodying variation at all the scales sampled. Periodic variation yields variograms with a periodic form. Complex experimental variograms can be modelled by sets of the variogram models given above (e.g. a double spherical model in which the ranges of the models match two distinctly separate scales of spatial variation).

Using the variogram to optimize sampling for mapping

Once the variogram is known, the value of an attribute at any point in a mapping unit can be predicted from the data points in that mapping unit which are located nearest to it. The error of the prediction depends only on the variogram, the number and configuration of the data points and the size of the block for which the prediction is made. Knowledge of the variogram can substantially reduce the number of samples required to make predictions of mean values (or location-specific point or block predictions) for a given prediction error as compared with the classical model (see Burgess, Webster and McBratney 1981; Burrough 1990).

Using the variogram for interpolation of point predictions

The fitted variogram can be used to determine the weights λ_i needed for predicting the value of an attribute Z at any unsampled point x_0 from measurements of Z at points x_i. The prediction is a linear weighted sum:

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i \cdot Z(x_i) \qquad [46.4]$$

with

$$\sum_{i=1}^{n} \lambda_i = 1$$

The weights λ_i are chosen so that the prediction

$\hat{Z}(x_0)$ is unbiased, and the prediction variance σ^2_e is less than for any other linear combination of the observed values.

The minimum variance of $Z(x_0)$ is obtained when

$$\sum_{j=1}^{n} \lambda j \cdot \gamma(x_i,x_j) + \varphi = \gamma(x_i,x_0) \text{ for all } i, \qquad [46.5]$$

and is

$$\sigma^2_e = \sum_{j=1}^{n} \lambda j \cdot \gamma(x_j,x_0) + \varphi \qquad [46.6]$$

The quantity $\gamma(x_i, x_j)$ is the semivariance of Z between the sampling points x_i and x_j; $\gamma(x_i, x_0)$ is the semivariance between the sampling point x_i and the unvisited point x_0. Both these quantities are obtained from the fitted variogram. The quantity φ is a Lagrange multiplier required for the minimalization.

Using the variogram for interpolation of block predictions

Equations [46.4] and [46.6] give predictions of the attribute and its prediction variance at unvisited sites for areas or volumes of soil that are the same size as that of the original sampling support. Very often there is a requirement to predict local average values for areas that are larger than units that can be practically sampled, such as the area under an experimental plot or that covered by a remotely sensed pixel or equivalent grid cell in a raster GIS. This can be achieved by modifying the kriging equations to predict an average value of Z over a block B, given by

$$Z(x_B) = \int_B \frac{Z(x)\,dx}{\text{area } B} \qquad [46.7]$$

is predicted by

$$Z(x_B) = \sum_{i=1}^{n} \lambda_i \cdot Z(x_i)$$

with $\sum_{i=1}^{n} \lambda_i = 1$, as before, but the weights are calculated using average semivariances between the data points and all points in the block (Burgess and Webster 1980b). The minimum variance is now

$$\sigma^2_B = \sum_{j=1}^{n} \lambda_j \gamma(x_j,x_B) + \varphi_B - \gamma(x_B,x_B) \qquad [46.8]$$

and is obtained when

$$\sum_{i=1}^{n} \lambda_j \gamma(x_i,x_B) + \varphi_B = \gamma(x_i,x_B) \text{ for all } i \qquad [46.9]$$

Figure 46.5 is an example of a spherical variogram fitted to experimental semivariances computed for the sand content of the 0–20 cm layer at 69 soil sites located on a regular 75 m grid in Turen, Venezuela (Mateos *et al.* 1987). Figures 46.6(a) and 46.6(b) display the interpolated surface and the associated kriging error surface for 15 × 15 m blocks. GIS display techniques can enhance the presentation of interpolated data (see Plate 46.1).

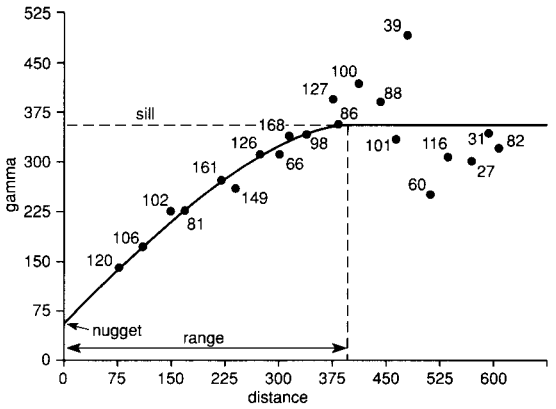

Fig. 46.5 Experimental variogram of per cent sand (0–20 cm) from an experimental field in Turen, Venezuela with a fitted spherical model: sill 355.09 per cent squared, nugget 57.20 per cent squared, range 410.5 m.

