SOIL DESCRIPTION AND MAPPING FOR LAND USE & MANAGEMENT

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ABSTRACT

Three soil surveys conducted on the Singleton Training Area examined limitations in the traditional Soil Landscape approach and investigated an alternate approach based on airborne measures of gamma radiation (radiometrics) and catenary position. All surveys embodied procedures for describing and analysing soils using objective measures so as to provide an indication of the reliability of the information. This paper outlines the concepts behind the methods using analogies between the classification of soils, species and plant communities.

The requirements for a soil classification scheme suitable for management are considered in relation to scale. It is suggested that the basis for most classifications is climate and topography when parent material and topography are most important in management. Also, most classifications are limited in practical application because soils are categorised or assigned to a soil type before the spatial relationships between soils are analysed.

The procedure proposed is analytical in seeking to determine the soil properties that best discriminate between soils in the area of interest. The structure for any associated classification is given by a sampling strategy, with descriptions being based on the measured properties. The selection of variables used to describe soil properties is discussed in relation to the development of the soil profile, with a focus on the use of continuous or pseudo-continuous variables to facilitate analysis.

The procedures outlined provide a means of determining and mapping patterns of soil properties at a level of detail appropriate to land use and management. They identify the causes and significance of differences between the mapped soil categories, and allow testing of the reliability of the generalisations. The procedures also provide a means of labeling the mapped soil categories in a manner that facilitates communication in that the descriptions have similar significance regardless of the area of application. These procedures have been incorporated in a comprehensive methodology called SoilSelect.

INTRODUCTION

Procedures for mapping soil information relevant to management were examined in three surveys on the Singleton Training Area that focused on identifying and mapping statistically significant soil classes (Tunstall and Gourlay, a., Gourlay and Tunstall, a., Tunstall et al., a). The mapping and associated soil sampling used a GIS implementation of the landscape mapping approach, and numerical analysis of airborne gamma radiation data (radiometrics). The descriptions, and analysis of significance, were based on measurements of soil properties.

The application of airborne radiometrics in soil mapping was novel when applied at Singleton, but this simply represents an alternate means of mapping patterns related of soils compared with an interpretation of the landscape. The method of soil description, and the provision of information on reliability through statistical analysis were also novel, and involved changes in concepts and approach.

As the focus on soil properties and statistical significance, and the use of radiometrics differ from convention, issues have arisen concerning the aspects of soils being classified, the relationships between the derived information and that provided by traditional procedures, and communication of information to allow application in management. These issues are addressed here.

Results from new procedures are usually compared with results from prior studies to assist comprehension. This approach has limited applicability here because the results from the different approaches differ markedly in nature and form. The series of papers on Singleton were designed to:

a. Identify the 'best' results that could be obtained using the Soil Landscape approach by reference to a highly detailed implementation.
b. Identify the limitations in the results provided by the Soil Landscape mapping implementation.
c. Implement a alternative procedure that addresses theoretical and practical limitations of the Soil Landscape method.

This paper examines the concepts behind the different methods, and identifies similarities and differences by reference to analogies between the classification of soils and vegetation.

CONTEXT

General Requirement

Traditional soil survey characterises soils by reference to an existing (prior) classification, with that of Isbell (1996) currently regarded as the Australian standard. Such identification of soil types involves an interpretation of the genesis of the profile as well as the identification of soil properties. An alternate procedure was used at Singleton whereby an analysis of soil properties was used to determine the characteristics that best discriminate between soils in the area of interest. This objective analysis of measured properties without the need to interpret genesis enhances the discrimination of soils and provides a measure of the reliability. It also provides information of direct relevance to management, such as soil depth and pH.

Classification systems are primarily designed to facilitate communication of complex systems through standardising the collection and presentation of data. However, classification systems are often also expected to provide a means of comparing and analysing data in a way that improves understanding. Soil classifications are usually designed to reflect the processes of soil formation, thereby providing a natural classification.

Plant and animal taxonomies provide the best examples of natural classifications and the concepts behind most soil classifications are modeled on biological systems. This may be considered appropriate because of the 'evolutionary' development of soils, but there are differences between the development of soils and the evolution of species. Genetics dictate the occurrence of a phylogenetic sequence with biota but for soils there is no such causal mechanism. Parent material influences soil development, but so do other factors such as climate. Also, several sources of parent material can contribute to a soil profile.

The evolutionary sequence of species defines an essentially rigid structure for plant and animal taxonomies that does not arise with communities. Vegetation communities are loosely defined assemblages of species, and their formation is not constrained to follow any set pathway. The development of communities depends on the species complement and the prevailing environmental conditions and is therefore similar to soils in reflecting the interaction between mixed materials and the environment.

The main concepts concerning development of vegetative communities are generally attributed to Clements and Gleason. These concepts represent the extremes with Clements (1916) suggesting the existence of a defined temporal pattern of vegetation development, represented by a successional sequence that leads to a maximum or climax. Gleason (1926, 1939) viewed vegetation as a continuum and essentially suggests that set patterns of community development do not exist.

The climax theory was developed by inferring temporal sequences from spatial patterns where this has been developed by Whittaker (1953). The continuum theory is based on the observation that a community derives from the interaction between its component units where this allows for an essentially infinite number of outcomes because of the number of factors involved. McIntosh (1967) and Anon (1968) address these conflicting views in detail. This divergence of views concerning complex systems that develop through the interaction between multiple components and controlling factors has parallels in soil description.

