496

Offprint from

THE JOURNAL OF SOIL SCIENCE

Volume 22 · Number 3 · September 1971

OXFORD
AT THE CLARENDON PRESS

THE RELATION BETWEEN COST AND UTILITY IN SOIL SURVEY (I–III)[1]

P. A. BURROUGH[2] AND P. H. T. BECKETT

(*Soil Science Laboratory, Oxford*)

AND

M. G. JARVIS

(*Soil Survey of England and Wales*)

Summary

A series of five papers compares the *cost-effectiveness* of different procedures for soil survey at medium scale. The first three are presented here.

The whole trial area of 120 km² in Berkshire, in south-central England, was mapped in soil series by free survey at 1:25 000 for publication at 1:63 360. Three contrasting sample areas of 1·26 km² were resurveyed to the same legend by free survey at 1:10 560, and by grid survey at a range of scales between 1:20 000 and 1:70 000, to both general purpose (soil series) and fifteen–twenty different single-property legends. The direct costs of producing each map were recorded.

The study confirmed how much the free survey procedure depended on the external features of soil boundaries to locate them. The density of soil observations required to map soil series by free survey at the same map scale in different terrains was approximately proportional to the length of mapped boundary/km², or to the number of separately mapped soil occurrences/km². The density was least where the soil boundaries had the clearest external expression. Survey effort/km² increased in proportion to the density of observations but was also affected by local differences in the ease of cross-country access, or in the effort necessary (by spade or auger) to identify the soil at a point.

For soil series grid surveys there are approximately linear relations between log(cost) and log(map scale) with gradients between 1·3 and 1·7.

A map of soil series by grid survey is more expensive than a map of the same units, based upon the same density of observations by the same surveyor, by free survey. But a series map by grid survey by a scientific assistant is cheaper than a series map based on the same density of soil observations by free survey by a scientific officer (diplomate or graduate). The cost of an isoline map of a single soil property depends very much upon the cost of determining the property mapped, and to some extent upon the number of different isoline maps produced from a single set of samples or observations. Even at the unusually low costs of chemical analyses assumed here, an isoline map of one chemical property costs nearly twice as much as a series map by grid survey.

Introduction

THERE have been no direct comparisons between the utilities of soil maps, measured in any defined or measurable way, and the costs of the soil surveys that preceded them.

[1] This is a series of five papers. The first three are presented here with a single summary at the beginning and a single list of References at the end. Figures and tables are numbered consecutively through the first three papers.

[2] Now with Land Resources Division, Directorate of Overseas Surveys.

Indeed there has been very little discussion at all on how to assess the utility of a soil map or the efficacy of a soil survey procedure. Webster and Beckett (1968) have suggested that the utility of a soil map depends on the uniformity of significant soil properties within the area of each mapped soil unit. They have reviewed the available data on the uniformity of soil properties within defined profile classes and mapped soil units (Beckett and Webster, 1971). Beckett *et al.* (1967), Beckett (1968), and Bie and Beckett (1970) have indicated how the utility of a soil map, assessed in this way, may be found to depend on the nature of the soil units mapped, on the map scale, and on the survey procedure employed.

There is not much published information on the costs of soil survey: Bie and Beckett (1970) have reviewed what is available. They relate the costs of soil survey (in money or effort) to the scale of the soil map produced.

This series of five papers presents the results of a preliminary field study of this complex subject.

Aim

The aim of the study was to ascertain, within a given area of moderate complexity, how the costs or effort of soil survey, and the utility of the soil map produced, depended on the survey procedure, map scale, and map legend, and on the complexity of the soil pattern surveyed.

Secondarily it examined the conventional or free survey procedures commonly employed to produce soil maps at medium scale. It attempted to estimate how far a soil surveyor depends on external features such as vegetation, land use, and landform in locating the soil boundaries he maps.

Part I describes the area of the trial, the survey procedures compared, and the measurements made. Part II discusses free survey procedures. It relates the survey effort per unit area, necessary in different parts of the trial area, to differences in the complexity of the soil pattern, in the soils themselves, or in ease of access. Part III presents the direct costs of soil survey by different procedures and at different map scales.

Parts IV and V (to follow) compare the utility or information content of the soil maps produced by different procedures and at different scales, and relate the utility to the cost of each map in order to compare the *cost-effectiveness* of different survey procedures.

I. THE DESIGN OF THE EXPERIMENT

(P. A. Burrough and P. H. T. Beckett)

Location

The *trial area* covers 120 km² of agricultural land in north-west Berkshire (Fig. 1*a*), 30 km WSW of Oxford, chosen to avoid built-up areas.

The solid geology and major alluvial deposits are shown in Fig. 1*b* The area was strongly affected by periglacial conditions during the

Pleistocene. There are extensive hill-wash and solifluction deposits on the scarps and on the lower ground beneath them. Chalky 'sludge gravels' (Webster, 1966) or silty drift cover considerable areas of the

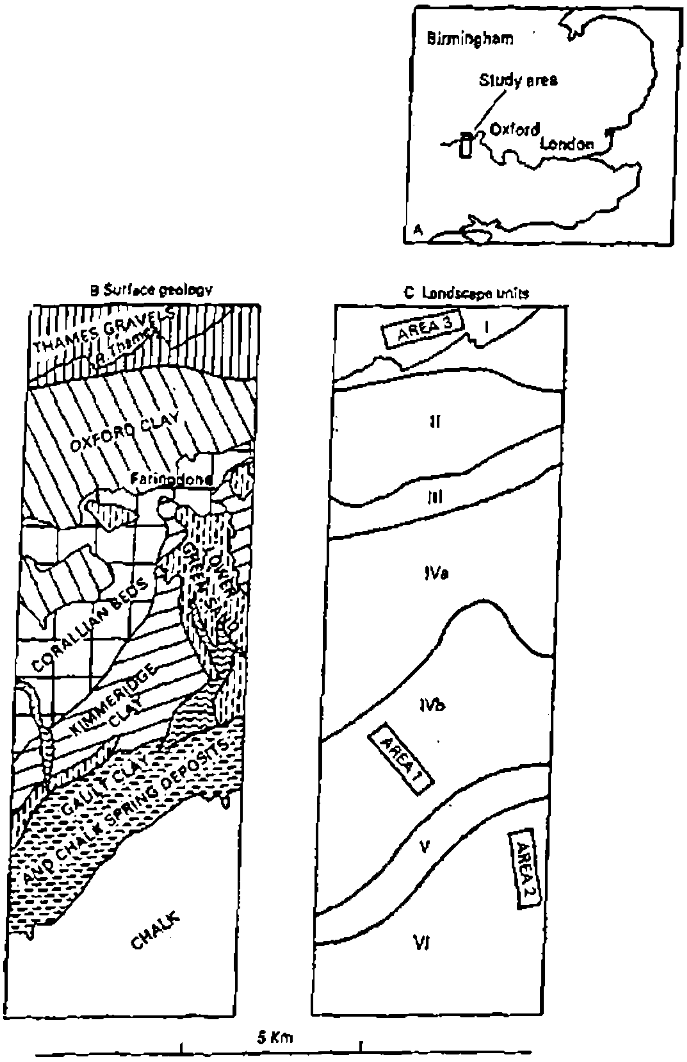


FIG. 1. The study area.

