Soil resources and their assessment

R. Webster

Phil. Trans. R. Soc. Lond. B 1997 **352**, 963-973
doi: 10.1098/rstb.1997.0075

Soil resources and their assessment

R. WEBSTER

Rothamsted Experimental Station, Harpenden, Hertfordshire AL5 2JQ, UK

SUMMARY

The assessment of the soil resource of any region has two parts, namely, an inventory of the kinds of soil and their distribution, and knowledge of the way each kind can be used and its performance under a range of circumstances. Soil varies substantially and intricately over short distances in most parts of the world. Inventory by field survey and air-photo interpretation must be done at a local scale. Inventories may be combined so that an individual nation state or region of similar size can know what kinds of soil it has, how much and where they are, how much each can produce, how to manage each in perpetuity, and the risks of degradation in use. Local classifications, with classes defined simply and identifiably on aerial photographs, will serve for mapping, and in combination with classical statistics can provide sound estimates from stratified sampling and agronomic experimentation.

Sound assessment should also be at this local scale initially. This should combine fundamental understanding of the soil's behaviour, strategic agronomic research on regional stations, and on-farm trials. The last are crucial for estimating productivity of the soil in practice.

Data from all sources can be stored, sorted and displayed by geographic information systems that now have abundant capacity. They should be indexed by soil class and other attributes, with clear distinction being made between assessments of productive potential and basic data. They should be publicly accessible, to ensure that data are readily available and never lost.

Estimates of the soil resource and its productivity for large regions, nation states, and the world can be compiled from local surveys by sampling through a 'bottom-up' procedure.

1. INTRODUCTION

> 'Not even the clearest thinking can atone for failure to start with the facts.'
>
> (M. Ginsberg, quoted by D. U. Peters)

Soil is enormously variable in its composition, its surface chemistry, its structure, its depth, in its sequence of horizons, its water regime, and its life; it varies in all the properties that affect its use, and these properties can vary more or less independently and on different spatial scales with more or less intricacy. Any inventory of the soil as a resource must reckon with this. To compile an inventory of more than the isolated field we must understand the nature of this variation, and its scale, in particular.

A population wishing to know what soil resources it has, how it might use, develop and conserve them, avoid degradation, and assign priorities will want answers to the following questions. (1) What is the soil like, and what is the range of variation, or what kinds of soil are present? (2) How much is there, i.e. what is the area, of each kind of soil? (3) How is the soil distributed? It needs a map. (4) What is the potential productivity of the soil, and how does the soil restrict land use and the choice of crops and the yields of those crops that can be grown? (5) What would yields be under a range of inputs? (6) How should potentially productive land be managed? (7) How can degradation be checked and its risk be made acceptably small?

The first three questions concern inventory, and answering them continues to be central to soil surveys in many countries. The answers document the resource. Answers to the last four questions belong to assessment. They are questions that should be asked whenever agricultural development, resettlement, forest planting or other substantial changes of land use are envisaged or planned. Failure to do so or to find satisfactory answers invites disaster, of which the East African Ground Nut Scheme was the most infamous in my lifetime. With modifications, the questions are ones posed by the Food and Agriculture Organization (FAO 1991) for the whole of the developing world. The FAO attempted to answer them, with some success, by overlaying maps of climate (and crop potential) and soil at a scale of 1:5000000, and assembling the information by 10 km × 10 km squares (2 mm × 2 mm pixels on the maps); see also Higgins *et al.* (1987). The result is an inventory of land potential and suitability for the principal crops, country by country. It answers questions (1) and (2), to some extent questions (3) and (4), and perhaps question (7) in part.

However, as the FAO (1991) wisely remarks, the procedure must be refined for practical use in individual countries. Oldeman & van Engelen (1993) make the same point: the detail must be sufficient for national and regional planning. 'Refinement' is an understatement; the task is substantial, and I will devote the remainder of this paper to it.

2. SIZE, SCALE AND METHOD

One might answer questions (1) and (2): 'What?' and 'How much?' by sampling. One could adopt a classification of the soil, select a random sample of points, visit them to determine the class at all the points, and then estimate the area covered by each class with a standard error. A large sample would be needed to achieve acceptably small errors if one had many classes. To be of much value, however, one must know *where* the classes are, answering question (3), and this is standard practice in soil survey. Practice is to record what is present, to ascertain the variety or kinds of soil in a region. The output almost always includes a classification of the soil and maps showing the region divided into the classes. Except at the largest scale, the classification is crucial to success, because it is through the classification that agronomic experience can be transferred. Detailed information from boreholes, pits, experiments, even farms, is inevitably fragmentary, and planners and advisors should be able to predict in a spatial sense what is between the sampling points. Otherwise, they would have to visit every site of interest themselves and repeat the experiments.

The survey technique by which to answer questions (1)–(3) is not obvious; nor is it made clearer by the competing claims of practitioners with different backgrounds, traditions and prejudices. Further, the language in which classifications of soil are couched and the minutiae of definitions have hindered communication with agronomists, engineers and planners rather than helped. Some surveyors will dig or bore numerous holes and mentally group their observations into spatially coherent classes. Others will record the properties that they believe to be the most relevant for the purpose on hand and classify the soil from their records. Yet others, often using aerial photography, are guided by landscape and physiography. In the last 20 years analysis of satellite imagery has become popular, and most recently we have seen much enthusiasm for geostatistics (the application of theory in spatial statistics) and geographic information systems (GIS) in which spatial data from various sources can be assembled, collated, related and displayed. They are not mutually exclusive, and sensible combinations depend primarily on the size of region being investigated and, related to it, the intensity of observation and the scale of presentation. What is eminently sound or feasible at one size can be inappropriate or need elaboration at another.

There are four or five principal sizes of region and associated scales that we can usefully recognize. I use the term 'scale' in its technical sense of the ratio of distance on a map to its corresponding distance on the ground. The sizes can be arranged roughly in a geometric progression in which the steps are two orders of magnitude in area and the scale decreases correspondingly one order of magnitude at a time.

(*a*) *Size*

(i) *The field*

At some scale almost all soil properties appear continuous. Diffusion, periglacial perturbation, cultivation, and sedimentary mixing have brought this about. If we confine our attention to a few hectares (ha) in the temperate zone or tropics, this is almost certainly how the soil will appear. This is the size of an individual field, which is sufficiently homogeneous to be treated uniformly. For practical purposes, the field comprises one kind of soil. There are unlikely to be differences of such magnitude as to demand differences in management because these will have been recognized already in delimiting the field. If you want to know the soil's properties and productive potential then you can sample it and experiment more or less formally.

We now know, however, that many such fields do not respond uniformly to management. Automatically recording harvesters are showing large variations in the yields of cereal crops within fields; two- and even three-fold differences over a few tens of metres are not exceptional. If soil variation is thought to be the cause, then the soil must be sampled intensely and mapped at a scale of about 1:500. With advanced computer technology to control the application of fertilizers, other agricultural chemicals, and satellite-assisted navigation, farmers can vary their treatment of the soil to match the variation present. The whole topic, known as 'precision farming', is being investigated in the developed world—see Robert *et al.* (1995). If the costs of soil sampling can be borne by the gains in production then local estimation using geostatistics (see below) is likely to play an important role.