The climax theory has been modified and adapted on many occasions to accommodate reality. The initial theory was based on the concept that communities develop to a climax, but the concept of a post climax community, amongst others, had to be rapidly introduced. Gleason's theory similarly has deficiencies as it suggests there should be no spatial patterns where pattern can be shown to occur (a continuum of environment does not necessarily result in a continuum of vegetation). Each approach to characterising the development of communities can be shown to be deficient.

The differences in opinion between Gleason and Clements, and the limitations when applying their theories, are associated with considerations of scale. Clements addresses outcomes while Gleason addresses process. Clements interprets regional pattern from environmental considerations while Gleason examines local pattern by considering interaction between individuals and their environment.

There is little doubt that climate largely determines the broad patterns of vegetation as evidenced by communities such as deserts and rain forests. Climate similarly determines broad patterns of soil characteristics. Regionally, climate is moderated by topography as it affects factors such as insolation, rainfall and runoff, and this moderation influences patterns of vegetation and soils. However, at regional levels the species complement also strongly influences the form of the vegetation. Deserts in America are markedly different from those occurring in a similar climate in Australia because of the species complement. Soils exhibit similar patterns with areas being subject to recent glaciations being markedly different from those in old weathered landscapes regardless of the current climate.

The above suggests that the validity and applicability of generalisations, as provided by classifications, are scale dependent. Interactions between individuals have a marked influence on the patterns of vegetation at local scales but are obscured in regional and global analyses. Differences in the mineralogy in determining soils will be more important at local than global scales because climate need show little variation across individual regions. Locally the climate can often be regarded as uniform.

Management operates at the local level, thus the climatic emphasis in most soil classifications makes them inappropriate for use in management. Consequently, there are increasing calls for surveys where the maps provide information on soil characteristics that is land use driven (McKenzie, 1991). A 'utilitarian classification' has been sought so as to organise soils into classes which show their relative suitability for a particular use (Hausenbuiller, 1985).

Every classification should serve some purpose and hence have utility. The issue relates to the utility that it serves as this determines the constraints that form the framework for the classification. Most existing soil classifications are designed for application at continental scales and so have utility in examining the development of soils in response to the environment. The utility considered here is land management, hence climatic effects on soils are of little consequence. The climate is generally effectively uniform for management areas and cannot be altered, whereas parent material and topography usually vary throughout a management area. A classification developed for the purpose of land management should therefore focus on parent material and topography.

Soil types are employed with traditional soil survey to provide general applicability, hence the desire for a unified Australian classification. However, interpretation of the characteristics of the soil types is required at each location to provide the detailed information required for management. Conversely, soil properties such as depth and pH have general applicability in management but alone do not provide a description or label for a soil useful for general communication. For management, the procedures should directly provide the information needed for management without the need for interpretation and a labeling procedure that has general applicability.

Evaluation of Soil Mapping for Land Management

Reference Soil Measurements

Evaluation is conducted against some reference, standard, or objective. Classifications as given by Isbell (1996) seek to provide an absolute reference, but they only categorise soils according to attributes considered important in reflecting profile development. Given the number of factors considered, and the lack of clearly defined boundaries, such categorisation reflects subjective assessment as to the significance of different attributes in reflecting profile development. The assessments can be supported through general observation but can never rigorously tested, and the boundaries between categories can rarely be accurately defined nor substantiated. Logically, even if a single correct classification does exist, there is no means of identifying that it has been produced.

The existence of a definitive, natural classification would theoretically address all applications. The absence of such a classification means that classifications must be specific to the application, as they are in practice. This approach provides simple solutions to issues where the applicability of the solutions can be readily defined and routinely tested.

There can be no absolute test of the accuracy of soil mapping and the applicability of the information will depend upon the need (the land use), and the ease of implementation. The main objective test is provided by an analysis of the reliability of extrapolation (spatial extension of point field observations) where this strongly reflects the methods adopted. The usefulness of the mapped and reported information is primarily subjectively determined by users. The extent to which the mapped information is used provides a basic indication of benefit and applicability.

Sampling Structure

Circularity can develop in the examination of the spatial patterns of soils where the sampling is based solely on existing concepts concerning the importance of factors in determining spatial distribution. The analyses can determine the variance explained by factors incorporated in the sampling regime but cannot demonstrate that the procedures used provide the best result. In consequence, current views about the requirements for the collection of soil data tend to reinforce existing views and concepts, but they seldom test the extent of their validity. Deficiencies in knowledge of spatial patterns of soils limits the development of concepts, while the application of existing concepts has limited the development of knowledge of the spatial patterns. Gunn (in Gunn et al., 1988) for example, suggests that geology is only important at the broadest level despite the effective absence of analyses examining the relative significance of parent material and topography.

This circularity arises in part because of the lack of an absolute reference for soils as without a reference there can be no absolute test of reliability, and hence no reliable basis for comparing results from different methods. However, it also relates to the poor ability to map soils as, even if soils were unambiguously defined, there is no means to unambiguously map their distribution to provide a reference for comparison of mapping procedures. For agricultural management these deficiencies are addressed by determining the extent to which the defined soil patterns accord with crop and pasture response. A similar evaluation can be conducted using local distributions of native vegetation provided the disturbance history and developmental patterns of vegetation are known.

The use of vegetation to assess patterns of soils is difficult because of confounding due to other factors. For example, knowledge is generally insufficient to allow evaluation of the relative significance of parent material and topography at the local scale despite the occurrence of classic examples, as with the change from rainforest to wet sclerophyll forest with change from basalt to granite in the Lamington National Park. Despite the very limited analysis, most comments suggest that topography is much more important than parent material in determining patterns of soils and vegetation.