Vale of the White Horse. Much of this lacks clear topographic expression (cf. Davies and Gamm, 1969). Similar deposits occur below the Corallian scarp. Both merge into the clayey alluvium of the minor streams of the Vale or of the Upper Thames valley. Without augering to 1 m or more it is not easy to distinguish clay alluvium or drift from clay soils formed *in situ*, nor is it possible to predict the distribution of calcareous or non-calcareous clays of either kind. Studies in adjacent areas (e.g. Avery *et al.*, 1959; Loveday, 1962) have revealed loess admixtures of variable depth on the plateaux of the chalk dipslope, and on one but not always both sides of the dry valleys in the chalk, and possibly elsewhere. Solifluction has produced considerable deposits of mixed 'head' material on the bottoms and sides of the dry valleys (cf. Ollier and Thomasson, 1957, in the Chiltern hills), of which the surface horizons are locally decalcified, particularly on lower or flatter sites.

Because of solution hollows in the chalk (area 2) and the irregular 'braided stream' deposition of the gravels (area 3), the depth of soil over chalk or gravel is highly irregular, and soil changes as great as those between series (area 2) or phases (area 3) recur frequently over short distances.

The northern half of area 2 has been under intensive arable cultivation for 20–25 years but the southern half only within the last 5–6 years. There is still a contrast between the OM contents (and hence CEC) of profiles in the two parts of the area, even within the same series.

The trial area may be divided on geology and relief into seven landscape units (Fig. 1*c* and Table 1). *Special areas* of 1·26 km² were selected to represent three contrasting landscapes.

Soil survey procedures

The free survey and grid survey procedures to be compared cover the range of procedures normally employed in soil survey at medium or large scale.

Free survey (Steur, 1961; Buringh *et al.*, 1962) describes survey procedures in which the positions of soil observations are not predetermined or regularly arranged. Free survey is discussed in Part II.

At the time of this study the trial area was being mapped in soil series by free survey at 1:25 000, for publication at 1:63 360 (Jarvis, in press) by M. G. Jarvis of the Soil Survey of England and Wales. The resulting map (63SS[1]) covered the whole of the trial area. Fig. 2 shows the part which covers special area 1.

P. A. B. remapped the special areas, to the same legend (with one phase subdivision in area 3) but on field sheets at 1:10 560 appropriate to publication at 1:25 000 (25SS[1]). Fig. 2 shows 25SS for area 1.

Grid survey. A basic rectangular grid of 6 × 21 sites at 100 m spacing (one site per hectare) was laid out within each special area; in effect as 'organized grids of random origin'. This shape covered the greatest variety of soils for a given effort. The grid for each special area was planned in the laboratory, and then approximately ten sites in each area were laid out to ±1 m with plane table and compass, and the remainder to ±5 m by compass and pacing. There was a slight and unbiased adjustment, not exceeding 5 m, of a few sites in area 1 which fell on disturbed ground.

[1] Throughout this series the first part of the symbol, e.g. 63, 25, indicates the map scale (1:63 360; 1:25 000) *or* the density of the sampling grid (100/100). The second part of the symbol is SS—Soil Series, API—Air Photograph Interpretation or, in the case of single property maps, OM (organic matter), Clay, etc.

TABLE 1

Description of the trial area

Landscape unit	*Geology*	*Relief and physiography*	*Soils*	*Dominant land use*	
Upper Thames Valley					
I. Thames Terraces	Limestone river gravels over Oxford Clay; flood plain alluvium	Very subdued flood plain and terrace	Brown calcareous soils, with and without gleying, on terraces; surface water gleys on clay	Arable (barley). Medium size (4–12 ha) open fields	Sandford (1924, 1965) Beckett (1966)
II. Oxford Clay Lowlands	Oxford Clay and Head over Clay	Low, broad hills capped with gravel. Moderate relief	Calcareous and non-calcareous surface water gleys	Arable pasture. Medium size *(4–12 ha) hedged fields	Arkell (1939, 1942, 1947)
III. Corallian Scarp	Corallian Limestones and Lower Greensand	Scarp face highly dissected. Strong relief	Sols lessivés on Lower Greensand. Brown calcareous soils on limestones. Some gleying	Pasture. Small (c. 4 ha) hedged fields	
Vale of the White Horse					
IVa. Corallian Dipslope	Corallian Limestones, Lower Greensand, and Kimmeridge Clay	Broad smooth slopes of moderate relief, dissected by broad valleys	As above. Gleying more pronounced in all soils	Arable. Small-medium (2–10 ha) fields	Arkell (1939, 1941, 1947)
IVb. Clay Vale	Kimmeridge and Gault Clays, Lower Greensand	Flattish; broad shallow valleys filled with alluvium and chalky drift. Subdued relief	Calcareous and non-calcareous surface water and ground water gleys	Pasture: small (4–6 ha) hedged fields	Webster (1966) Kerney *et al.* (1964)
The Downs					
V. Chalk Scarp	Upper Greensand, Lower and Middle Chalk	Dissected by large Coombe valleys. Strong relief	Brown calcareous soils, rendzinas and sols lessivés	Pasture/arable. Medium (6–8 ha) open fields	Kerney *et al.* (1964) Small (1964)
VI. Chalk Dipslope	Middle Chalk	Broad N–S oriented valleys with smaller valleys incised in floors. Moderate relief	Brown calcareous soils, rendzinas and sols lessivés	Arable. Large (20–30 ha) open fields	Ollier and Thomasson, (1957) Loveday (1962) Avery (1964)

When a site had been located the soil series (or phase) present was identified according to the legend of 25SS, by examination with the 2·5 cm auger. Then the principal features of the main horizons (Table 2) were recorded. Finally fifteen auger cores, 0–20 cm, were taken from within 5 m of the site and bulked for subsequent laboratory analyses (Table 2). Preliminary trials (cf. Reed and Rigney, 1947) suggested that much of the short-range variability between individual cores could be eliminated by bulking this number.