(ii) *The farm or estate* 100–1000 ha

At this scale (1:5000) differences in soil and land become important. Changes that appear at the scale of the individual field often become relatively sharp boundaries separating different classes of soil. Each soil type has its potential, and it might need managing separately. So it should be characterized separately, and its performance should be measured. The results can be stored in a data bank, which need be no more than a book, and many farmers do this. If sampling is designed with sufficient randomization—see Cochran (1977), Yates (1984), or Webster & Oliver (1990) for spatial schemes—then for any one class the same properties and performance can be predicted elsewhere with known confidence. Experienced pedologists often choose typical sites as representatives, instead of randomly, and prediction from these can work well, as Leenhardt *et al.* (1994) have shown.

(iii) *Physiographic region* 100–1000 km^2

Increase the area by another two orders of magnitude and the patches of land distinguished by boundaries will often appear on a map at 1:50000 in some kind of repetitive pattern or mosaic. The same principles of classification, sampling, and prediction hold because there is no added complexity: effectively we have more of the same. However, the data banking is more important, partly because there are likely to be more data, but mainly because the same data can be used more widely by more people, if only they know where. National and other agencies in many countries have mapped soil at this scale or somewhat larger

(1:25000), whether they recognized the link with physiography or not.

Note that one pixel in the FAO's land inventory of the world is of this size: 100 km^2. In most such pixels there will be a variety of soil types, each with its particular characteristics and potential that may differ markedly from that of its neighbours. The pixel at this scale is not homogeneous, and this must be a matter of concern.

(iv) *Nation state* 10000–100000 km^2

A further increase of area to tens of thousands of km^2 brings us to the size of many nation states, which one might map at 1:500000. Regions of this size typically embrace several different patterns, and in many instances the patterns are readily distinguished. They are usually associated with important variations in climate too. They had been recognized by geographers from early in this century and were proposed by Bourne (1931) as the mapping units for a resource inventory. It was the widespread use of aerial photography after the Second World War, however, that enabled resource surveyors to exploit the idea and to delineate the patterns, first in Australia and soon after in other countries.

The areas covered by individual patterns are typically of the size on which governments and international agencies like to choose priorities for investment and development. Many are not homogeneous, however: they can encompass huge variety. Figure 1, of a part of Uganda mapped by Ollier *et al.* (1969), shows the kind of contrast that can occur. The plateau is formed of laterite, the slopes are mantled by deep well-drained red earth, the valleys are floored by wet clay and peat. These are homogeneous units required for management. They are too small to be mapped individually at the working scale. Nevertheless, they are the units that determine agricultural potential, and they must be recognized separately when compiling an inventory of soil resources. So only can question (2) above be answered. Questions (4)–(7) are largely specific to these units, too. When it comes to implementing plans for agricultural development, the units must also be mapped, thereby answering question (3).

(v) *The World* 1000000 km^2 *and more*

This is the scale of climatic zonation of soil which has stimulated much academic interest and research. Mapping has been typically at 1:5000000 and smaller. The result is broad generalization, but in my opinion of no great practical value. Cropping potential on this scale is determined by climate. Variation in the thickness, stone content, waterlogging and salinity of the soil, and gradient of the land, all of which might in addition affect potential, is local.

3. THE PLACE OF GEOSTATISTICS IN LARGE-SCALE MAPPING

Geostatistics, that is the application of theory in spatial statistics to the distribution of properties in the Earth's crust, on the Earth's surface, and in the atmosphere above, and kriging in particular have captured pedologists' imagination. The idea of spatial prediction without bias and with minimum variance, which is what kriging uniquely offers, appeals. Some of us were seeking just such a technique in the 1960s. So were the miners and petroleum engineers, and they found it first, building from both experience (e.g. Krige 1966) and theory (Matheron 1965). The combination of a coherent theory, powerful computers and software, and the economic benefits of their application in ore evaluation and reservoir estimation gave the subject its impetus, which pedologists could immediately exploit.

Soil turns out to be almost the ideal medium for geostatistics. It is 'well-behaved' as a realization of spatial random processes. It is accessible almost everywhere, so that surveyors can sample soundly. Sampling is cheap enough for surveyors to get enough data, but also sufficiently dear in relation to benefits that they want to make the best use of data, and not oversample.

This is not the place to go into detail of geostatistics. But two points must be made for its proper and successful application to soil survey. The first is that the soil properties that matter must be measured and be spatially correlated at the working scale in the region of interest. In general this means that the soil at places close to one another is more alike on average than at places further apart. This correlation can be modelled, and indeed it must be modelled, to proceed to kriging. Correlation is not guaranteed, however: it might be of too short a range, and the sampling interval might be larger than that range. In these circumstances the variation will appear to be uncorrelated spatially, or 'pure nugget' to use the mining jargon, and neither kriging nor, incidentally, any other form of interpolation without other information will give us local estimates that are better than the global average.

Secondly, the variation should be continuous. Sharp boundaries, whether natural, arising, say, from geological faults or terrace bluffs, or man-made by the division into fields and the creation of terraces and polders, for example, break the continuity. In these circumstances kriging needs to be combined with some form of stratification. Voltz & Webster (1990) did this and showed that the combination can work well.

Geostatistics has an important place in resource survey. Seasonal temperatures, rainfall, vegetative cover, and fish stocks have all been mapped successfully over more or less large areas using its techniques, in addition to metal ores and petroleum. It is proving advantageous for special-purpose surveys of soil, for irrigation planning (Hajrasuliha *et al.* 1980), reclamation of alkaline land (Samra & Singh 1990), and pollution (Schulin *et al.* 1994), and the number of research applications is now legion. Its evident success is now attracting farmers and contracting companies who wish to practice precision farming, for which the main stumbling block seems to be getting sufficient data on nutrient concentrations and water storage to use the technique.

The maps are at large scales for small areas; they are not at the scale of the nation state, and this distinction is likely to remain. Larger regions should be stratified first by other means.

4. TWO-TIER PHYSIOGRAPHIC CLASSIFICATION

Let us return to the scale of what I have called the nation state, though the scale may be of any similar-sized region. The need is for a classification of soil into homogeneous types that can be managed as if they were uniform. However, to make comprehensive maps of a large territory at the required scale, say 1:50 000, is likely to take too long or require too many surveyors. For example, the Soil Survey of England and Wales covered only about 30% of the 70 000 km^2 in detail at scales of 1:25 000 and 1:63 360 in 30 years. There are even fewer professional soil surveyors in the less developed countries, and means are needed to accelerate survey.