The experience of the author is that parent material is at least as important as topography in determining the floristic composition and structure of native vegetation, and that local vegetation patterns are associated with differences in soils. In the Shoalwater Bay Training Area (SWBTA) in central coastal Queensland a change in vegetation from bloodwoods and stringy barks to gums and boxes is associated with a change in parent material. Fine differences in soils are associated with this change but two previous surveys (Gunn et al., 1972, Grant et al., 1979) did not discriminate the areas (the parent materials and soils were regarded as equivalent).

The observation of floristic changes associated with parent materials in SWBTA led to the application of airborne radiometrics. The paper by Tunstall et al. (1990) on SWBTA identifies patterns in vegetation related to radiometric patterns where these patterns were not detected in the prior surveys. However, that paper only identifies a few of the many associations that have become apparent following improved identification of patterns of parent material. A further example relates to the distribution of poplar box (*Eucalyptus populnea*) and grey or gum-topped box (*Eucalyptus mollucana*). These species occur on very similar soils in identical edaphic locations but they rarely (essentially never) grow together. In SWBTA they occur on different parent materials and in association with different species. The species most commonly occurring upslope from gum topped and poplar box are lemon scented gum (*Eucalyptus citriodora*), and narrow leafed ironbark (*Eucalyptus crebra*) respectively, where these associations are distinctive but have yet to be quantified. The associations were not observed in the prior surveys because of the methodologies used.

The limitations in the methodologies used in the prior surveys in SWBTA relate to the focus on topography with only general attention to parent material, and the analysis of spatial data using procedures that do not take spatial relationships into account. For example, the approach to vegetation analysis used by Walker (in Gunn et al, 1972) compares floristic composition across samples treated as being independent and spatially unassociated. The analysis is completely unstructured and there is no way of determining if some species or floristic associations always occur in close proximity to others. The Singleton results (Tunstall and Gourlay, a), where catenary position was insignificant when treated as a factor and significant when treated as a variable, illustrate the importance of taking spatial relationships into account.

The general conclusion is that the sampling structure used for evaluation should take account of the characteristics of the system and address all factors that could be significant. For a landscape based approach, the minimum requirement is to be able to separate the effects of parent material and position in the landscape. This approach provides the best evaluation of the applicability of results and maximises the effectiveness of field measurements.

Mapping Procedures

Basic Stratification

The mapping and associated sampling of soils in Australia is generally currently achieved by:

a. Subdividing the area into broad geological categories.
b. Subdividing the broad geological categories according to broad morphological characteristics such as elevation or local relief amplitude (geomorphology).
c. Subdividing the geomorphological categories according to position in the landscape (catenary position).

This approach has been reinforced by the available technology. The idea that changes in landscape features coincide with the boundaries between soils has enabled most soil mapping to be conducted by the interpretation of aerial photographs (API). While some soil mapping systems focus on parent material (Turner et al. 1990), the traditional and generally applied methods represent an interpretation of the landscape, and hence focus on topography.

Statistical analyses examining relationships between soil properties and parent material and position in the landscape (catenary position) for SWBTA (Tunstall et al., 1998b), Singleton (Tunstall et al., a), and Mt Bundey (Tunstall et al., 1998a), support the view that parent material is at least as important as topography in determining patterns of soil properties. The number of significant relationships between parent material and soil properties in these studies was around five times greater for parent material than topography, and topographic effects were usually only significant after the effects of parent material had been accounted for. Reliable mapping of soil information for use in management should therefore be based on detailed consideration of the parent material.

Description Detail

The tendency in soil survey is to obtain highly detailed measurements for few sites. This facilitates interpretation of genesis and allows the presentation of detailed descriptions in reports, but the limited number of observations and mode of description usually prevents analysis of the validity of spatial extrapolation. The level of detail given in the descriptions greatly exceeds the capacity to reliably map the information.

For practical application the soil description need not be detailed provided the appropriate information is determined and can be reliably mapped. There should be a balance between the level of detail provided by the measurements and the ability to map that information. Any bias in development should likely be directed towards improving the discrimination of mapping as the existence of a detailed and reliable map generally allows ready determination of additional important soil properties. This requirement is met by maximising the number of sample sites, and measuring the soil properties that maximise discrimination in the area of interest.

SOIL DESCRIPTION

Measurement Characteristics

Number of Variables

Plants provide a reference for the development of descriptions for use in classifications because of the well-established taxonomy. Plant taxonomy has centred on descriptions of flowers and fruits as the reproductive parts of plants are highly specialised structures that reflect genetic origins. Alternate methods have been applied, the most common being to suggest that a classification would best be based on all available information. Numerous variables are measured and the patterns or groups determined statistically. This ‘shotgun’ approach has met with limited success because measures reflecting phylogenies are masked by measures that are either held in common or vary independently of phylogenies. That is, some variables are more important than others in determining characteristics and measuring all possible variables will not necessarily give the best classification.

The soil variables considered important will vary with the characteristics of the area and land use, which suggests that numerous classifications may be required. However, measurement of some variables allows calculation others. Derived variables are calculated using defined (necessary) relationships, while correlations or empirical associations between variables can be used to predict the likely levels of unmeasured variables. Such statistical relationships can have limitations due to the validity of the result depending on the range of observation but this can still be a viable option.

The variables used to construct the classification should address the application, but they need only define patterns at the finest level of detail required as lowest order taxa can be grouped to form higher taxonomic levels as required. Also, for practicality, all variables should be capable of being readily and objectively determined. These constraints allow identification of a minimum or core set of variables that can be used to determine the significant patterns of soil properties where this initial determination of pattern allows reduced sampling for variables that are difficult and/or expensive to measure.

