SOIL SURVEYING AND SOIL VARIABILITY

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INTRODUCTION: NATURE AND PURPOSE OF SOIL SURVEYS

The aim of soil surveys is to collect and organize information about soil variation. Soil, whether considered as the medium in which plants grow, or as the superficial zone modified by pedogenic processes, is invariably anisotropic in a direction normal to the ground surface, and also varies more or less continuously from place to place. To deal with this 3-dimensional continuum, the soil profile (or pedon) is usually taken as the unit of study: selected attributes of the soil profile, recorded at regularly or irregularly located sampling points, are used to characterize and classify areas of soil delineated on maps.

The mapped areas may be delimited using external (physiographic) as well as internal (profile) criteria. To facilitate transfer of information, the delineations in systematic general-purpose soil surveys are related to classes (e.g. soil series and great soil groups) in a general system of soil classification based primarily on profile characteristics. Thus, each set of areas identified as a unit by a specific colour or symbol in the map legend represents a collection of soil bodies in which profiles (or pedons) of one or more specified classes predominate.

The usefulness of such a survey depends partly on the attributes defining soil classes, and partly on the accuracy with which areal variability is represented. Ideally, class differentiae should be related to as many other properties as possible; and if the purpose of the survey is to make valid predictions about the use and behaviour of the soil, the properties chosen should be significant for this purpose.

However, to provide an effective basis for mapping, differentiating characteristics must be identifiable in the field, in so far as soil

variability is the main factor limiting predictions that can be made, and few sites can be characterized by tests on samples in the laboratory, compared with the many that can be characterized in the field for the same expenditure. Moreover, some soil properties are seasonally variable, and/or are readily altered over short periods by management. Hence criteria used in soil mapping are the more permanent properties that can be observed or measured in the field with reasonable precision, and related directly or indirectly to land-use potential and management requirements. Ancillary laboratory measurements are made on selected samples: (i) to confirm field estimates of properties used in classification; (ii) to determine additional properties that may serve further to characterize map units, when between-unit variance is significantly greater than within-unit variance.

In current classification schemes for use in soil surveys (Soil Survey Staff, 1960, 1967; De Bakker and Schelling, 1966; Northcote, 1965), the criteria are: (i) presence of identifiable horizons (e.g. argillic horizons of clay accumulation, structural (cambic) B horizons; gleyed horizons, thin iron-pan; peaty or humic surface layers); (ii) texture (particle-size distribution) and stone content of specified horizons or 'reference layers', occurrence of carbonates and other morphological features indicating significant differences in the composition of horizons. Compared with earlier schemes, both soil series and higher categories are defined by specified characteristics that can be directly observed or measured, rather than by inferred qualities, e.g. 'drainage', parent material, or mode of origin. The classes group profiles (pedons) according to their similarity, irrespective of their proximity or of how or where they occur. However, emphasis is placed, in selecting differentiae, on pedological or other features that can be related in their distribution to environmental factors (e.g. land-form, natural vegetation) so that the surveyor can use such relationships to predict lateral changes.

It is in fact the existence of some uniformity in the distribution of soil properties over areas that makes soil surveying possible, as the feasible sampling density is very much smaller than that needed to make reliable predictions if variation were largely random. Thus, one screw-auger boring per m^2 represents a 0.04% sample, and one m^2 pit per hectare a 0.01% sample. We know empirically that adjacent

profiles are usually similar, and Dokuchaiev's postulates relating soil changes to changes in climate, parent material, vegetation, relief and age of ground surface have not been seriously challenged.

VARIABILITY WITHIN SOIL MAP UNITS

Because of lateral variability and sampling limitations, most areas delineated on soil maps include portions containing more than one soil series, even at scales as large as 1/2,500. According to the U.S.D.A. Soil Survey Manual (1951), a map unit can be identified by a soil-series name when at least 85% of each area conforms to one series; otherwise it is named as a soil association, a soil complex or an undifferentiated group, depending on the scale of the map and the pattern of occurrence of the component kinds of soil. However, the few retrospective statistical studies made of variability within map units suggest strongly that this provision is unrealistic when applied to most soil-series maps. For example, McCormack and Wilding(1969) analysed field data obtained on 10 randomly selected profiles within each of 22 delineations on 1/15,840 maps of part of Ohio*, and found that only 37% of the 220 profiles fell within the stated series limits. (When the limits were narrowed in accordance with new U.S.D.A. system (Soil Survey Staff, 1967) for differentiating soil families, only 17% were in the proper family!) In an earlier study in a less complex area (Wilding et al 1965), more than 30% were outside the limits. Accordingly, the current convention in the United States (Simonson, 1968) is that each area of a map unit identified by a soil-series name should include a major proportion of soil conforming to that series, and other soil included should be 'closely similar or form small proportions of the whole'.