Christian & Stewart (1953) faced such a task when they began a survey of the remote underdeveloped parts of Australia, first around Katherine and Darwin in the Northern Territory, and later elsewhere. They divided each region into 'land systems', areas characterized by distinct patterns of physiography, soil and vegetation, which they recognized on aerial photographs and mapped. The recurrent elements of the patterns they called 'land units'. These were too small, individually, to be mapped at the working scale, and as above the survey teams were too small to do it in the time allowed. Instead they were described in the reports.

Christian & Stewart's survey of the Katherine–Darwin region became a model which was to be elaborated for other parts of Australia. It was adapted by the Land Resources Division (LRD) of the British Directorate of Overseas Surveys in the late 1950s for its regional inventories of former colonies and protectorates in Africa and elsewhere, of which there were many. Governments, particularly their ministries of agriculture, were thereby provided with basic data on their land resources from which they could plan strategic development.

The precise way in which agricultural planners might use the results of these surveys was not spelled out, and it fell to engineers to formalize the approach. What were needed in addition to mapping the patterns were component land units defined and described in such a way that they would be recognized readily by anyone with a reasonable 'eye for country'.

The engineers also needed to be assured that the units were homogeneous, and they tackled this aspect first. Morse & Thornburn (1961) had already discovered that they could treat soil series, the homogeneous classes of soil maps made for agriculture in the USA, as uniform when building roads. Kantey & Williams (1962), working in South Africa, sampled the units of their maps at random and found that each was indeed homogeneous. Webster & Beckett (1968, 1970) took the matter a stage further by conducting the same kind of survey in southern England and several parts of Africa. They called the land units of Christian & Stewart 'land facets', or simply 'facets', and they showed by analysis of variance that both the mechanical properties of the soil within each were reasonably homogeneous and that classification into facets was profitable in diminishing the within-class variance substantially from that in the population as a whole. They further showed that one could hardly do better for engineering practice (Webster 1981).

Land management depends on the peculiarities of the homogeneous land units. If they are not or cannot be mapped in national or regional surveys, then users must be able to recognize them, and ideally all users should be able to recognize the *same* ones so that they can pass information to one another. Webster & Beckett (1970) also investigated this. They developed a 'do-it-yourself' kit comprising for each land system one or more annotated stereopairs of aerial photographs, a perspective block diagram, a verbal description and, in some instances, ground photographs. They assembled such kits for Uganda (Ollier *et al*. 1969), western Kenya (Scott *et al*. 1971) and Swaziland (Murdoch *et al*. 1971) into atlases. Figure 1 and table 1 are part of the kit for one land system. Note in passing the scale and that contrasting types of land (facets) are no more than a few hundred metres across. Several of the surveys of the LRD followed the same style, e.g. that of northern Zambia by Mansfield *et al*. (1975–1976). Further, they tested the ability of others to use the kits, and they found that people who were familiar with aerial photography, but who had had no special training in soil science or physiography, could identify and map the constituent units of a land system confidently. Legros *et al*. (1996) have recently confirmed that students quickly learn to map units of terrain in this way when presented with examples.

The ideas were contagious. They were adopted by several survey agencies in addition to the LRD in different parts of the world, and the principles and practice were taught in universities and other institutes of higher education. Again, South Africa took the lead in building its engineering data bank on such a two-tier classification. Perhaps more importantly in the present context, Stobbs & Jeffers (1985) of the LRD turned it into a quantitative tool for their work in Malawi. They overlayed two-dimensional randomized patterns of sampling points on to aerial photographs. By counting they then estimated the area of each land facet, and hence each kind of soil, and thereby answered my question (2). They also recorded from the photographs the land use for each point, to produce a valuable quantitative database of land use for the whole country.

Changes in policy at the end of the 1960s shifted responsibility for systematic survey and data collection from the British Government to overseas governments and other agencies. Yet, paradoxically, within a few years (and 50 years after Bourne had recommended it) the home surveys energetically embarked on just such comprehensive tasks for England and Wales, and Scotland. The soil map of England and Wales (Soil Survey of England and Wales 1983), and the books that accompany it, constitute a fine example of what can be achieved.

But politics was not the only or even the main reason. By the early 1970s, satellites were beaming

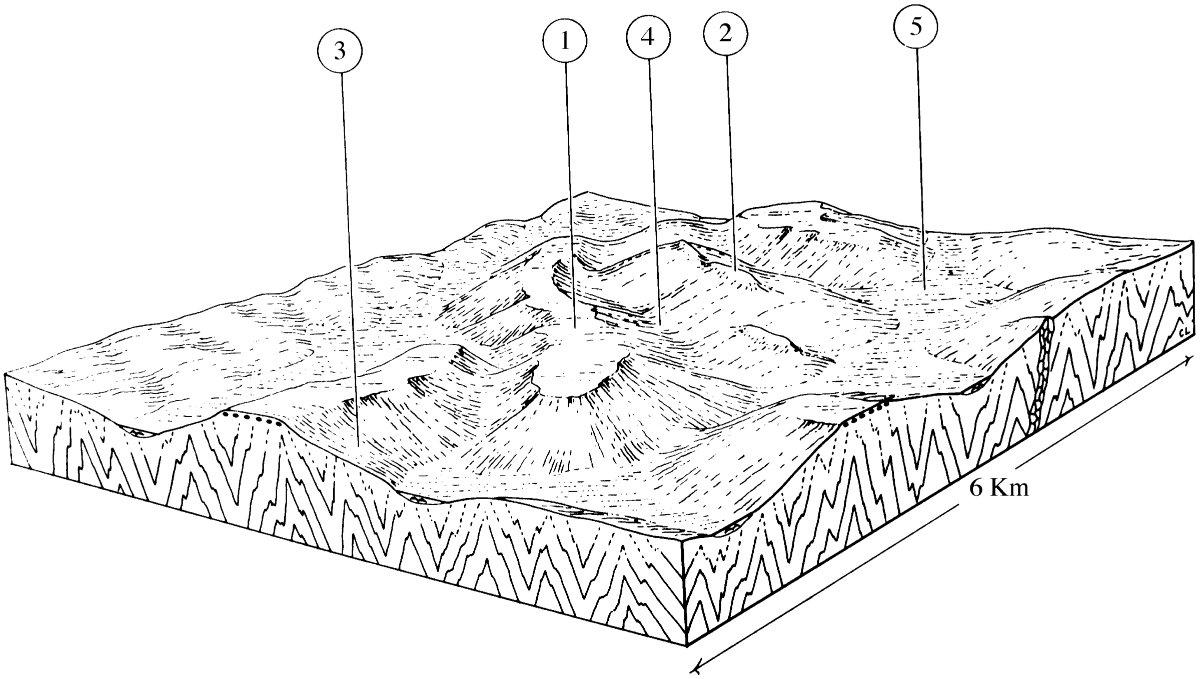

Figure 1. Perspective diagram of the Masaka land system of Uganda.