Type of Variable

Land users and managers must readily understand the information provided on soils for effective and efficient application. The users must be able to locate the different soils in their area and understand the relevance of the description to their application. This requires either accurate maps, or that users be able to readily identify soils in the field. It also requires knowledge of associations between soil descriptions (eg. soil types) and their need or application. None of these requirements is currently being adequately met. Soil landscape maps poorly define the spatial pattern of soils, and the soil types in most soil classifications can usually only reliably be identified and interpreted by soil scientists.

A view exists that problems associated with the application of existing soil information in management can be resolved by employing more soil scientists. This approach cannot work because soils are important for all land use and management. There can never be sufficient soil scientists to meet all needs and any increase in resources applied to soils would increase the deficiencies in other areas. The appropriate solution is to develop methods that allow more general application of soil information.

The problem of application was addressed by the Northcote (1979) system for soil classification. Soils are described using a small number of readily measured variables considered most indicative of soil development, and are classified using a well defined but artificial logic. Despite the debate as to the value of this system it gained widespread use because of the ease of comprehension and application.

Much of the debate surrounding the Northcote system centred on the value of the variables, particularly the relative emphasis placed on variables in the classification. Carbonate concretion, for example, is given high importance, and this has particular relevance in the region in which the classification system was developed. However, carbonate concretion is of little consequence across large areas of Australia. The use of colour has been similarly criticised, and this can be used to illustrate the limitations of soil types when mapping soils.

The Northcote description of soil type is derived by identifying categories for variables such as colour, and profile trends for pH and texture, and this type description is used to analyse the distribution of soils. The application of a prior classification invokes judgements as to the natural subdivisions between soils that cannot be tested hence the significance and validity of the final typing are difficult to ascertain. Soils in a study area can be either yellow or red, or a mixture of yellow and red depending on the thresholds used in the classification. Application of the Northcote and other classification systems introduces significant limitations due to application of the classification prior to the analysis of the patterns of soils as the classifications largely determine the outcome.

The alternate approach to using a prior classification is to describe soils using generally known and understood physical and chemical variables, such as depth and texture, and to group the soils into classes (classify) according to relationships between the measured soil properties.

Profile Characterisation

Another suggested limitation of the Northcote system is the assumed existence of a vertical structure to the soil profile. A principal profile form is assumed that requires an ability to discriminate A1, A2, B and C horizons. This need for horizon recognition introduces some limitations but it is difficult to see a practical alternative. The ‘correct’ alternative is to measure a continuous profile and make judgements on profile development after all measurements have been taken, but this is impractical. Another is to take measurements at set intervals and likewise make judgements based on the measurements, but this is inappropriate because the intervals of importance vary considerably within and between profiles. The practical solution is to identify locations of change and characterise the significance of the changes through measurement.

An analogy can be drawn between principle profile form and vegetation structure. The structure of vegetation is usually considered to be layered, where the layering relates to the relative sizes of the life forms of components such as trees, shrubs, grasses, forbs and lichens. The clarity of the layering varies considerably and in some instances may be absent, but where present it provides a convenient means of improving the resolution and reliability of a classification without recourse to high-resolution measurements. For example, a 10% measurement accuracy would effectively allow the reliable recognition of 5 categories of tree cover, but combined with measures for grasses and shrubs the number of categories that could reliably be distinguished rises to 125.

The example of vegetation structure has further relevance to soils as vegetation was traditionally described using floristics. In Australia vegetation is now most commonly described using structure, with the dominant species often being identified to provide additional resolution and information. The reasons for the change were three fold. Reliable floristic information is difficult to obtain, analyses of floristics poorly define vegetation communities (boundaries between communities are diffuse, and the communities identified vary with the methods used and the range of observations), and the results of a detailed floristic analysis are difficult to interpret and apply. Vegetation structure is comparatively easy to determine and its relevance is easy to comprehend because of the physical rather than categorical basis. Structure has been found to have greater relevance than floristics for some purposes because of the physical (functional) basis.

The functional basis for a structural description of vegetation is simple as the structure of systems largely reflects the balance between the conflicting requirements of absorbing radiation and CO2, and conserving water. The vertical structure of soils similarly has a functional rationale with the A1 horizon being a zone of accumulation of organic matter, the A2 a zone of leaching, and the B a zone of accumulation of clay and ions. The movement of water through the profile and of water ions by vegetation develops a vertical structure.

While soil and vegetation systems have similar structural characteristics by way of depth and openness of vertical layers, there is a major difference as vegetation develops from the bottom up while soils develop from the top down. The lower limits to a soil profiles are often not as well defined as the upper limits to vegetation, and structures such as pans can be difficult to accommodate using a ‘standard’ profile form.

Descriptions based solely on vertical layering assume horizontal homogeneity within layers, which is appropriate for some soils but not others. The issue relates to scaling and the degree to which an average measure characterises a given situation. There is no single or simple answer and the usual approach when modeling soil processes is to assume vertical homogeneity within layers or horizons and lateral homogeneity within mapped areas. Situations where this is inappropriate are treated on a needs basis rather than attempting to apply a complex general solution.

For soil survey the requirement is to maximise the discrimination between soils, where this is best achieved by sampling at points that reflect maximum profile development. Conceptually these are the zones of maximum leaching (A2) and accumulation (B2), where this conclusion is supported by statistical analyses associated with radiometric surveys.