SOIL SURVEY PROCEDURES

Recognition that lateral variability is the major factor limiting the prediction value of soil maps, coupled with the need to produce the

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* 'carefully prepared medium intensity surveys': mapping rate 320 acres (125 hectares) per day.

maps as economically and efficiently as possible, has led to critical examination of survey procedures. These may be categorised as grid survey, free survey and physiographic survey (Steur, 1961; Beckett, 1968), depending on the extent to which the mapped boundaries are based on field observations of the soil profile, rather than on associated land attributes as observed on the ground, on air photos, or on topographic maps.

In grid survey, boundaries are drawn in accordance with profile observations made at regularly spaced points. This method is used for very detailed surveys (e.g. of experimental fields or farms), and where soil differences have little surface expression. According to Buringh et al (1962), about 9 observations are needed in an area represented by 1 cm^2 on the published map, to plot boundaries with sufficient accuracy from borings alone (e.g. 140/sq.km. at 1/25,000).

More commonly, the direction of traverses and/or the spacing of observations is varied according to the expected alignment of soil boundaries as indicated by relief or surface appearance. This procedure, transitional to free survey, needs fewer borings, and has been much used for semi-detailed mapping in the Netherlands and in lowland Britain with 25-100 borings per sq.km. (1 to 2½-10 acres) for production of published maps at 1/25,000 or 1/63,360.

In grid surveys, profile characteristics are recorded at each sampling point, and any recorded attribute or set of attributes can be used for classification. The map legend can, therefore, be constructed, and boundaries inserted, after the data have been collected. In free survey, by contrast, the mapping legend is established, following a reconnaissance to identify the soil classes (series) represented and to discover relationships between their distribution and external features, chiefly land form. Profile observations are then located irregularly, primarily to confirm the expected relationships and to verify the positions of putative soil boundaries, which are plotted in the field as survey proceeds.

Free survey has been used for medium and small-scale mapping (publication scales ranging from 1/15,000 to 1/250,000), particularly in the United States, Britain and New Zealand, on the assumption that an experienced surveyor can map the distribution of soil classes at least

as accurately as by the grid method with fewer observations. However, it is less effective where soil differences have little surface expression, and the profile observations made cannot be relied on to give an unbiased estimate of variability within map units.

In physiographic survey, boundaries are based on external features of soil and landscape, e.g. as observed on air photos, aided by available information on geology, geomorphology, etc. Field observations are made afterwards, not primarily to locate boundaries, but to identify or describe the soil within each map unit (Goosen, 1967; Beckett, 1968). This procedure has been most used to make quickly small-scale maps showing compound units (soil associations), especially in underdeveloped areas where native vegetation, as well as land form, often aid in boundary location.

Physiographic survey depends more than free survey on the existence and constancy of well defined soil/landscape relationships, and on the surveyor's skill in identifying them. To achieve the economy that is its major asset, field observations are usually limited to few sample areas or transects; more are needed to verify that a given change in air photo tone or pattern always denotes the same soil change, and that the same kind of soil or soil pattern always gives a distinctive tone or pattern on the photo.

LATERAL CHANGE IN SOIL VARIABILITY

As Beckett (1967, 1968) and Webster and Beckett (1968) emphasized, a soil map is good when both precise and correct statements can be made about the map units, the aim being to minimize intra-unit variance in as many properties of interest to the user as possible.

The precision of such statements increases with increasing subdivision of mapped soil classes (e.g. in the order great soil group, sub-group, family, series, phase). With increasing class subdivision, it may be expected that bodies of soil conforming predominantly to a single sub-class will be smaller, so that a larger map scale and a greater sampling density will be needed to represent their distribution with a given degree of accuracy. However, landscapes differ greatly in the extent to which profile similarity is associated with contiguity,

and different soil properties change laterally at different rates, depending on causative factors.