Table 1. *Facets of the Masaka land system of Uganda*

facet	form	materials and hydrology	cover
1 plateau	flat, 100–300 m across, short steep margins	thick massive laterite over Pre-Cambrian schist and gneiss with brown sandy soil containing murram to the surface in many places. Drainage free above influence of ground water.	*Themeda–Cymbopogon* grass savannah.
2 ridge	steep-sided with rounded crest. Usually on interfluve summits, but occasionally on mid-slopes	quartzite, bare rock or with thin stony soil.	*Themeda–Cymbopogon* grass savannah.
3 convex interfluve and slope	straight slopes up to 7° and rounded crests, locally steeper below laterite plateaux (facet 1) and above valley floor (facet 5)	(i) reddish yellow loam to ⩾ 1 m over stone line over weathered schist; few or no concretions. (ii) red clay loam or clay with little quartzite over murram or hard laterite or both over weathered schist. Drainage free above influence of ground water.	cultivated or *Pennisetum* fallow. Evergreen forest on some of steepest sites.
4 side valley	narrow valleys with rounded bottoms, locally broadening to 100 m with flat bottoms	as for facet 3 but grading down slope to mixed alluvium on flatter ground within influence of ground water.	moist deciduous forest
5 main valley floor	flat 100–500 m across	sand with local layers of gravel and mottled clay. Rich in humus, infrequently peat. High ground water.	*Papyrus* and *Miscanthidium*.

back to Earth radiometric data that could be analysed by computers of ever-increasing power and converted into images. The problems were many, and the new field attracted numerous research scientists, mathematicians, and engineers to find rigorous solutions and practical applications for land resource assessment. And with the solutions one was able to filter, analyse, classify, identify, and collate data from two or more passes. There was no glamour in old-fashioned field surveys and aerial photo interpretation after that!

Imagery from Landsat and SPOT satellites has a place for mapping resources. It has proved useful in arid lands for mapping soil, most of which is bare, and where the surface condition is characteristic, for example, in Sinai (Abd El-Hady *et al.* 1991) and North Africa (Vogt & Vogt 1996). These authors list the kinds of surface materials, stone, sand, salt, and calcareous and gypsum crusts, that they could distinguish. Both sets of authors make the point that an understanding of the physiography is crucial to their ability to recognize these. In other situations, one might be able to see how the vegetation responds to the seasonal cycle or less regular fluctuation in weather by comparing data from time to time and monitoring of the response. Some people distinguish patterns of landscape, and hence soil, on satellite images more readily than they can from air photography. Lack of true stereoscopic cover is a serious deficiency, however, and for local detail there is no substitute for stereoscopic examination of individual aerial photographs combined with a ground survey.

5. PURPOSE-ORIENTED SURVEY

Two other lines of thinking have, I believe, hindered the application of soil survey as much as they have helped. The first I shall call purpose-oriented survey. The idea is that one first decides what one wants to do with the land. The intended use will determine the properties of the soil that are important and that are to be recorded during the survey. For the individual field it can work well. One usually knows the main constraints, and the finer details for managing the soil may depend on variation in one or a few properties, such as clay or sodium content of the soil under irrigation. These can be mapped individually, and they can be combined into a simple classification when their distributions have been mapped.

Trouble can arise for larger areas when the classification is created without regard to the distribution in the field. If the actual values fluctuate locally around the critical values of the classification, then it is almost impossible to map boundaries at those values. A farmer or developer wanting to divide land according to critical values would have great difficulty doing so in these circumstances. In some countries surveyors have been asked or told to go out and find land suitable for this or that. Charter (1957) derided it as 'pedological procurement'. Even if it is successful the classification can become redundant if the purpose or policy change, and Dalal-Clayton & Dent (1993) deliver a detailed and stinging critique of this.

Related to the first is 'top-down' classification generally. In this approach the soil of a nation or of the whole world is divided into classes, which in turn are subdivided until the desired refinement is achieved. It can stem from the desire to classify for specific purposes, but it is more often promulgated to achieve uniformity throughout a national territory and internationally. Only by classifying soil in this way can sparse experimental data on the soil be made to go a long way, so argue the proponents of 'technology transfer'. The intentions might be laudable, but the attempts at their application fly in the face of all the evidence of the way soil is distributed. If surveyors are expected to go out and map soil in this way, they will almost surely fail. Just as the limits designated for special purposes may be difficult to delineate on the ground, so the conceptual divisions of soil that one might recognize at the national or international level rarely have their geographically coherent counterparts. They rarely appear as recognizable boundaries. I drew attention to this long ago (Webster 1968), and McBratney and I (Webster & McBratney 1981) demonstrated it even within a small region. Butler (1980) elaborated the point. He named the mismatch between the divisions of a top-down classification and a local classification arising from a mapping programme as the 'taxonomic hiatus', and he thought that it was inevitable, and even desirable.

If the aim is to assess the resource, then we should record what soil is there, and then discover what it can be used for and how to manage it effectively. I move on to these two matters now.

6. ASSESSMENT–FIELD EXPERIMENTS

We can map patterns of land, and we can classify the soil in each pattern and provide the means by which each class is to be recognized. We need, in addition, to know what each kind of soil is good for, what its potential is for exploitation and production, and how it should be managed to sustain production without degradation, or whether it is best left to nature, managed for amenity or built on—the answers to my questions (4)–(7). We want quantitative estimates of how much each kind of soil will yield and of the amounts of fertilizer needed to achieve particular yields.

Agronomists in the industrialized countries have experimented over many decades to provide the information in a time of fairly free international trade. Except during war-time, they have done so against an economic background of world market prices more or less sheltered by national governments, so that ultimately the test of a soil treatment or use has been whether it pays. If not, then the soil is not treated or used that way, and any shortfall in produce is imported.

The poor agrarian countries are in a different situation. They export little, and so they can rarely afford to import food to make good shortfalls in their own production, and they cannot afford enough fertilizer to correct deficiencies in the soil. They must produce their own food, and in these circumstances the test of the goodness of any particular soil or its management is whether it supports the human population there. They need to know the number of people, the carrying capacity, that each type of soil can support sustainably. The global problem posed by Malthus thus becomes local.

Allan (1949) developed methods for calculating human carrying capacities of the soil in subsistence economies, and he and Peters (1950) applied them in what is now Zambia. Allan (1965) describes them and presents many results, including ones from other parts of Africa. He recognized the essentially physiographic associations of soil described earlier by Trapnell (Trapnell & Clothier 1937; Trapnell 1943), and in several instances his assessment combined the productivities of different soil types within them, especially ones with different water regimes, to arrive at final figures.

In practice, many subsistence systems are less than optimal. Even poor communities can afford some fertilizer and machinery for better cultivation. From the late 1930s onwards statistically designed experiments, such as those of Yates (1936), have revealed the responses of crops to fertilizers and other treatments of the soil. The approach has been unashamedly empirical: try plausible and even not-so-plausible treatments alone, and in combination, and observe the effects. Some of the results have been spectacular. Many of the experiments were concerned not so much to discover limitations in the soil but to find out how the soil should be tilled, drained, protected, as well as fertilized, to increase crop yields.