TABLE 2

Soil properties determined at grid points

In the field, by 2·5 cm screw auger	
(*a*) *Soil series* (or phase) identified	
(*b*) *for each major horizon*:	
Munsell hue, value, and chroma	
Degree of mottling	(areas 1 and 3 only)
Hue, value, and chroma of mottling	(area 1 only)
Clay and sand content*	
Carbonate content*	
Structure and consistency	(topsoil 0–20 cm, in areas 2 and 3 only)
(*c*) *Depth* to carbonate, mottling, gravel or bedrock	
In the laboratory (on sample bulked from 15 auger cores within 5 m of site)	
Organic matter	
Clay content†	
Cation exchange capacity	
pH	
Available K and Mg‡	

* Clay and sand estimated manually; carbonate by effervescence with HCl.

† Per cent clay estimated manually by comparison with mechanical analyses of a few samples.

‡ By standard N.A.A.S. procedure.

The list of properties to be determined in the laboratory included one (available K) likely to have been much affected by farmers, some which probably were less affected (pH, available Mg,[1] and to some extent organic matter and cation exchange capacity), while clay content was likely to have been little affected.

Records were kept of the time taken to lay out the grid and to visit every grid site in each special area, and sufficient records to calculate the average time necessary to identify the soil series, to describe and record soil properties, and to collect and bulk a soil sample, at a grid site in each area.

From the 126 grid data for each special area it was possible to extract sets of data appropriate to grids of lower density; in particular we extracted 63 grid sites at spacing of $100\sqrt{2}$ (= approx. 140 m) (140/140), 42 sites on grids of 100 m × 300 m (100/300) and vice versa, and 14

[1] Unfortunately, and unknown to us at the time of the survey, part of area 2 lay within a former RAF bombing range. Broad bands of high Mg still mark the fall of flares and incendiary bombs, but other properties seem to be unaffected.

sites at spacings of 300 m × 300 m (300/300). As well as a legend of soil series, as for 25SS, it was possible to draw up several kinds of single-property map legends from the same basic data. A list of classes was drawn up for each soil property measured or recorded. Where available we used class limits already in use by the Soil Survey of Great Britain (Soil Survey Staff, 1960) or the National Agricultural Advisory Service (1967). Otherwise the values for a property were divided into classes of equal range.

Grid maps were drawn for series and for every soil property recorded or measured, for every density of grid sites in each area.

The interpolation of the boundaries or isolines was purely mechanical, unaided by any external soil expression on the ground or on air photographs. This extreme application of the grid survey procedure facilitates a clear-cut comparison with free survey which does make use of external soil features to locate boundaries. But it will bias subsequent comparisons (Part IV) against grid survey.

Without any external aids the boundaries on grid maps of soil series had to be straight lines midway between grid sites. Fig. 2 illustrates the 100/100 and 300/300 maps of soil series for area 1. Undoubtedly such stepped boundaries are ugly and unnatural; but the debatable area between smoothed boundaries and the corresponding stepped boundaries may not be very great. In the 140/140 maps of soil series, boundaries midway between grid sites would have lain across all the sites not used in plotting the map, leaving none by which to check its utility (Part IV). So in this case the boundaries were very slightly biased, just enough for each site not on the 140/140 grid to be allocated to the series to which the majority of its nearest neighbours belonged.

Boundaries on the grid maps of single properties (Table 2) were plotted as isolines (Fig. 2). Records were kept from which to calculate the average time taken (per km^2) to draw up the legend of a single-property map, and to interpolate its boundaries or isolines.

Air photograph interpretation (API). There already existed a map (63 API) of physiographically defined soil-landscape units for the whole trial area (Beckett and Webster, 1965) produced by air photograph interpretation with limited ground check (i.e. about 10 per cent of the area was visited). The air photographs used were old and of poor to average quality, and stereo-overlap was incomplete. Area 3 was re-surveyed (40 API) by Dr. R. Webster by means of new and better photographs at a scale of 1:20 000, without ground check but drawing upon comparable prior experience of the area.

Finally all these were combined to produce a *best possible map* (BPM) for each special area, based upon all free and grid soil observations, and all available aids to the interpolation of boundaries. Fig. 3 presents the result for area 1.

Virtual map scale

We wish to compare the costs and efficacies of the range of maps thus produced. But, to compare like with like, it is first necessary to order them according to the amount of detail they purport to show.

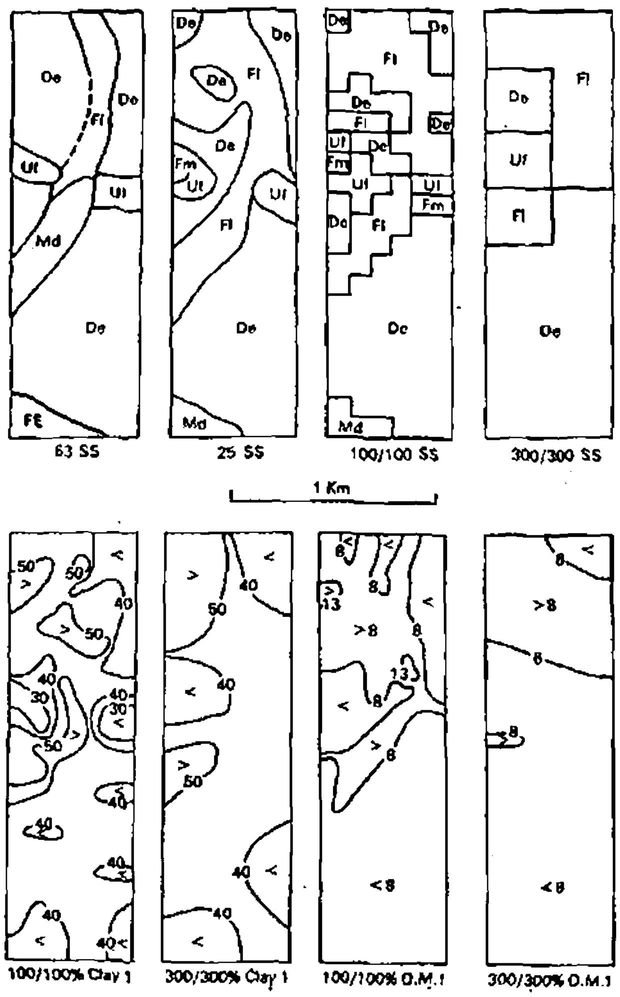


FIG. 2. Examples of soil maps of special area 1.