Beckett (1967) discussed the significance in soil surveys of 'periodicity' in lateral soil change, as exemplified by changes in variance of particular properties, measured at randomly sited points within sample areas of progressively increasing size. Thus variability in physical, chemical and biological properties related to worm holes, ped formation, stones, roots, etc. is usually already pronounced in sample areas of 10 x 10 cm^2, but may not increase much more as the sample area is increased. However, total variability increases more or less stepwise as other causes become effective, such as tonguing of horizons, tree throw, mole hills, ridge-and-furrow cultivation, irregular fertilizer distribution, or lateral segregation of soil materials as in patterned ground or gilgae, over distances of 1-10m. or more, and other changes in parent material or hydrologic condition over greater distances.

Soil surveys are primarily concerned with lateral changes in the variability of relatively permanent soil properties above that present within areas of say, 1 m^2 (i.e. between pedons), insofar as the map units are characterized and predictions made in terms of mean values of properties of blocks of soil about this size. Such changes may be continuous, with no well defined inflexions in rate of change, or discontinuous when two distinct but relatively uniform bodies of soil adjoin: they may be further characterized as systematic (orderly) or unsystematic, according to whether there is a discerable regular pattern of change.

Systematic continuous changes are exemplified by progressive changes in profile morphology (involving such properties as amount, kind and distribution of organic matter and inorganic products of weathering, horizon development and solum thickness) attributable to the effects of changing climate on a uniform parent material. Others of more local significance include those related to gradational changes in parent material, drainage or time available for undisturbed profile development on floodplains, fans and pediments, and in areas of loess deposition, metamorphic aureoles, etc. Many catenary changes in soil properties on hill slopes are also continuous (cf. Milne, 1947), as demonstrated by recent studies of trends and variability across loess and

drift landscapes in Iowa by Walker et al (1968). Others, reflecting sharp changes in parent rock or age of ground surface in 'mixed' or 'polycyclic' catenas, include well defined discontinuities.

Wherever changes in soil properties are continuous, any mapped soil boundary is necessarily arbitrary. However, in many catenary patterns the distribution of properties such as degree of mottling, depth to carbonates, or solum thickness, can be related to land-form elements, and the relationships used to predict the location of boundaries based on one or more such properties, so long as other factors, chiefly parent material, remain uniform.

Systematic discontinuous changes include those bounding natural soil-landscape units as conceived by Knox (1965). They usually coincide with the boundaries of discrete, sedimentary or igneous rock bodies, extant or 'fossilized' ground surfaces (Butler, 1959), or some combination of these, and may or may not be periodic (cyclic) in the sense of recurring at regular intervals. Where, as often happens, they also coincide with consistently identifiable changes in external land attributes, they afford an economical and effective basis for soil mapping by free or physiographic procedures, providing that they occur at intervals recognizable at the map scale used. Where short-period discontinuous changes occur, as in patterned ground (e.g. Watt et al 1966) and some alluvial landscapes produced by braided streams, the variability cannot be resolved at any ordinary map scale, and the area is most usefully mapped as a soil complex, insofar as the large variation over short distances is itself a major factor affecting land-use potential.

Much short-~~period~~ range variability has been recorded in England and Wales particularly associated with Pleistocene or earlier deposits evidently disturbed under periglacial conditions, irregular dissolution of calcareous substrata, lithologically variable sedimentary rocks in erosional situations, and Fenland landscapes with intricate creek patterns. Especially in the first two situations, sub-surface discontinuities are seldom reflected in surface relief and can easily escape notice, although air photos will often reveal them and the exact nature of the pattern can then be investigated on the ground.

In many if not most landscapes, systematic variation in soil properties involves both continuous and discontinuous changes of varying

periodicity. The range and pattern of variation depend chiefly on parent material and geomorphic history, and any change in one or other of these changes the pattern or the nature of the soil in particular land-form elements. Superimposed on any systematic variations are unsystematic (random) variations, which can account for much of the total variability. Thus, Walker and Protz (1968) found much variability in relatively simple Iowa landscapes was unrelated to land-form parameters and attributed it to relict subsoil features and irregular distribution of animal burrows. In general, however, the most important factors apparently causing unsystematic variation are firstly parent-material variation, and secondly biological (including human) factors, e.g. land-use history and (occasionally) random distribution of plants such as kauri trees (Agathis australis) which have a powerful influence on soil evolution.