The designs and analysis have been elaborated in recent years to improve efficiency and, in some instances, to take into account the complexity of certain systems of cropping. They are modest improvements. The basic method devised in the 1930s remains the means by which to assess the short-term potential of the soil. It is the way to estimate quantitatively and accurately the responses to new agricultural practices.

The results did not immediately benefit farmers to the same extent, however, and for at least two important reasons. (1) The experiments were and still are done on stations established for the purpose, like those in Europe and North America earlier. Only long-term experiments can show whether particular regimes of cropping and management are sustainable, and these are almost inevitably confined to stations. The stations are few, they cannot represent all of the important kinds of soil in a territory, and so many results remain specific to the stations themselves and to the kinds of soil on them. Even if the results are valid on other kinds of soil one would not know. (2) Experimental stations, in the temperate zone as well as in the tropics, almost always give larger and more consistent yields than those that a farmer can obtain, but see Pingali (1994) for an exception with paddy rice in the Philippines. They usually have better equipment and more staff, so that they can time operations better and do them more thoroughly. They are less constrained by circumstances and affected by the weather in the way that the farmer is.

Once the euphoria of the 'Green Revolution' had waned, scientists turned their attention to this matter. They realized that more experiments should be done on farms, and as far as possible with the participation of the farmers themselves. In some instances scientists would do the experiments, in others they would instruct the farmers, providing them with seed or fertilizer and simple designs for their trials. The realization was not restricted to the poorer countries. In Britain, the company ICI stimulated farmers to increase their yields of wheat with its 'Ten-tonne Club', and Weir *et al*. (1984) analysed the results. Again, the yields actually attained (averages of 6.86 and 7.37 t ha^{-1} in 1979 and 1980, respectively) were generally much less than 10 t ha^{-1} which was thought from results on experimental stations to be readily achievable at the time. Incidentally, Weir *et al*. also demonstrated that soil type was more important in determining yield than any other factor.

Farmers participating in such exercises have personal interests in the outcome, learn from the experience, and can feed information both back to the scientists and to neighbours. People obtain results on their soil, and from them they can build for their own benefit. Further, it is only by experimenting on farms under the constraints placed on farmers that they and scientists together can learn what the soil can yield in practice. In much of the tropics cropping systems are complex; cultivation may alternate with fallow, several food crops may be grown together, and they may be grown in strips interspersed with shrubs and trees (agroforestry). Also, successful farming often comprises a system in which different parts of a landscape are used differently.

The ideas were embodied in the programmes of outreach of the research institutes supported by the Consultative Group on International Agricultural Research in the 1970s. They became incorporated in a wider topic of farming systems research, summarized by Simmonds (1986). More recently, they have been described in a series of papers in *Experimental Agriculture*, introduced by Farrington (1988), of which those by Maurya *et al*. (1988) and Kean (1988), and a further one by Fujisaka (1989), are especially pertinent. What we have is a bottom-up empirical assessment of what can be achieved in practice on each particular kind of soil.

The approach is often criticized for its empiricism, for its lack of fundamental and proper understanding. There is of course place for the latter: the research institutes and their experimental stations play a vital role in improving productivity and soil management. They also provide an environment for speculative research that farmers cannot or will not contemplate because crop failure would mean lost earnings, or worse, destitution and starvation. Certainly subsistence farmers cannot afford the risk. But research on stations and on farms should progress in concert.

A second criticism is that developing countries cannot do the experiments because they have not got the resources, the scientists principally. So they and their First World partners embroil themselves in research designed to relate plant growth to soil properties and behaviour, with the ultimate aim of predicting crop performance and yield without further empirical evidence. It is a nice thought, but the models they build demand ever more intimate knowledge of the soil, its water, nutrient and oxygen supply, and how they change on almost a daily basis. Look at almost any collection of papers from such meetings, e.g. Bunting (1987), and you will read *ad nauseam* that to be useful this and that model will require many more data than are currently available. Obtaining such knowledge demands more effort than anyone is prepared to devote, so the scientists turn to soil maps in the hope that they will match the many sites for which they want predictions to the few sites where they know, or can measure readily, the crucial properties of the soil. The detail they want can be obtained only by painstaking field-work. Predictive models might work, but only when they have been verified in the field and backed by a survey. The soil must be questioned; and there is no avoiding the agronomy.

I find it hard to believe that any country on the brink of the Malthusian Precipice, except perhaps those very dry countries with sparse populations, lacks the human resources to experiment in a simple way. It takes time and effort, as Farrington (1988) makes clear, but most rural communities still have the time to discover how much each important type of soil in their localities can produce and the management required for the purpose. On-farm experimentation is surely a part of the way forward.

7. GEOGRAPHIC INFORMATION SYSTEMS (GIS)

The above describes the two principal actions needed to assess the soil of a large region: (i) a classification in which the classes can be recognized readily and confidently, and (ii) sampling and experimentation to provide data on management and productivity for each class. The whole may be regarded as a system in which the classification (i) consists of a set of files, one for each class, and the data from (ii) are the contents of the files. Beckett *et al.* (1972) built just such a physical bank for engineering data on soil, and they demonstrated it in action for terrain evaluation.

Since then modern computers have brought a power and capacity to store, index, search and analyse such data in ways and at speeds of which we could only dream a few years ago. Those dreams have now been turned into reality, with friendly interfaces that hide the complexity of the processing from the user. Further, programs have been written to collate geographic data from disparate sources, and to analyse and display them as maps and diagrams. These are the geographic information systems (GIS). Some of them have been designed specifically for particular tasks, such as analysing remote imagery and the agroecological zoning of the FAO (FAO 1991). Others are more general, and we should expect to use them provided that they can index and sort data on soil and its management by an acceptable classification of the soil. Further, now that we can store, retrieve and disseminate data so readily by computer, the desire for all-embracing national and international classifications for transferring knowledge about soil and experience of using it has waned. Classification that 30 years ago seemed essential for the orderly assembly of facts and inference from them is no longer seen to be so.

It is a truism that no data bank or GIS, however sophisticated, is better than the data that it holds, and we need to ensure that the data entered are (i) relevant and (ii) of good quality based on sound sampling. Faulty data are likely to mislead; less obvious is the need for the data from different sources to be compatible. Comparison of one region with another is often vitiated because the data derive from samples on different 'supports', i.e. areas of different sizes and shapes or depths, measured in different laboratories using different methods, or from field experiments with different designs and treatments. Procedures should be standardized or at least planned so that results from them are convertible.

Perhaps demanding full compatibility is asking too much in an imperfect world. Nevertheless, a valuable service that the developed countries and the international organizations could provide is a general data bank, accessible via the Internet. It could hold results from trials and experiences that are never published, and it would ensure that results from the least developed countries are no longer lost (see Dalal-Clayton & Dent, 1993).

8. CONCLUSIONS

I have shown that soil varies importantly on a local scale: change occurs at intervals of a few hundreds of metres in most parts of the world, which affects the land's potential for use and its management. The extensive plains of the Americas and Russia are exceptions rather than the rule. I have described how to survey and to map soil at this scale using methods that were developed during the 1930s and 1940s and which, substantially aided by air photointerpretation, were added to the survey repertoire in the 1950s and 1960s. The human effort required per unit area is modest.