Given the variogram (or other estimate of the covariance function), eqs [46.4], [46.5], [46.7] and [46.8] permit the prediction of the value of an attribute Z at any location within the map unit for blocks of land having a minimum area of the sample support or larger. By predicting the value of Z at points on a regular grid, the attribute can be mapped within the map unit and a map of the associated prediction errors can be made. Note that, because the error of these predictions depends only on the covariance function and the configuration of the data points, we have a way in which – once the variogram is known – sampling strategies can be designed to give any required minimum interpolation error (Burrough 1991).

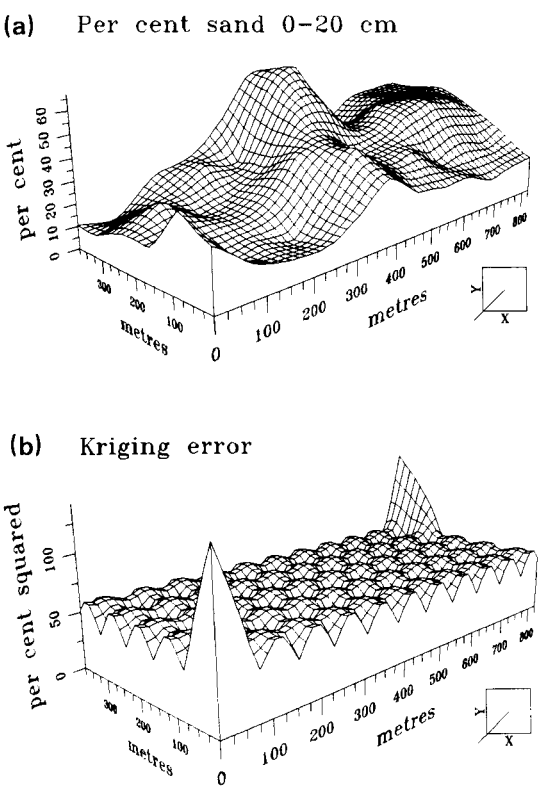

Fig. 46.6 (a) Interpolated surface of sand content for the topsoil of an experimental field in Turen, Venezuela. The surface has been constructed by interpolating from a data grid spacing of 75 m to blocks of 15 × 15 m. (b) Kriging error surface of surface in Fig. 46.6(a). The errors are lower for the 15 × 15 m blocks that are centred over data points, except at the two corners where errors increase markedly because of missing values.

Extensions of kriging in soil science

Choosing the correct spatial domains

The first attempts to use kriging in soil science compared the results of interpolation with the results of classical mapping (van Kuilenburg *et al.* 1982). They suggested that kriging did not always produce results that were better than those obtained by treating each mapping unit (set of soil polygons) as a homogeneous unit characterized by a mean and standard deviation. Further work showed that the relative success of the interpolation depended greatly on the type of soil and the processes that had controlled its development. Work by Stein *et al.* (1988) and Burrough (1986) has shown that an average variogram for a whole area is often insufficient for distinguishing between the kinds of spatial covariation that may occur in different landscape units. Consequently, it may be sensible to divide the landscape up into major soil units before selecting the soil profiles for interpolation (see Fig. 46.7). There is a possibility that, when a soil mapping unit has multiple occurrences (as is often the case), the spatial variation of any given natural attribute within all occurrences may be characterized by a single variogram. If this were so – and it has yet to be demonstrated – then the parameters of the variograms for each important property could be stored as new attributes in relational tables that are linked to each soil polygon.