63SS—Soil series maps by free survey at 1:25 000 (18·2 obsvns./km²).

25SS—Soil series map by free survey at 1:10 560 (140·8 obsvns./km²).

100/100SS—Soil series map by grid survey at 100 m spacing (100 obsvns./km²).

300/300SS—Soil series map by grid survey at 300 m spacing (11·1 obsvns./km²).

De = Denchworth; FE = Ford End; Fl = Fladbury; Fm = Fernham (now Shellingford); Md = Mead; Uf = Uffington (now Kingston) series.

100/100 Clay 1, 300/300 Clay 1—*isoline maps of clay in the surface horizon from grid observations at 100 m and 300 m spacing.*

100/100OM1, 300/300OM1—ditto, for organic matter in surface horizon.

The scale of a published soil map is commonly and conveniently taken to be an approximate indication of the amount of detail it shows. Up to a point this is justified, as the *minimum scale for a soil map is the ratio of the smallest area that can be printed to the smallest area of soil that has been distinguished by the surveyor.* But often the map scale is not the minimum possible, and it is affected by other factors too. For example there are several different conventions for the ratio between mapping scale and publication scale (e.g. Bie and Beckett, 1970), and the scale of the field maps may be limited by the availability of suitable base maps, or publication scale may be uniform for the whole region covered by one organization. If the map scale has been affected by any of these it may not provide a suitable measure of the amount of detail shown. Nor is there any obvious relation between the scale of a base map and the publication scales of soil maps derived from grid observations of varying density upon it.

Some workers calculate the map scale appropriate to a given amount of detail, by relating it to the density of soil observations. Thus Vink (1963) quotes recommendations that the scale should be adjusted to give on average nine observations per cm² of published map (Soil Survey Staff, 1951); five observations/cm² (Steur, 1961); two observations/cm² (ORSTOM), all for surveys not depending upon air photograph interpretation. Boulaine (1966) recommends a virtual map scale such that there are four observations /cm² of published map.

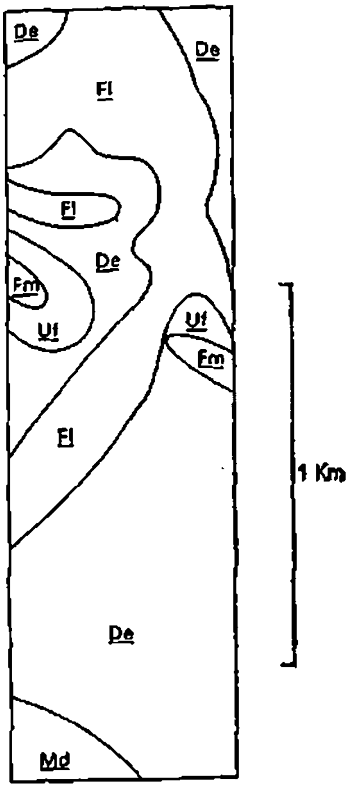


Fig. 3. 'Best possible map' (BPM) of soil series in special area 1, compiled from 25SS, from series observations on a grid at 100 m spacing, and from all available aids to the interpolation of boundaries. Soil series as in Fig. 2.

There is some justification for adjusting map scale to the density of observations. An experienced soil surveyor tends to adjust the density of his observations according to the amount of detail he wishes to record. There would be no point in making extra observations to map out a soil boundary more tortuously than could be represented on the published map, or than it needs to be known by the potential users of the map. In any one procedure of soil survey the density of observations is likely to be related to the amount of detail shown as long as only a few boundaries, or a roughly constant fraction of boundaries, are located mainly on their external features. The number of observations necessary to map a given amount of detail must fall off in proportion to the fraction of boundaries that may be mapped on their external appearance. Even so, the density of observations seems to provide a better measure of detail than map scale, and one less affected by arbitrary or unrelated factors.

So we have calculated a virtual scale for each map, such that on average there will have been five soil observations/cm² of each map.

This figure is approximately medial to those quoted by Vink; it is also the whole number which most nearly brings Jarvis's survey of the whole trial area to the scale of 1:63 360 at which it was to be published.

Table 3 lists the virtual scales thus calculated. For subsequent comparisons note that this convention tends to attribute a somewhat smaller scale to soil maps by free survey than is justified by the amount of detail they show.

We have taken its publication scale of 1:63 360 for 63API, and 1:40 000 (twice the scale of the air photographs from which it derives) for 40API.

TABLE 3

Virtual scales of the maps to be compared

		Density of observations/km²			Virtual scales		
		Area			Area		
		1	2	3	1	2	3
Free survey	25SS	140·8	127·0	127·0	1:18 000	1:19 840	1:19 840
	63SS	18·2	12·0	10·9	1:52 400	1:64 500	1:68 000
Grid survey	100/100SS		100·0			1:22 400	
	140/140SS		50·0			1:31 600	
	300/100SS 100/300SS		33·3			1:38 800	
	300/300SS		11·1			1:67 000	
API	40API		..			1:40 000	
	63API		..			1:63 360	

II. CONVENTIONAL OR FREE SURVEY

P. A. Burrough, P. H. T. Beckett, and M. G. Jarvis

Introduction

The term *free survey* was proposed by Steur, 1961; and by Buringh, *et al.*, 1962, to distinguish soil survey procedures in which direct soil observations (by auger, pit, or cutting) are irregularly located according to the judgement of the surveyor as survey proceeds. It was contrasted with grid surveys in which observation points are predetermined and/or regularly positioned. The term free survey commonly carries the connotation that soil boundaries are located partly on changes in external soil features such as landform, vegetation, land use, though this was not part of its original definition. In this respect there is no sharp distinction between free soil survey and soil survey by air photograph interpretation (API). Free survey procedures tend to be used where there is some external expression to soil boundaries (or most of them), though not sufficiently consistent for mapping by API.

At present most soil maps at medium scale in north-west Europe and North America are produced by free survey.

Aim

This paper describes free soil surveys of the whole trial area for publication at 1:63 360 (63SS), and of the three special areas at 1:25 000 (25SS). It discusses the decisions and compromises implicit in free survey.