Assessing the soil's potential is also best done by designed experiments using statistical techniques developed in the 1930s, which subsequently were elaborated. It seemed at one time that the task demanded more scientific expertise than would be available, at least in the countries most in need, and that we should be able to experiment adequately only at a few well-chosen sites, and therefore assess only a small proportion of the soil types of a large region. On-farm experimentation is proving that to be a pessimistic view. Local farmers, properly instructed, can experiment within bounds, and when they do it they learn simultaneously what to do to increase yields and, we hope, conserve the soil. Discovering the soil's potential to produce, and how to realize that potential in principle, depend to a large extent on investigation and technological innovation in research institutes and on experimental stations. They are essential for progress. Realization of that potential, like soil classification, are bottom-up processes. They are done by people on the ground where they live, as in ICI's Ten-tonne Club. I do not believe that they can be determined and controlled by international agencies; to attempt that would be like looking through a telescope the wrong way round. Nevertheless, if we want a world view and are prepared to put in the effort we can build from local information using classical sampling theory, as Stobbs & Jeffers (1985) showed.

Of the more modern techniques I am disappointed with satellite imagery. I find it a poor substitute for aerial photography for soil inventory. Geostatistics is perhaps the biggest single advance in survey technology since the 1960s. It is proving itself for mapping soil variables at large scales, but it seems less valuable for soil survey at small scales. GIS are the exception: we can use GIS to store, marshall, and display data. Soil or land classification and data from experience and experiments provide the structure and content of an information system. The basics are simple, and thereafter we may collate and analyse the information in as complex ways as we wish.

Geostatistics and GIS might enable us to make better use of information than we should without them. They cannot work without data, though. The combination of field inspection, aerial photography and the intuition or flair that can assemble the information to produce useful soil maps, and its follow-up by agronomic experimentation, are vital. We must get surveyors and agronomists back on to the ground. They must dig, auger, observe and experiment. They must design and analyse. And they must report. I see no reliable alternative. If I am right, and this is the only way to get the information to plan development and increase production without degrading the soil resource, then it is not a question of whether we can afford it: we cannot afford not to if we are stay clear of the Malthusian Precipice.

REFERENCES

Abd El-Hady, A. M., Rognon, P., Escadafal, R. & Pouget, M. 1991 Contribution of Landsat data (MSS) to soil survey: application to the soil of southwestern Sinai (Egypt). *Int. J. Remote Sens.* **12**, 1053–1061.

Allan, W. 1949 *Studies in African land usage in Northern Rhodesia*. Rhodes–Livingstone Papers No. 15. Cape Town: Oxford University Press.

Allan, W. 1965 *The African husbandman*. Edinburgh: Oliver & Boyd.

Beckett, P. H. T, Webster, R., McNeil, G. M. & Mitchell, C. W. 1972 Terrain evaluation by means of a data bank. *Geogrl J.* **138**, 430–456.

Bourne, R. 1931 *Regional survey and its relation to stocktaking of the agricultural and forest resources of the British Empire*. Oxford Forestry Memoirs No. 13. Oxford, UK: Clarendon Press.

Bunting, A. H. 1987 A personal view of the workshop. In *Agricultural environments* (ed. A. H. Bunting), pp. 311–317. Wallingford, UK: CAB International.

Butler, B. E. 1980 *Soil classification for soil survey*. Oxford, UK: Clarendon Press.

Charter, C. F. 1957 The aims and objects of tropical soil surveys. *Soils and Fert.* **20**, 127–128.

Christian, C. S. & Stewart, G. 1953 Survey of the Katherine–Darwin region, 1946. Land Research Series No 1. Australia: CSIRO.

Cochran, W. G. 1977 *Sampling techniques*. 3rd edn. New York: John Wiley & Sons.

Dalal-Clayton, D. B. & Dent, D. L. 1993 *Surveys, plans and people. A review of land resource information and its use in developing countries*. Environmental Planning Issues 2. London: International Institute for Environment and Development.

Food & Agriculture Organization (FAO) 1991 *How good the Earth?* Rome: FAO.

Farrington, J. 1988 Farmer-participatory research: editorial introduction. *Expl Agric.* **24**, 269–279.

Fujisaka, S. 1989 A method for farmer-participatory research. *Expl Agric.* **25**, 423–433.

Gohl, B. 1995 The relationship between field experiments, the station and laboratory. In *Agricultural science for biodiversity and sustainability in developing countries* (ed. F. Dolberg & P. H. Petersen), pp. 78–96. Denmark: Jordbrugsforlaget.

Hajrasuliha, S., Baniabassi, N., Metthey, J. & Nielsen, D. R. 1980 Spatial variability of soil sampling for salinity studies in southwest Iran. *Irrigation Sci.* **1**, 197–208.

Higgins, G. M., Kassam, A. H., van Velthuizen, H. T. & Purnell, M. F. 1987 Methods used by FAO to estimate environmental resources, potential outputs of crops, and population-supporting capacities in the developing nations. In *Agricultural environments* (ed. A. H. Bunting), pp. 171–183. Wallingford, UK: CAB International.

Kantey, B. A. & Williams, A. A. B. 1962 The use of soil engineering maps for road projects. *Trans. South African Inst. Civil Engrs* **4**, 149–159.

Kean, S. A. 1988 Developing a partnership between farmers and scientists: the example of Zambia's adaptive research planning team. *Expl Agric.* **24**, 289–299.

Krige, D. G. 1966 Two-dimensional weighted moving average trend surfaces for ore-evaluation. *J. South African Inst. Mining Metallurgy* **66**, 13–38.

Leenhardt, D., Voltz, M., Bornand, M. & Webster, R. 1994 Evaluating soil maps for predicting soil water properties. *European J. Soil Sci.* **45**, 293–301.

Legros, J.-P., Kölbl, O. & Falipou, P. 1996 Délimitations d'unités de paysage sur des photographies aériennes. Eléments de réflexion pour la définition d'une méthode de tracé. *Etude et Gestion des Sols* **3**, 113–124.

Mansfield, J. E., Bennett, J. G., King, R. B., Lang, D. M. & Lawton, R. M. 1975–76 *Land resources of the Northern and Luapula provinces of Zambia: a reconnaissance assessment*. Land Resource Report No. 19, Vols 1–6. Tolworth, UK: Land Resources Division.

Matheron, G. 1965 *Les variables régionalisées et leur estimation*. Paris: Masson.

Maurya, D. M., Bottrell, A. & Farrington, J. 1988 Improved livelihoods, genetic diversity and farmer-participation: a strategy for rice breeding in rainfed areas of India. *Expl Agric.* **24**, 311–320.

Morse, R. K. & Thornburn, T. H. 1961 Reliability of soil maps. In *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering* 1, pp. 259–262. Paris: Dunod.