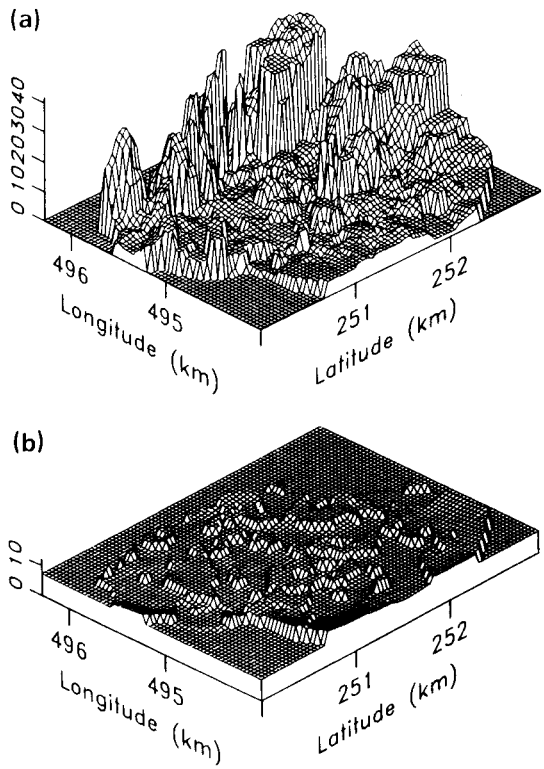

Fig. 46.7 (a) Co-kriged map of 30-year average moisture deficit (MD30) based on stratification according to soil type; (b) Standard deviation of the prediction error. (From Stein *et al.* 1988, Geoderma, Elsevier Science Publishers B. V.)

Co-kriging

Very often data are available on cheap-to-measure attributes but it is necessary to make reliable statements about expensive or difficult-to-measure attributes – for which there are fewer observations available. If there are sufficient data then the expensive-to-measure attributes can be estimated and mapped using one of four approaches : transfer models (i.e. empirical relations between cheap-to-measure and expensive-to-measure soil properties – see Bouma and van Lanen 1987), regression equations, numerical models and co-kriging. Co-kriging is a multivariate analogue of kriging in which the spatial variation of two or more attributes and their joint spatial variation is used to guide interpolation. This is done by estimating the variograms for both attributes and their joint co-variogram (McBratney and Webster 1983b; Alemi, Shariari and Nielsen 1988; Stein *et al.* 1988; Leenaers, Burrough and Okx 1989; Leenaers, Okx and Burrough 1989).

Disjunctive kriging

Many applications in soil survey and environmental assessment do not require that the actual value of a soil property at a point be known with a given confidence level. Often it is sufficient only to know if the value exceeds a given threshold with a known probability. This information can be valuable for management decisions, such as those taken for adding lime (Webster and Oliver 1989), or for evaluating decisions to install septic tanks (Yates and Yates 1988). The use of disjunctive kriging requires point data from sample sites, knowledge of critical levels of the attribute in question and the conditional probability distribution of the attribute. Disjunctive kriging is particularly useful in situations where data are non-normally distributed.

APPLICATIONS

Many national soil survey agencies, such as the USDA Soil Conservation Service, the Canadian National and Provincial Agencies and the Dutch Soil Survey Institute (now part of the Staring Institute for Integrated Land, Water and Rural Survey) use GIS, as described above, as general tools for mapping and providing soils information to users. In many cases, the use of GIS has become standard rather than innovative and many regular products of these organizations could not be produced without automation; the latter ranges from the electronic collection of data to the production of digital maps. The wide range of applications can be illustrated by examining some of the ways in which soil data are now being analysed.

Soil data in a GIS can be manipulated in several ways even when only the digital soil map and associated attributes are used. A greater range of manipulations is possible if the data from the soil profiles are also used to create new single or multiple property overlays (e.g. by interpolation or modelling). Non-spatial applications (where, for example, only the soil profile data are used as happened in many earlier soil information systems) will not be mentioned.

Using the soil polygon map and associated attributes

Regardless of its scale, the soil polygon map can be used to create derived maps in the ways shown below.

Renaming, reclassifying and recolouring of the polygons

These actions are based upon a logical evaluation of the associated attributes. One example is the creation of a map of the major soil texture classes by renaming all the individual soil units in terms of the texture classes of the map units. Note that there is no difference here whether the graphics data are held in raster or vector form. These kinds of empirical functions are sometimes called transfer functions (see Bouma and van Lanen 1987). Plate 46.2 shows a typical land evaluation procedure using a GIS.

Logical overlays of the soil polygons with other coverages

Soil polygons are frequently overlaid with other 'coverages' such as climatic zones, soil parent material or land use to yield new composite overlays indicating various grades of soil suitability. These overlays can be computed when the graphics data are held in either raster or vector form. Typical applications are in natural resource management

(Walsh 1985), rangeland management (Best and Westin 1984) or land evaluation (see Plate 46.2).