The maps are compared with each other, and with check observations at 126 grid points regularly spaced at 100 m in each special area, to ascertain: (1) How far the time (or effort) required to produce a soil map at 1:63 360 depends on the complexity or intricacy of the soil pattern as mapped. It is useful to distinguish between *complexity* or the number of separate soil occurrences in a given area, and *intricacy*, which indicates the tortuosity of their boundaries. (2) To what extent the extra effort required to produce soil maps at larger scale is justified by the increased accuracy.

The Procedures of Free Survey

Many authors have discussed the conventional soil survey procedures referred to here as free survey (e.g. Soil Survey Staff, 1951; Clarke, 1957; Buringh *et al.*, 1962; Vink, 1963; Findlay, 1965; Hodgson, 1967). They agree more or less on the main stages, though individuals and organizations disagree on details and on the order of some of the stages. The main stages are:

Establishment of a provisional legend

(1) From published works on local geology and geomorphology, from previous soil surveys in similar areas, and from reconnaissance traverses designed to sample every local combination of parent material and topography, the surveyor *either* (*a*) draws up a list of every type of soil found in the area, and groups them into profile classes,[1] which are briefly described: an area within which one or other, or a stated combination, of the profile classes predominates, then becomes a provisional mapping unit,[1] *or* (*b*) resolves the soil-landscape directly into provisional mapping units; these are commonly but not always chosen because they can be mapped by their external features.

As the survey proceeds and the surveyor perceives the associations between profile classes and discernible elements in the landscape, a provisional legend of type (*a*) tends to develop into one of type (*b*). Some organizations allow mapping units to be modified during a survey; others (e.g. Soil Survey Staff, 1951) require that the legend be complete before survey begins. There are disadvantages to both procedures.

(2) For either legend the mapping units are usually described in terms of their constituent profile classes, except for miscellaneous landscape units such as 'badlands', 'minor alluvial bottomlands', which are defined as such.

Mapping

(3) The profile class at any point is identified by auger or spade. Commonly the surveyor works along a loose traverse looking for the changes in the external features of the soil which he can show to be associated with soil boundaries. On encountering an unfamiliar change

[1] *Profile classes* are groups of similar soil profiles, which need not be contiguous. *Mapping units* are coherent areas of land, the soils of which may be adequately described for the purpose of the map by simple statements. As usually defined a soil series is a profile class, but a mapping unit in which one series predominates commonly carries the same name. The *map legend* is the list of mapping units.

in external features, he may make several soil observations in order to verify that it is related to a soil boundary.

(4) Once located, a soil boundary is extended, *either* by repeated soil observations *or* by plotting external features known to be associated with it, with occasional check observations to confirm the constancy of the association.

(5) Additional observations may be made to confirm that the soil within a boundary is uniform.

(6) Typical examples of each profile class are described in detail and samples taken for analysis.

The relative contributions of the two procedures in (4) depend on the individual surveyor, on the consistency and clarity of the external expression of soil changes, and on the time available. Clarke (1957) insists that the boundary between mapping units be located by frequent augering and Vink (1963) estimates that up to 80 per cent of all soil observations may be required to locate boundaries. Buringh *et al.* (1962), Findlay (1965), and Hodgson (1967) refer to the aid of external features, but stress the importance of frequent augering.

But Goosen (1967) notes that there is often insufficient time to locate all boundaries by augering; the best possible use must be made of the 'correlations between soil profile differences and soil landscape changes'. Faced with a soil boundary lacking clear external expression, the surveyor has to decide whether to combine the two adjacent soils into a compound mapping unit, or to spend time on extra observations to locate all the boundary (as in 25SS below), or to make an inspired guess. Whatever his decision, the surveyor cannot adequately map soil bodies that are not discrete or coherent at the scale of mapping.

This Investigation

Sequence of operations

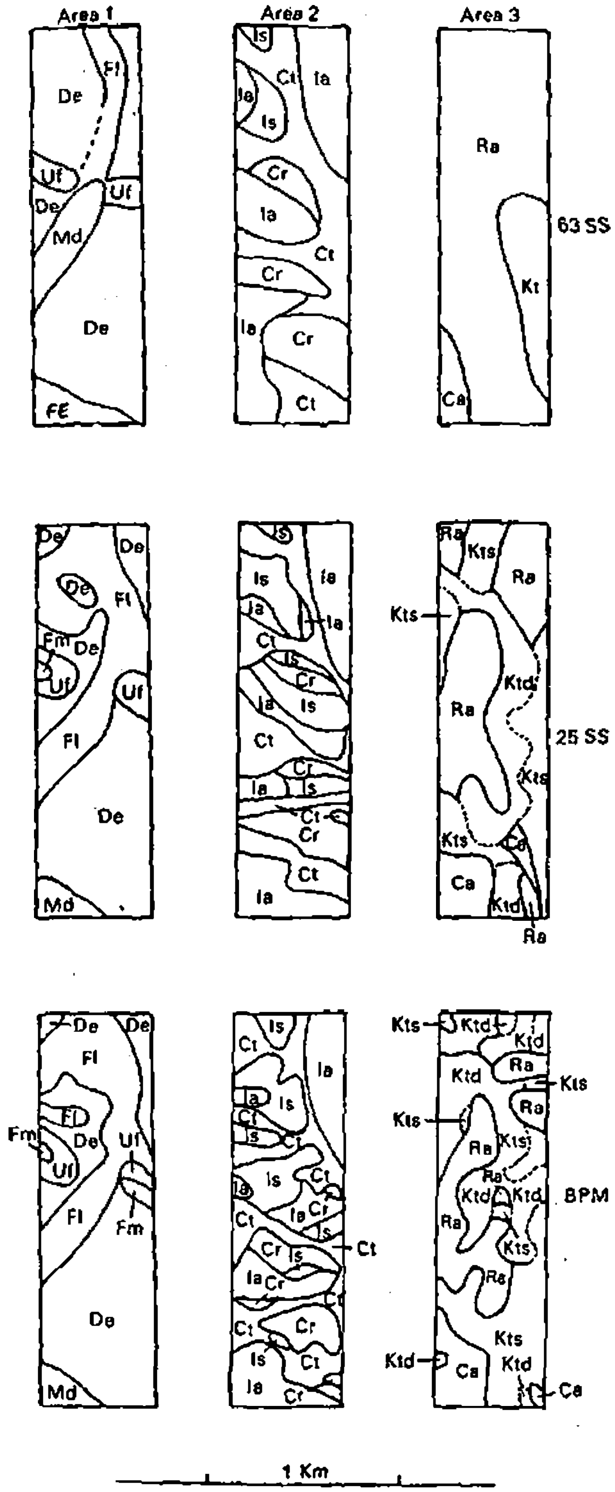
Part I describes the trial area and resolves it into seven landscape units on geology and relief (Fig. 1*c*).