Variable Selection

The main constraints affecting the selection of variables determined during survey are that measurements should be rapid and reliable, and be amenable to analysis as a continuous variables.

Core Structural

The simplest structural description of a soil profile would be the thickness and openness of the soil layers. Thickness can usually be determined from depths to the horizons but the thickness of the A1 can be difficult to determine in many areas because of the nature of the soil profile and/or disturbance. Measurement of the thickness of the B horizon is desirable but may not be warranted because of the time and effort required for its determination. Also, measurement cannot be guaranteed for hand based sampling where soils have high gravel contents.

Openness is less well defined and has traditionally included considerations such as texture, bulk density, fabric, air porosity and hydraulic conductivity. Texture and bulk density appear to be the most useful variables that can be readily determined during survey. Field estimates of texture are often confounded because of the difficulties of discriminating between organic matter and clay, and the measure lacks sensitivity at high clay contents, but field texture can be consistently determined and hence be useful for discriminating between soils.

Accurate estimates of bulk density can be difficult to obtain but simple procedures can provide adequate resolution for survey. However, even simple measurements are often time consuming, and the determination of bulk density may best be accomplished after the significant patterns of soils have been determined from other variables.

The most common structural feature not identified above is the occurrence of gravel. This is generally given low significance in soil classifications but has a marked influence on the water holding and penetrating characteristics of the soil as well as root behaviour. Gravel effectively decreases the water holding content of the soil proportional to its occurrence. The proportion of gravel in soils should therefore be a core measure and can readily be objectively measured by sieving.

Statistical analyses indicate that texture is generally strongly positively correlated with profile thickness and, of the structural measurements, texture provides the best discrimination between soil patterns mapped using the airborne radiometrics.

Core ‘Chemical’

The simplest chemical description is given by the pH and colour of the soil layers. Soil pH is strongly related to the parent material with surface measures being moderated by vegetation. Soil colour is influence by many factors such as parent material, leaching, waterlogging and organic accumulations (Stace, 1956). This dependence on a number of factors potentially limits its use but, sampling according to an appropriate design allows some separation of effects, thus colour may be a useful variable (Gourlay and Tunstall, a).

Colour is of most consequence in identifying the level of oxidation / hydration, where the oxidation-reduction potential can be objectively measured. Moreover, the oxidation-reduction potential (Eh) can be converted to a measure of concentration (pe) comparable to pH. As the solubility of ions depends on the ratio of pe to pH this ratio is significant in soil profile development (Bass Becking et al., 1960). Of the chemical measures, the ratio of pe and pH appears to provide the best discrimination between soil patterns mapped using the airborne radiometrics. The main limitation relates to the need to determine the Eh shortly after obtaining the soil sample.

Specific conductivity can be rapidly and objectively measured and provides information useful for management. However, dispersibility should additionally be measured where salinity is an issue to provide an indication of sodicity.

Ancillary

The above variables provide the basic or core measurements and situations will arise where these do not provide the required level of discrimination between soils, or where they do not provide the required information. These situations can, and usually should be treated differently. The survey must discriminate between the soils of interest, hence any limitation in this regard must be addressed during the survey. However, deficiencies in information on the soils can be addressed either by collecting the required information during the survey or by subsequent sampling based on the patterns determined from the core variables. The latter option is most efficient for time consuming and expensive measurements.

The main limitations in the core measurements relate to information required for modeling processes such as the hydrologic regime, and the determination of fertility. These properties address specific requirements that are cost effectively met by sampling according to patterns identified from core properties. The expense of measurements for hydraulic conductivity and fertility places a premium on the effective location of sample sites.

Pans and other accretions represent significant structural and chemical features associated with soil development not characterised by the core measurements. They most commonly occur as pans or nodulations towards the base of the B horizon, but in the case of pisoliths can be abundant in the A horizon to the point of constituting more than half the volume. Pans and accretions should always be characterised even though there is currently no obvious means of conveniently analysing the results because of their categorical nature.

ANALYSIS

Variables

Categorical data, such as soil types, can be statistically analysed but with limited effect. Soil types are defined as either the same or different, and the analyses examining reliability seldom allow determination of levels of similarity or difference. The ideal situation is to record all soil properties as continuous variables but this is seldom possible. The procedure used at Singleton was to measure properties as continuous variables wherever possible, and to convert categorical data to pseudo-continuous variables for analysis.

The derivation of pseudo-continuous variables from categorical data can introduce limitations, but these are minimal with linear sequences such as catenary position. The limitations can become significant when multi-dimensional data are reduced to a single dimension, as with texture and colour. The question to be addressed is the degree to which any reduction in the validity of the results arising from the approximations inherent in the simplifications compares with the benefits derived from improvements in the analysis. This question can be difficult to resolve as the answer can be case specific, but the ability to determine the reliability of results where this was previously seldom done because of the mode of collection and presentation of data confers considerable benefit.

Sampling Stratification

The sampling structure depends upon the detail provided by the base or reference map used to extrapolate results. The requirement for horizontal stratification can be met by identifying blocks of parent materials, with sampling stratified according to parent material and catenary position, or by identifying patterns of parent material and weathering in the airborne radiometrics. General geology maps do not provide the detail on parent material required because of the focus on hard rocks hence additional information, as provided by radiometrics or a regolith map, is required to identify sampling patterns.