Murdoch, G., Webster, R. & Lawrance, C. J. 1971 *Atlas of land systems in Swaziland*. Christchurch, UK: Military Vehicles and Engineering Establishment.

Oldeman, L. R. & van Engelen, V. W. P. 1993 A world soils and terrain digital database (SOTER)—an improved assessment of land resources. *Geoderma* **60**, 309–325.

Ollier, C. D., Lawrance, C. J., Beckett, P. H. T. & Webster, R. 1969 *Terrain classification and data storage. Uganda land systems*. Christchurch, UK: Military Engineering Experimental Establishment.

Peters, D. U. 1950 *Land usage in Serenje District*. Rhodes–Livingstone Papers No. 19. Cape Town: Oxford University Press.

Pingali, P. L. 1994 Technological prospects for reversing the declining trend in Asia's rice productivity. In *Agricultural technology: policy issues for the international community* (ed. J. R. Anderson), pp. 384–401. Wallingford, UK: CAB International.

Robert, P. C., Rust, R. H. & Larson, W. E. (eds) 1995 *Site-specific management for agricultural systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America and Soil Science Society of America.

Samra, J. S. & Singh, V. P. 1990 Spatial dependence of soil reclamation. *Soil Tech.* **3**, 153–165.

Schulin, R., Webster, R. & Meuli, R. 1994 A technical note on objectives, sampling design, and procedures in assessing regional soil pollution and the application of geostatistical analysis in such surveys. Environmental Documentation No. 25. Berne, Switzerland: Federal Office of Environment, Forests and Landscape (FOEFL).

Scott, R. M., Webster, R. & Lawrance, C. J. 1971 *A land system atlas of Western Kenya*. Christchurch, UK: Military Vehicles and Engineering Establishment.

Simmonds, N. W. 1986 A short review of farming systems research in the tropics. *Expl Agric.* **22**, 1–13.

Soil Survey of England and Wales 1983 *Legend to the soil map at 1:250,000 of England and Wales*. Harpenden, UK: Lawes Agricultural Trust.

Stobbs, A. R. & Jeffers, J. N. R. 1985 (ed. I. P. Anderson) *Land use survey of Malawi 1965–67*. Report No. 150. Tolworth, UK: Land Resource Development Centre.

Trapnell, C. G. 1943 *The soils, vegetation and agriculture of North-Eastern Rhodesia*. Lusaka: Government Printer.

Trapnell, C. G. & Clothier, J. N. 1937 *The soils, vegetation and agricultural systems of North-Western Rhodesia*. Lusaka: Government Printer.

Vogt, T. & Vogt, H. 1996 Formations affleurants et sols. In *L'aménagement des zones marneuses dans les bassins-versants des montagnes de l'Atlas Tellien semi-aride*, pp. 33–43. Eschborn, Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.

Voltz, M. & Webster, R. 1990 A comparison of kriging, cubic splines and classification for predicting soil properties from sample information. *J. Soil Sci.* **41**, 473–490.

Webster, R. 1968 Fundamental objections to the Seventh Approximation. *J. Soil Sci.* **19**, 354–366.

Webster, R. 1981 Soil survey: its quality and effectiveness. In *Soil resource inventories and development planning*. Technical Monograph No. 1, pp. 53–62. Washington DC: US Department of Agriculture.

Webster, R. & Beckett, P. H. T. 1968 Quality and usefulness of soil maps. *Nature* **219**, 680–682.

Webster, R. & Beckett, P. H. T. 1970 Terrain classification and evaluation using aerial photography: a review of recent work at Oxford. *Photogrammetria* **26**, 51–75.

Webster, R. & McBratney, A. B. 1981 Soil segment overlap in character space and its implications for soil classification. *J. Soil Sci.* **32**, 133–147.

Webster, R. & Oliver, M. A. 1990 *Statistical methods in soil and land resource survey*. Oxford University Press.

Weir, A. H., Rayner, J. H., Catt, J. A., Shipley, D. G. & Hollies, J. D. 1984 Soil factors affecting the yield of winter wheat: analysis of results from ICI surveys 1979–1980. *J. Agric. Sci., Camb.* **103**, 639–649.

Yates, F. 1936 *The design and analysis of factorial experiments*. Technical Communication No. 35. Harpenden, UK: Commonwealth Bureau of Soil Science.

Yates, F. 1984 *Sampling for censuses and surveys*. 4th edn. London: Griffin.

Discussion

A. Young (*University of East Anglia, UK*). Soil surveys in the past have failed to meet a need, by concentrating too exclusively on mapping. It is time that they adopted a more dynamic approach. A fourth task should be added to the three proposed by the speaker: 'In what condition are the soils?'. Some 25 years ago, R. P. Moss advocated an ecological approach to land resource assessment, but this was not followed up. In 1991, I proposed that soil monitoring should become a basic task for soil surveys (*Soil Use Mngt* 7, 126–130). Following the attention given to negative nutrient balances, and the World Bank's programme on land quality indicators, there are encouraging signs that attention is now being given to the dynamic aspect; some European countries and the USA are now doing so. National soil survey organizations in developing countries should be monitoring erosion, nutrient depletion, or whatever are their local problems of land degradation. They should be reporting to their governments on the severity of degradation, and its consequences for soil productivity.

R. Lal (*Ohio State University, USA*). Following the previous questioner's remarks on the soil's condition I find it difficult to make the concept of 'condition' or 'quality' quantitative and objective. 'Soil health' is another term expressing the same idea, but it is too vague and subjective. It is important that concepts are kept quantifiable and objective.

R. Webster. Dr Young raises several rather loosely connected though important issues, and I can deal only briefly with each. First, the 'condition' of the soil, or 'soil quality', which Dr Lal prefers for the same concept, can embrace one or more of many things; the plant nutrient status, the soil's salinity, its bulk, density, drainage, and heavy metal burden, all of which can change with time. One may measure and map them individually. Alternatively, one might first classify the soil by other means and then use the classes as strata for sampling, and record the condition of the soil class by class. In this instance the condition of the soil belongs to assessment in the formalism of my paper.

Monitoring the soil's condition and assessing change effectively add time to the spatial dimension of soil survey. They involve no new scientific principle, and, apart perhaps from some additional complexity in banking and analysing the data, current technology can cope. They do add substantially to the cost of survey, however, and they raise the questions of who is to pay and how. It is pointless to criticize soil survey for not incorporating the temporal dimension if the potential beneficiaries (either the farmers or the wider community) will not pay. More seriously, they raise the questions of responsibility and stewardship. Who is responsible for monitoring the condition of the soil, for maintaining the soil in good heart, and for restoring it to health if it has been allowed to degrade? In Britain and many other countries of the Old World there is no doubt that the answer is the land owner or tenant; they are stewards. Tenancy agreements often specify that the soil fertility should be maintained, and local laws exist to prevent farmers from allowing soil to erode off their land and from polluting watercourses. Experience in the New World has shown the need for communal action to combat erosion and salinity on a catchment scale; farmers have a shared responsibility in those circumstances, and they may have to call on expert agencies, such as the Soil Conservation Service in the United States, to coordinate the work. Pollution, especially fall-out from industrial emissions, may spread more widely still, and stewardship for the land then extends beyond the local rural community. Some national governments have monitoring stations and legislation for control. Switzerland is notable in this respect with its ordinance relating to pollutants in soil—see FOEFL (1987).