40 per cent of the area, mainly in landscape units IVb and V, had already been surveyed by one of us (M. G. J.) before this study started, for publication at 1:63 360 (63SS). The first author (P. A. B.) accompanied him in the field during 49 days between January and June 1967 while he surveyed the remaining 60 per cent. He noted the decisions made, the observation points, and all time spent.

Some months later he (P. A. B.) resurveyed the three special areas in landscape units I, IVb, and V on field sheets at 1:10 560 (25SS) to the same legend and by the same procedure, but with no other reference to 63SS. Observation points and times were noted. After this he located 126 (6×21) sites on a 100×100 m grid in each area, and identified the profile class at each.

FIG. 4. Soil surveys of the three special areas at 1:25 000 (63SS), at 1:10 560 (25SS), and by adding to the latter information from 126 grid points in each area (BPM).

Symbols represent soil series (and two phases): Ca = Carswell; Cr = Charity; Ct = Coombe; De = Denchworth; FE = Ford End; Fl = Fladbury; Fm = Fernham (now Shellingford); Ia = Icknield; Is = Ilsley; Ktd = Kelmscot (deep phase); Kts = Kelmscot (shallow phase); Md = Mead; Ra = Radley (now Badsey); Uf = Uffington (now Kingston).


Area 1
Area 2
Area 3
63 SS
25 SS
BPM
1 Km

The 'best possible map' (BPM) of each area combined all observations from 25SS and the 100/100 grid, with the maximum possible use of all external aids to the location of soil boundaries.

There were also two maps compiled from air photographs: 63API at 1:63 360 and 40API at 1:40 000.

Figure 4 compares 63SS, 25SS and BPM for the three special areas.

Free survey at 1:25 000 for 1:63 360 (63SS). The surveyor had a provisional legend of tentative mapping units based on the profile classes (soil series as defined by Findlay (1965)) he had listed on a preliminary reconnaissance at the start of the survey three years earlier. Several profile classes were adapted from the more loosely defined units of Kay's (1934) survey in the Vale of the White Horse, whereas others had been first defined in similar landscapes elsewhere (e.g. Robinson, 1948; Osmond *et al.*, 1949; Avery 1955, 1964). Some were modified during the survey. Several pairs of tentative mapping units have been combined on the published map which was drawn up after this study was completed (Jarvis, in press).

Profile classes were identified in the field by means of a 2·5 cm screw auger.

At *'noted' observation points* the soil profile was briefly recorded in a field notebook, and on the field map sheet as a numbered dot. These were mainly to ascertain which profile classes were present in areas not previously examined, or to record soils within mapped boundaries. *'Check' observations* were mainly to verify boundaries: these would not have been recorded except for this study (by P. A. B.). Table 4 records the average densities of noted and check observations overall, and in each landscape unit.

Only 'noted' observations had been recorded in the areas of units IVb and V surveyed before this study started. Soil patterns in these units are of comparable complexity to units I and III (Table 6). So the total densities of observations in units IVb and V were estimated from the ratios of total/noted observations over the whole area, and also in units I and III.

On average only 30 per cent were 'check' observations to verify boundaries, or to verify their association with external features; the other 70 per cent were 'noted' observations to describe the soils within them. This contrasts with the experience of Buringh *et al.* (1962), in an area where the soil boundaries lacked external expression, who used 75 per cent of 'plotting observations' to locate soil boundaries, and only 25 per cent to identify soils within them. On days when survey commenced in a new landscape unit (the 'exploratory days' of Table 4) the ratio of noted to check observations fell to about half (Burrough, 1969): in an unfamiliar area the surveyor needed extra observations to verify the association between soils and external features.

From this and from the large proportion of noted observations, it is evident that the boundaries mapped were mainly located on their external features, as suggested by Goosen (1967). This probably happens more often than might be inferred from some of the publications

TABLE 4

Effort for free survey in relation to landscape and map scale

	Landscape unit	*Mean survey time h/km²*	*Noted obsvns./km²*	*Check obsvns./km²*	*Total obsvns./km²*	*% Noted obsvns./Total*	*Mean Time per obsvn. (h)*
(a) 63SS	I	2·1	7·4	3·4	10·9	68	0·193
	II	3·8	12·8	5·2	17·9	72	0·219
	III	4·5	13·9	7·9	21·8	64	0·206
	IVa	3·5	14·4	5·1	19·5	74	0·179
	IVb	3·7–3·8§	13·5	6·1‡–6·4†	19·6‡–19·9†	68*–69‡	(0·19)
	V	3·2–3·4§	11·1	5·0‡–6·3†	16·1‡–17·4†	64*–69‡	(0·197)
	VI	2·5	8·3	4·0	12·3	68	0·203
(b) 25SS	I (Area 3)	9·1	17·5	109·5	127·0	..	0·071
	IVb (Area 1)	23·3	21·4	119·4	140·8	..	0·165
	VI (Area 2)	13·2	27·0	100·0	127·0	..	0·104

* From landscape units I and III.

† Calculated from assumed ratio (as *) and records of 'noted' observations.

‡ Calculated from regression (units I, II, III, IVa, VI) of 'check' against 'noted' observations (Burrough, 1969): if 'exploratory days' (see text) are excluded from regression, IVb gives 18·2 total observations/km²

§ Calculated from density of total observations (from † or ‡) and overall regression (I, II, III, IVa, VI) of survey time against total observations: IVb gives value of 3·5 h/km² if exploratory days are excluded from regression.

referred to. Certainly the 'purity' of the mapping units (Table 7) on 63SS was highest where their boundaries had the clearest external expression.

Table 4 also presents the mean effort (h/km²) of survey in each landscape unit. The figures for units IVb and V are calculated from the total densities of observations calculated as above, and a regression of survey effort against observation density (equation 1) calculated for the other units (Burrough, 1969):

$$\text{(survey effort in h/km}^2\text{)} = 0{\cdot}40 + 0{\cdot}17(\text{observations per km}^2) \quad (r = 0{\cdot}83^{**}). \quad (1)$$

These figures for effort refer only to productive field time. They exclude time spent on interviewing farmers, sheltering from rain, and travel within the survey area, or on travel to and from the survey area. In this respect the figures differ from the 'man-days per km²' quoted elsewhere (Bie and Beckett, 1970, 1971) which include total time in the field, and time for compiling the final map.