Parent Material

The radiometrics mainly reflect parent material and weathering and hence do not unambiguously identify patterns of parent material. Interactions between the two controlling factors can produce the same radiometric signal from different materials, and this can be common at low emissions as the signal to noise ratio limits discrimination. Some of this confounding can be reduced through analysis of the spatial and spectral characteristics of the radiometrics alone, as with Tunstall and Marks (1998a). Careful reprocessing of data involving griding as well as classification allowed identification of narrow bands of transitional classes that defined the boundaries between some materials. However, the uncertainty can only currently be completely removed through field observation.

High-resolution radiometric data almost invariably discriminate catenary patterns, thus blocks of parent material are usually represented by a number of radiometric classes. Each radiometric patch can be regarded as unique, as at Singleton (Tunstall et al., a), but sampling each radiometric patch is inefficient. That is, while the catenary (weathering) information in the radiometrics is useful for mapping patterns of soils it hinders the development of an efficient field sampling strategy. The initial requirement for the development of an efficient soil sampling strategy is therefore to attempt to identify blocks of parent materials by reference to the available geological information, the radiometrics, and other geophysical information such as magnetics. Field observations are usually also required, where these are best associated with an initial soil sampling program.

The identification of blocks of parent materials allows removal of confounding in the radiometric classification. Classes indicative of different soils in different parent materials can be split to remove ambiguities. The classes in the revised radiometric map can then be used as a basis for field sampling.

Landscape

The usual stratification is to sample according to catenary position where this involves an interpretation of the landscape. For Singleton this categorisation was sequenced according to likely wetness to allow representation of catenary position as a pseudo-continuous variable.

Landscape effects can be represented as a continuous variable without the need for categorisation of catenary position but this still involves some form of interpretation. The usual approach is to attempt to categorise the potential for erosion and accumulation of material by analysing water flows. No generally accepted procedure exists, but the analyses that appear most useful take account of rates of steady state flow, slope, and curvature (concentrating or dispersing).

The availability of high-resolution radiometric data can avoid the need to characterise the landscape as the radiometrics identify landscape-related patterns in soils. The sampling is then based on patterns known to exist rather than on landscape characteristics thought to be important, and it avoids the need to apply an interpretation of the landscape. As a landscape interpretation effectively cannot be applied in flat terrain, the radiometrics can sometimes provide the only objective basis for stratifying sampling other than through use of inefficient geostatistical techniques.

Profile

The vertical distribution of the properties within the profiles provides further sampling structure.

Model Structure

The sampling regime identifies the model structure where the basic structures identified above are:

a. Parent Material x Catenary Position x Profile Horizon
b. Radiometric Class x Profile Horizon

These model structures are amenable to analysis using an Analysis of Variance (ANOVA) or generalised linear modeling. However, the profile horizon has not been included in the analytical model to date, thus full use has not been made of the available information. The existing statistics underestimate the level of discrimination achievable.

This model structure allows analysis of the relative effects of parent material and catenary position in determining patterns in soils. It also allows analysis of the significance of differences between soil properties for the radiometric classes. Maps can be produced where all mapped classes are significantly different at the 95% probability level.

Alternative statistical techniques can be used to determine soil groups or patterns in data but their applicability is generally limited by the poorly defined analytical structure. Clustering algorithms can be applied to identify similarities in properties among the radiometric classes, and the results can provide a useful overview, but the results are seldom definitive. Neural networks provide an alternative to statistical analysis but their applicability is limited with soils because of the lack of a correct answer (absolute reference).

The strength of generalised linear modeling lies in the sampling structure. This structure allows use of the embedded spatial information (catenary position) where positions can be blocked within transects, and transects replicated within parent materials. The significance of this can be seen in the first Singleton paper (Tunstall and Gourlay, a) whereby effects of catenary position were not significant when treated as a factor but were when treated as a variable. Treatment as a factor assumes no relationship between catenary positions whereas treatment as a variable requires the existence of a defined relationship between positions. The sampling structure and analytical design must examine spatial pattern rather than simply treating profile measurements as a number of spatially unrelated observations.

The weakness of a structured analysis is that it will only determine patterns encompassed by the sampling structure, as illustrated by the second Singleton study identifying soil patterns that were not determined in the first study (Gourlay and Tunstall, a). The validity and applicability of the results from the analysis therefore depend strongly on the reliability and resolution of the categorisation of parent material and catenary position. Considerations relating to profile structure and the soil properties measured are important in determining the result, but their effect on the mapped results is generally less than for the stratification used for sampling.

The influence of sampling structure on the results suggests that this approach only becomes viable where high resolution can be achieved in the discrimination of spatial patterns of parent material. This inference is only partly correct as catenary position can also be used to determine the sampling pattern, and the relative importance of parent material and catenary position will vary with the area of interest. Comparatively, the significance of catenary effects could be expected to be low in areas exhibiting pronounced patterns in parent material but be high in areas of homogeneous parent material. Never the less, the level of discrimination of patterns of parent material will likely always strongly influence the reliability and applicability of the results.

Application of statistical analysis for each soil property identifies the properties that best discriminate soils in the area of interest. It also allows production of thematic maps that identify the distribution of properties, provided that the variance within classes is not high. This association of mean soil property values with mapped classes also provides a mechanism for site selection whereby soils having particular characteristics, say for depth, texture and pH, can be mapped.

Labeling

The soil mapping, sampling and analysis procedures outlined above provide a means of determining patterns of soil properties in a manner that improves understanding. They therefore fulfil one requirement of a classification. This section is concerned with the requirement for communication of soil information in a management context.