CONCLUSION

Insofar as the nature and periodicity of lateral variability differ considerably between landscapes and largely determine the effectivenes, of particular soil mapping procedures, it may be argued that soil pattern, rather than map scale, should dictate procedure. To achieve a uniform standard of reliability, an appropriate balance has to be established between the complexity of the soil pattern in relation to map scale, the precision of the legend units and the density of observations. This is best obtained by an adequate preliminary reconnaissance, using air-photo interpretation in conjunction with closely spaced ground observations (transects or random sampling studies) in sample areas to identify major soil-landscape units in the area, and to assess the range and pattern of variability within each, particularly over short distances.

Free survey based on such a reconnaissance is likely to be more efficient than grid survey (i.e. with the same number of observations) wherever major discontinuities occur at mappable intervals and have consistent external expression, or where systematic continuous variation can be related to land form. It is also likely to be more effective, though less economical, than physiographic survey in most areas, because the mapping procedure is specifically directed to verifying the

constancy of soil/landscape relationships and adjusting the location of boundaries in accordance with a consistent mapping legend, and this becomes critical wherever departures from the expected pattern occur.

Wherever there is much variability within land-form units, grid mapping is likely to be more effective than free survey. However, unless the soil varies consistently with a periodicity appreciably larger than the grid spacing, no significant improvement in resolution may be achieved.

The chief advantage of grid sampling is that reasonably reliable numerical estimates can be made of: (i) the proportions of defined kinds of soil in an area; (ii) modal or mean values and variance of any measurable attribute recorded, providing that the grid spacing is close enough to give enough samples. It should be noted, however, that values obtained for a map unit are inapplicable to individual delineations, and vice versa. In McCormack and Wilding's (1969) study, 10-15 observations were needed in each delineation to identify dominant and subdominant soil series with reasonable certainty, and at least as many (often many more) to estimate population means within 10% of parameters such as depth of leaching of $CaCO_3$, depth to distinct mottles and horizon thicknesses.

As noted by Steur (1961), a combination of grid and free survey, using regularly spaced observations to estimate the composition of map units, and a free procedure to locate boundaries, offers the best means of producing a map in which maximal reduction of intra-unit variance is combined with an acceptable standard of reliability, but needs many observations and is therefore expensive. Systematic grid sampling can also be combined with physiographic survey, as recommended by Rudeforth (1968), but a soil map produced in this way is likely to be of poorer quality, as judged by comparing total and intra-unit variance, when boundaries are based on physiographic (air-photo) interpretation alone.

Free survey entails first establishing a mapping legend, which provides a consistent basis for identifying map separates and delineating boundaries. If legend units are defined in accordance with a suitable general (locality-independent) system of soil classification, information about the units can be transferred accordingly, and map units in different areas readily correlated. In principle, each map unit is

identified by the most commonly occurring class of soil, or by two or more classes if it is demonstrably multi-modal.

Webster (1968) referred to the difficulty arising when well defined areal units have peak frequencies in one or more differentiating attributes close to a predefined class limit. In practice this problem generally appears less serious than the basic one of economically identifying, delineating and grouping areas of land which are indeed relatively homogeneous and are also closely similar in the distribution of several soil properties of interest. It is almost certainly a misconception to imagine that all delineations of a map unit usually correspond to essentially equivalent soil bodies bounded on all sides by well defined natural discontinuities. Rather, experience suggests that few natural landscapes of any extent conform to this idealized model. In most landscapes, because of the superimposition of continuous and discontinuous variability of variable periodicity, and the occurrence of uncoordinated relationships between soil properties, arbitrary criteria are needed to delineate map separates that can be grouped and characterized as a single legend unit in terms of soil properties.

However, there are undoubtedly areas where rigid adherence to predefined class limits can entail splitting a population at or near the peak frequency of a particular attribute, and hence result in an inaccurate or misleading map. When reliably demonstrated, such situations may indicate that the classification is generally ill suited to the purpose intended and ought to be changed: otherwise, if the class limits have been found generally acceptable, the map unit concerned may be recognized as an 'intergrade', in the sense that it is unimodal, with a mode at or near a class limit and a range comparable with that of a single class. But the situation must be clearly identified as such, and not confused with a multi-modal mosaic of two or more classes.

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