Inevitably soil mapping involves compromises. Small areas of a unit may be overlooked altogether. Even when observed, areas too small to be represented on a map have to be ignored or combined with the most similar of the adjacent units. For example in area 2, soils of the Ilsley series are shallow like Icknield series, but many have a brown B horizon like Coombe series; all three are calcareous. The profile classes change frequently within short distances (Burrough, 1969; Cuanalo, 1966), so that many bodies of Ilsley series were not coherent enough to be mapped as such, and had to be mapped with either Icknield or Coombe series according to which they most resembled in topographic situation.

Then some soil profiles differed in one or more features from all the classes in the provisional legend. Small differences could be ignored, especially where the land-use capability of the aberrant profile seemed similar to that of the profile class it most nearly resembled. If the differences seemed to be more significant the surveyor usually made further observations near by to see whether an aberrant profile was typical of a mappable area. When it was, the legend was modified by broadening the definition of an existing class or defining a new one; when it was not, the anomaly was ignored.

Such compromises diminish the uniformity or 'purity' of mapped soil units; they are less frequent at larger map scales.

Free survey at 1:10 560 (25SS). The legend of 25SS was the same as that of 63SS, except that the Kelmscot series in area 3 was separated into shallow and deep phases. Figure 4 shows 25SS for the three areas, and Table 4 the greater density of observations and the slower rate of survey.

Much of the increased effort was spent on locating small areas of one soil within the limits of another, and on locating boundaries more accurately.

The distances between observation points were much shorter, so less time was spent walking and the average total time per observation was nearly halved (Table 4) in areas 2 and 3, where augering was easy and many soils could be distinguished on properties apparent at shallow depths. The average time per observation was not reduced so much in area 1 where many soils were clayey, some soils could be distinguished only by augering to 1 m, and hedges or ditches were more frequent.

Soil complexity and survey effort

Only 63SS covered all landscape units; Table 4 shows how the rate of survey differed between landscape units.

TABLE 5

Rate of soil survey in the three special areas

Landscape unit *Area*	I 3	IVb 1	VI 2
Average time per site (h)			
1. To identify series at 100 sites/km²	0·049	0·113	0·076
2. To collect topsoil samples, bulked from 15 cores within 5 m	0·100	0·135	0·117
3. To locate and visit 130–40 sites/km² during free survey at 1:10 560, and to identify series at each	0·071	0·165	0·104
4. To locate and visit 100 sites/km² on 100 m grid	0·042	0·10	0·067
5. Approx. time to visit 130–40 sites/km² during free survey at 1:10 560 (calc. as 3−1)	0·022	0·052	0·028

These differences seem to have arisen partly because of differences in ease of access (see Table 1, part 1), or in ease or depth of augering. Thus Table 5 shows how the average time to identify series (or to collect samples), and the time to move about within the landscape to lay out a grid or to conduct a free survey, differ between the three special areas.

But also the mapping of more frequent changes in soil or of more tortuous soil boundaries, needs more observations per unit area mapped (e.g. Tyurin *et al.*, 1959, Buringh *et al.*, 1962). For areas of equal accessibility, and soils equally easy to auger, survey effort (h per km²) might have been expected to increase with the density of observations.

Simple analysis of variance (Burrough, 1969) confirmed that the densities of observations differed significantly (1 per cent level) between landscape units. Scheffé's test showed significant contrasts between II and IVa, and between (I+VI) and (II+VIa): contrasts between II and IVa or I and VI were not significant.

Presumably the density of soil observations found necessary will tend to increase with the intricacy or complexity of the soil pattern, unless the areas compared also differ in the external expression of their soil boundaries (p. 367).

But there is no simple criterion for the intricacy or complexity of soil pattern. Beckett (1967) suggested that a graph of the variance of a measured property against the size of the area sampled describes soil complexity with regard to that property, and Beckett and Webster (1971) give some examples. This study lacked the necessary data.

Instead, the number of separately mapped soil occurrences, the total length of mapped soil boundary, and the average distance between the nearest two soil boundaries to each of five random points were determined for every kilometre square on 63SS in the trial area. Figure 5 presents isopleth maps of their values and Table 6 their averages for each landscape unit. These are crude measures of soil complexity.

Figure 6*a* shows how the density of observations is approximately proportional to the length of mapped boundary per unit area, and inversely proportional to the average distance between boundaries. The values of observation density and survey effort for units IVa and V were calculated indirectly (pp. 372–4). Even so, some part of their discrepancy from the regression lines is probably real; the soil boundaries in unit V have marked external expression, while parts of some boundaries in unit IVb (notably between soils on 'solid' and drift clays, and between three drift soils of heavy texture) required much survey effort.

Figure 6*b* relates survey effort in the different landscape units to their average boundary spacings and to the total length of boundary per unit area. As expected the rate of survey decreases as the complexity of the soil pattern increases.

The result of increasing survey effort

In order of increasing survey effort we have the API maps at 1:63 360 and at 1:40 000 (area 3 only), and the soil maps 63SS, 25SS, and BPM. Except that one series in area 3 is mapped as two phases on 25SS and BPM, the last three all have the same legend, but with average densities of observation which increase in the proportions 1:10:17.

Figure 4 compares 63SS, 25SS, and BPM for the three special areas. Table 7 shows by how much the extra effort increased the detail they show. The following discussion compares the maps, and the 'purities' of the mapping units in 63SS and 25SS. 'Purity' is the percentage of the 126 grid sites in each special area at which the profile class found was that indicated on the maps. In free survey without plane table there may be minor plotting errors, so that correctly identified boundaries are incorrectly located on the map: we have allowed for this.

Though detail and purity do increase on passing from 63SS to 25SS (Table 7) the increases are not the same in the three areas, and they are not related to the purity of 63SS. The three areas will be discussed in turn.

In *Area 1* all three soil maps and 63 API agree (Fig. 4) on the boundaries between soils on the Lower Greensand and soils on clays.