Communication of results for a local area is achieved through the spatial aspects of the analysis. The soil map defines the location and spatial extent of the soil properties, and soil categories are identified for particular purposes. However, communication to those outside the area of observation depends on the labeling of the mapped soil categories in a manner that is readily understood, and where the labels have general applicability. The labels applied to the soil categories should have similar meaning regardless of the area of application.

The procedures for labeling the radiometric soils map in the third Singleton study (Tunstall et al., a) illustrates a generic method for labeling using the measured soil properties. The analysis of data provides mean values of properties for the classes where these can be converted to descriptive categories through use of simple decision logic. For example, the procedure for converting categorical descriptions of texture to pseudo-continuous variables can be reversed to obtain a texture description for the category. Similarly, soil depths can be categorised as convenient for description, eg, shallow, intermediate or deep. Soil pH can be categorised according to the degree of acidity or alkalinity, or the reaction trend.

The labels assigned to the radiometric soil classes at Singleton were based on the depth of the A horizon, the texture contrast between the A and B horizons, colour and texture. These variables were important for discriminating between soils in that study but alternate labels could be developed where other variables are found to be important. For example, colour could be omitted and replaced by the pH or reaction trend, while gravel content was important in the Northern Territory (Tunstall et al., 1998a). However, texture and the depth of the A horizon appear to be basic requirements in the label. The full complement of descriptors important in characterising the soils in the radiometric mappings were given in an accompanying table (Table 4, Tunstall et al., a).

The labeling system developed to date centres on soil properties and does not contain specific information on parent material or the processes of soil formation. These could be added, as through use of a prefix based on geological categories such as basaltic, granitic or sedimentary. Alternatively, descriptors indicative of the mineralogy and hence development of clay minerals could be used. Information on geology is simplest to provide whereas information on mineralogy is probably of most benefit but can be difficult to obtain.

Information on soil genesis should likely be provided as an additional description rather than being included in the label proposed here because of the interpretation associated with its derivation.

Mapping

The radiometric classification used to stratify the field sampling and analysis can provide the base map. Ambiguities arising through a given class being associated with different parent materials are removed by mapping either blocks of parent material, or zones within which the classes are unambiguous (Tunstall et al. 1998a). The latter solution is possible because ambiguities only arise between a limited number of parent materials.

Mapping is more difficult where sampling has been based on catenary position as, for efficiency and objectivity, the catenary positions must be interpreted through numerical analysis of terrain information. The techniques available for such landscape categorisation are improving but are still difficult to apply and the results are of uncertain reliability.

Alternate methods can be used for mapping soils where reference spatial information exists, and where relationships have been determined through field observation. Vegetation patterns determined through numerical analysis of satellite imagery were combined with information on parent material mapped from radiometrics were used to provide a higher resolution soil map than could be provided by the available radiometric data (Tunstall et al., 1998b). With this procedure the vegetation is used as a replacement for the landscape or catenary information. The method used will depend on the availability of information, where derivation of the base map from the radiometrics alone is desirable to maximise opportunities for application of the information using GIS.

Development of the spatial expression of the sampling stratification (the base or reference map), and the associated databases of soil properties for these categories allows production of maps for any desired themes. For example, the distribution of soils having clay textures, depths greater than 50cm, and pH greater than 6 can readily be mapped. Such thematic maps are produced to address specific requirements, as with site selection for particular crops.

Evaluation

The usual approach expected when 'validating' a new technology is to compare results with those obtained using existing methods. However, such direct comparison of results has limited validity and utility as the existing procedures set the standard, and are regarded as providing the correct result. With most comparisons the existing procedures are considered to have no error (100% correct), and the results provided by any new technique must on comparison be less. As there is no absolute reference for soils, this limitation can only be fully overcome by comparing results obtained using different methods with an independent result considered important for the purpose of the soil survey.

The methodology for soil description and mapping proposed here automatically tests the significance of the soil categories, and the reliability of the associated map. The significance of the mapped patterns is routinely tested. However, as noted above, these procedures do not test whether a better result could be obtained using an alternative sampling strategy. A large proportion of the variance invariably remains unaccounted for but without reference to additional information there is no way of determining whether this is random error or associated with significant spatial pattern.

The SoilSelect methodology employs a two stage test of reliability whereby initial field sampling is used to identify classes that either do not provide the required discrimination, or where the differences between classes are two small to be of practical significance. The latter classes are grouped, while the former are split either by reanalysing the radiometric data to improve the discrimination, or by the incorporation of ancillary information such as geomorphology or land use. The latter is most appropriate where the radiometric classes have low signal levels, and allows elimination of errors associated with factors such as irrigation.

A third field sampling could be conducted and this approach is sometimes applied with unstructured models such as neural networks. However, the third sampling serves only to test the robustness or applicability of the model structure to the sample area. It tests process rather than outcomes, and hence would not contribute to evaluating the applicability of the results. The reliability of every application of SoilSelect is routinely tested, and the statistical tests are more detailed and comprehensive than normally applied in research.

The detail of mapped spatial pattern depends on the quality of the reference information, and not all patterns of soils need be mapped. One mile spacing radiometric data, as used at Singleton (Tunstal, Gourlay & Marks, a), tends only to identify lithology, hence landscape related effects must be evaluated and mapped by other means. The mapping techniques is then equivalent to a Soil Landscape approach but with the landscape mapping achieved using the radiometrics rather than visual interpretation of aerial photography and other information. High resolution radiometric data, as obtained with acquisition at 100m flight line spacing and 40m height above the ground, usually additionally maps landscape related patterns.