Calculation of new attribute values from those for the soil polygons

For example, estimates might be computed of annual soil loss (A) from the Universal Soil Loss Equation

$$A = R \times E \times S \times L \times C \times P$$

from annual rainfall (R), the erodibility of the soil (E), slope angle (S) and length of slope (L) computed from a digital elevation model, and land cover (C) and protection indices (P) from land use and cropping overlays (Wischmeier and Smith 1978). The model can be applied in two ways. For vector overlays, the model can be applied once to the set of attributes for each individual polygon; the polygon network then shows the distribution of the results of the calculation. For raster overlays, the model can be applied to each pixel position separately. This requires much more computing but permits a better spatial resolution to be used because single pixel estimates of slope and slope length can be used instead of polygon-lumped averages. The same approach can be used with other models, such as crop yield models and simple land evaluation models (cf. Bouma and van Lanen 1987; Dumanski and Onofrei 1989). Heuvelink, Burrough and Stein (1989) have studied the use of geostatistics for understanding error propagation through these kinds of models.

Retrieval of profiles within polygons and generation of new polygon attributes

One such example is the computation of the average clay content of the topsoil and its variance for a given class of soil. The computed attributes can then be added to the list of soil mapping unit attributes in the relational database. An instance of this approach is a recent Dutch Soil Survey study to analyse the phosphate loads of soils in a small catchment in The Netherlands (Breeusma *et al.* 1989).

Using the profile data

Estimation of quantitative descriptors of soil properties

This includes means, modes, variances and semivariances of all quantitative soil properties. As described earlier, the semivariances give an estimate of the spatial autocovariance structure of the attributes (which is often expressed as the variogram); they can be used for interpolation, for designing sampling schemes and for simulating the spatial variation of soil attributes both within polygons and over the landscape at large. Statistical tests can reveal how meaningful the division of the landscape into soil polygons has been. If profile data have been collected using a nested sampling strategy, then useful estimates of the appropriate sampling spacing can be made (Webster 1977; Oliver and Webster 1986; Riezebos 1989; Webster and Oliver 1990).

Production of single-attribute maps by interpolation from the profile data

These maps can be made by standard non-statistical interpolation methods but if possible should be made using geostatistical methods (e.g. kriging). Co-kriging may allow expensive-to-sample attributes to be mapped more reliably from observations on cheap-to-measure attributes. Multi-attribute maps can be made by first submitting the profile data to principal components or principal coordinates analysis and then mapping the principal component scores. If the results of these interpolations are mapped as blocks on a regular grid (block kriging), the resulting overlays can be used with other coverages as indicated above. These methods are finding increasing use, particularly for soil pollution studies (see Leenaers, Burrough and Okx 1989; Leenaers, Okx and Burrough 1989) and erosion studies (Beurden and Riezebos 1988).

Creation of crop yield or other quantitative models from soil profile and other data

The results of these models can then be interpolated to give new coverages – see, for example, van Diepen *et al.* (1989); van Lanen *et al.* (1990) or Petach and Wagenet (1989). There are many different kinds of crop model, most of which have been reviewed by Dumanski and Onofrei (1989). Plate 46.3 is an example of crop yield modelling using a large soil database (van Lanen *et al.* 1990).

All these different ways of manipulating soil data in GIS are currently used in projects ranging from international scales (e.g. SOTER – Baumgardner and van der Weg 1989 and the European Community CORINE Project – Verhey 1986) through national soil advisory systems in large

countries (e.g. Mausbach and Reybold 1987) to land evaluation in developed countries (e.g. Meijerink, Valenzuela and Stewart 1988; Batjes and Bouwman 1989) where soil data are often used in combination with remotely sensed data (Helldén 1987; Olsson 1989). Soil information systems are not just limited to large national soil inventories but are currently also used for local studies on agricultural experimental farms, for real-time control of fertilizer placement in the tractor cab (Robert and Anderson 1987; Robert 1989) and for soil pollution studies (e.g. Leenaers, Burrough and Okx 1989; Leenaers, Okx and Burrough 1989).

CONCLUSIONS

GIS are not new to soil science, but have been introduced into the profession during the last 15 years. Although the original soil information systems were limited to soil profile data, the recent developments in mapping technology, interpolation methods, remote sensing and modelling have provided soil survey and environmental agencies with useful tools that are used for standard production of maps and reports and for research. The impact on soil science has been gentle but profound as soil scientists have gradually moved from a descriptive to a quantitative science. As a result of being able to handle much larger volumes of data, soil scientists have come to grips with the difficult problems of describing the spatial variation of soil and they are now providing useful information services to a wide range of different kinds of land user, ranging from urban planners in western countries to land resource experts in developing lands.

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