In developing countries soil is surveyed, if at all, primarily for development. When development of a region is complete the survey is seen to have served its main purpose, though the classification and maps should remain as frameworks for monitoring. The problem, as Dr Young well knows, is that the development agencies are unwilling to accept responsibility for ongoing work of this kind, and some governments would rather not know about degradation because they do not wish to spend money on counteracting it. And for something as serious as erosion even adding the monitoring function is not enough; what is needed is the means of forecasting or risk assessment so that erosion can be forestalled. In a modern commercial economy consumers of the food and other products of the land ultimately pay for maintaining the soil in a good condition. In the poor countries it is not at all clear who pays. But what is clear is that each time a farmer allows his soil to degrade irreversibly, for whatever reason, is a step towards the Malthusian Precipice.

Finally, I cannot let pass Dr Young's attribution of the ecological approach to R. P. Moss without comment. I do not doubt that Moss advocated it 25 years ago. But by then it had already been incorporated in the soil survey of Zambia for nearly 40 years—see Trapnell & Clothier (1937) and Trapnell (1943) above—and later by myself and colleagues, e.g. Astle *et al*. (1969). There are many examples from the 1950s and 1960s in other countries.

The merit of the approach is hardly in doubt where the vegetation is natural and where cultivation and grazing rely on natural regeneration and are closely integrated with it. As agriculture both extends and intensifies, however, so the association between soil and vestiges of natural vegetation weakens, and the ecological approach in its usual sense becomes increasingly impractical. Likewise, the more man imposes his regime on the soil, the less appropriate is the approach. We might not like the idea, we might want to live in harmony with nature, but the dissociation between the higher native plants and animals and the soil is almost inevitable as the human population increases.

In any case, what is ecology but the relation between organisms and their environment? To grow crops we replace one set of organisms, wild ones, with another, the farmer and his crops and livestock. And if soil survey views the soil as the farmer sees it or would like to see it, does that make survey any the less ecological?

H. Fell. How important is 'precision farming' to optimize yields in fields showing considerable variation?

R. Webster. Mr Fell, I think, is asking me to expand somewhat my remark on 'precision farming' in the context of increasing agricultural production. At present most of the land in the temperate zone is managed in blocks or fields of several hectares or more, each, as I said, being treated as if it were uniform, even though the crop does not see it that way. If the variation is in the mechanical or hydraulic properties of the soil, then cultivation has to be a compromise. If it is in nutrient supply, then the farmer may either underfertilize the poorest soil or overfertilize the richest, or both. In the first case the farmer loses potential yield. In the second, he may waste fertilizer, which might leak into the ground water or streams and lakes to become a nuisance. In the example I showed, for which I am indebted to Mr C. J. Dawson, it seemed that the farmer was applying more phosphorus fertilizer than he needed in some places because for other reasons the soil could not produce sufficient crop there to take it up. Precision farming aims to recognize this within-field variation, to measure it, and to provide the farmer with the technology to deal with it by optimizing his response to it. Recording harvesters, accurate navigation by satellite, optimal local estimation by kriging, and automated control of distributors of fertilizers and other agrochemicals promise the realization of these aims. The biggest single stumbling block at present seems to be the cost of getting the information on the soil at a sufficiently fine resolution at an affordable price.

E. Craswell (*International Board for Soil Research and Management, IBSRAM*). Could combine harvesters equipped with global positioning devices be used to collect data on the effect of soil erosion on yield at different parts of the landscape? Such information would be invaluable as a contribution to the debate on the on-site and off-site impacts of land degradation.

R. Webster. Dr Craswell pursues the same line of thought. Recording harvesters equipped to record their instantaneous positions and the yields can indeed provide the data on spatial variation in the crop. They cannot judge whether the variation is caused by erosion, however; that must be based on additional information about the state of the soil. Again, the problem is to obtain that information at a resolution approaching that from the harvester, a formidable task.

As a contribution to the debate one could investigate a sample of fields. This would embrace for each field several steps: (i) obtaining yield data for several years; (ii) obtaining soil data pertaining to erosion (particle-size distribution, porosity and permeability, thicknesses of horizons, organic carbon, and perhaps nutrient concentrations); (iii) a study of the correlations between crop performance and soil data; and (iv) an explanation of the correlation in terms of cause and effect.

Ultimately, the debate would be resolved only if the erosion itself were measured. Otherwise, we should be left with inference, even if well-informed.

F. L. Sinclair (*University of Wales, UK*). I question the validity, for resource-poor farmers in the tropics, of the assertion that, at a field scale, their agronomic management is uniform but crop response is variable because of underlying soil variation. There is mounting evidence that resource-poor farmers in Africa and elsewhere recognize short-range variation in their soil and manage their land accordingly. For example, farmers often add organic residues to less fertile patches of soil in their fields and match crop species to microsites in mixed cropping systems. These microsites may be delineated in terms of microtopographical, soil textural, and fertility variation as well as those created by the presence of trees in fields which alter both atmospheric and soil conditions in their vicinity. While farmers operating high-input systems seek to ameliorate the soil resource base to make it uniform, largely by adding inorganic fertilizer and using powerful cultivation techniques, resource-poor farmers, who cannot afford such capital intensive inputs, appear to recognize variability and, at least to some extent, use ecologically complex agronomic practices to accommodate it. What often appear to be haphazard mixed cropping arrangements in fields are, in fact, sensible responses to the soil on which the crops are being grown.

R. Webster. Evidently, I over-generalized in my paper, and Dr Sinclair is right to point out that many farmers in the tropics already distinguish small patches within their fields and treat them accordingly. They do this partly because they are poor and wish to maximize production from their land and limited fertilizer and manure. We should realize, however, that it is only because each has little land, often less than 1 ha in total, and works it by hand, that it is feasible. In this way they are able to do what farmers in the temperate zone would like to do, but who have for many years been unable to do because each must manage a much larger area. Significantly, the new 'precision farming' on large farms which I mentioned aims to achieve by modern technology what the small farmer can already do from intimate knowledge. Both aim to optimize the use of resources to produce crops from the land, whether for profit or production. And both emphasize the importance of local knowledge and its storage for future use in the brain, on paper, or in a computer.

References

Astle, W. L., Webster, R. & Lawrance, C. J. 1969 Land classification for management planning in the Luangwa Valley of Zambia. *J. Appl. Ecol.* 6, 143–169.

FOEFL (Federal Office of Environment, Forest and Landscape) 1987 *Commentary on the ordinance relating to pollutants in soil* (*VSBo of June 9, 1986*). Berne, Switzerland: FOEFL.