Situations arise where moderate quality radiometric data readily map the main patterns of soils, and these are commonly geologically simple in containing few parent materials. Situations have also been observed where airborne radiometric data will never map all soil patterns because of the fine spatial detail, and these can be addressed as in the same manner as soil landscapes. The mapped category can be identified as containing several soils. The requirement in field sampling is to separately identify the samples for different soils rather than attempt to obtain averages. This ensures that the statistical evaluation provides a reliable test of the significance of the mapped information.

The practical limitation of statistical tests, that they evaluate the results according to a defined model structure, is addressed in the SoilSelect methodology by involving those with detailed local knowledge in the implementation. A completely independent check is applied to ensure the absence of major errors. This check is often biased towards particular applications, such as agriculture, engineering or biodiversity, but, given the absence of an absolute reference for soils, bias towards particular applications is inevitable.

Independence of Observations

The question of independence of observations arises where the soil map is to be used in subsequent analyses. The soil descriptions obtained during field sampling are independent except where relationships are intentionally defined, as within profiles and between catenary positions. However, extrapolation of the site data using terrain information would result in the mapped soils information being related to other spatial layers that incorporate, or were derived from topographic information. The soil profile descriptions are produced independently from other information used in environmental analysis but information in the associated soil map would not be where the map is derived from topography.

Catenary position and other landscape information are derived from an interpretation of elevation, where elevation is typically used in environmental analyses. The use of terrain information in the derivation of soil landscape maps therefore precludes their use for environmental analyses involving terrain. There is considerable merit, therefore, in attempting to derive the soil map solely from radiometric data so as to maintain independence between the main layers of information used in land management and evaluation. The mapped soil results can then be used to examine relationships between parent material, landscape and soils, and relationships between vegetation, soils and terrain.

The use of terrain information in the development of soil maps, as with soil landscape mapping, greatly limits application of the mapped information in land use applications that involve spatial analysis, as with GIS.

APPLICATION

The above outlines the theoretical considerations behind the development of the SoilSelect methodology. However, the full SoilSelect methodology also includes procedures for facilitating the transfer of soils information for application in management.

As identified above, the traditional methods for describing soils involve detailed descriptions of soil characteristics and require interpretation of the genesis of the soil profile. Development and application of this information requires personnel with high levels of experience and knowledge. Indeed, as with plant species, reference or characteristic soil profiles are used to standardise or calibrate descriptions and classifications of soil types, and knowledge of the reference soil types is almost essential in application. The requirement for such knowledge has restricted the collection and application of soils information.

The SoilSelect methodology is designed to overcome such limitations by describing soils using simple objective measures that are readily comprehendible and generally applicable. Also, the identification of sampling framework allows clear specification of appropriate field sampling sites. This objective measurement at clearly defined sites allows the collection of soil samples by anyone with an interest in soils.

The involvement of farmers and members of land care groups in collecting soils for analysis in the laboratory facilitates the transfer of information. It improves the land manager's knowledge of their environment by improving understanding. It can also provide significant cost savings as the time spent in field sampling represents a the greatest part of the total cost of implementing a soil survey. The participation can also improve the results as the local knowledge can rapidly identify significant limitations or errors in the mapped information. Involvement of the beneficiaries often provides the most effective means of testing the reliability and applicability of results.

The process used to involve beneficiaries in the soil mapping commences with a workshop to explain the nature of the information in the reference map, and the procedures to be applied in field sampling. In particular, tuition is required to illustrate the characteristics of soil profiles encountered in the region to ensure consistency in the pattern of sampling. Use of GPS when locating sample sites is essential.

The first workshop also identifies the needs of the clients or beneficiaries, and the issues they regard as important. These issues are further addressed in a second workshop held to present the results. This second workshop focuses on the application of the results to address the management and environmental issues in the region.

This involvement of beneficiaries in data collection has the potential to decrease the quality of the results due to inconsistencies in sampling. However, the method is sufficiently robust that, while statistical significance may be reduced, the applicability of the results in management is little affected. Moreover, the facilitation of information transfer associated with such involvement compensates for any reduction in quality. Overall, the results are generally improved by accessing the extensive local knowledge.

CONCLUSIONS

The procedures outlined here provide a means of:

a. Mapping spatial patterns of soils relevant to management.
b. Determining the relative importance of soil properties in identifying those patterns.
c. Examining the relative significance of factors in producing the spatial patterns.
d. Testing the reliability of the mapped soil information.
e. Labeling the mapped soil categories to facilitate communication.
f. Transferring information to ensure effective application.

The procedures therefore provide a means of determining, mapping and communicating mapped information on soils at a level of detail appropriate to land use and management. These procedures have been incorporated in a comprehensive methodology identified as SoilSelect.

Development of the SoilSelect methodology was based around the processing of airborne gamma radiation data (radiometrics), but this is only part of methodology. Moreover, the role radiometrics can be filled by other data, as with numerical processing of optical imagery to highlight different lithologies. The essential elements of the methodology are:

a. Mapping of soil related patterns.
b. Field sampling according to mapped patterns, soil property measurement, and statistical analysis.
c. Production of thematic and feature maps, and reports.
d. Conduct of workshops to identify issues and communicate results.

Benefits provided by the SoilSelect technology include:

a. Measurement of soil properties relevant to management.
b. High resolution soil maps (paddock level) across regions, with tests of reliability.
c. Analysis of factors determining patterns of soil properties.
d. Cost efficiency.
e. Development of community awareness and knowledge.

The method is most cost-effective when applied across a region as the regional analysis identifies the main structural or geological constraints to soil development, and the costs are spread across many beneficiaries. However, the method is also cost-effective for small areas where detailed soils information is required.

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