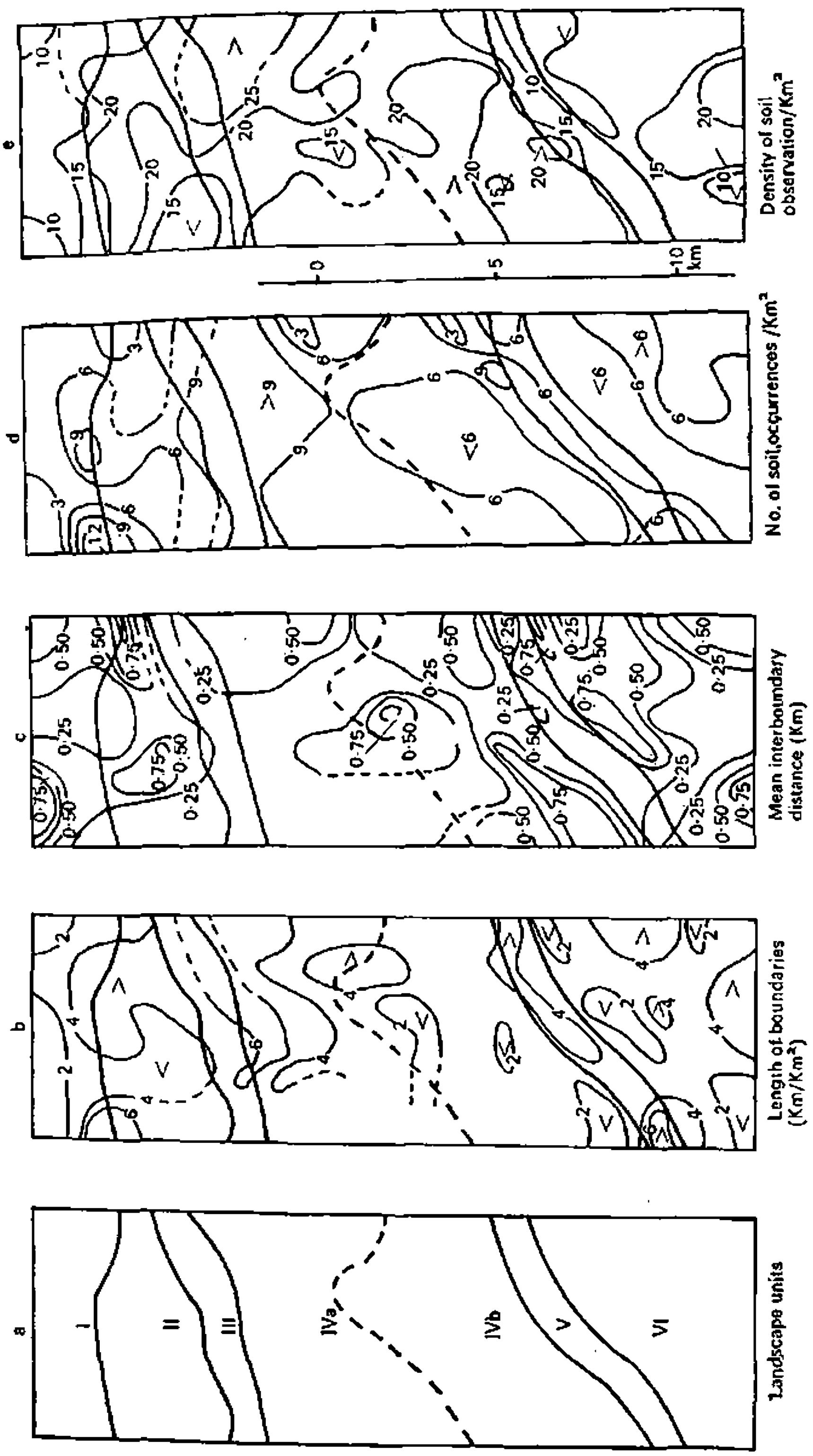


FIG. 5. (a) Landscape units of the trial area. (b) Length of mapped soil boundary per unit area (km per km²). (c) Mean interboundary distance (km). (d) Number of separately mapped soil bodies per km². (e) Density of observations made during survey. (b)–(e) relate to 63SS.

TABLE 6

*Soil complexity in the trial area**

Landscape unit	*Mean no. of soil occurrences*	*Mean length of boundary*	*Mean boundary spacing*	*Mean density of obsvns./km²*
	per km²	*km/km²*	*km*	
I	5·2	2·3	0·5	10·9
II	6·7	4·0	0·36	17·9
III	9·6	5·6	0·16	21·8
IVa	7·4	4·5	0·27	19·5
IVb	5·6	2·9	0·49	19·6–19·9†
V	8	5·2	0·16	16·1–17·4†
VI	5·2	3·1	0·45	12·3

* Average of values for complete kilometre squares of 63SS, each square being allocated to its predominant landscape unit.

† See Table 2.

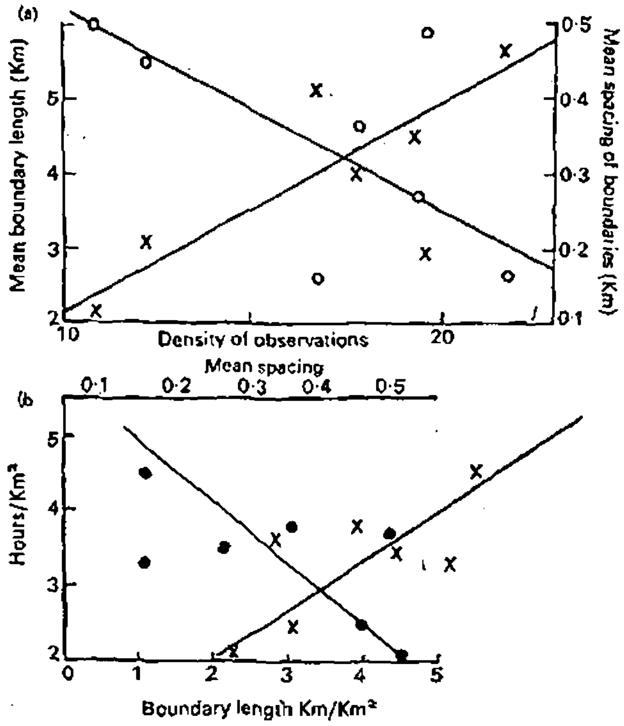


FIG. 6. (*a*) Regressions of mean boundary length (×) and mean boundary spacing (○) on mean density of observations, within each landscape unit. (*b*) Regressions of mean survey effort (man hours per km²) on mean boundary spacing (●) and mean boundary length (×) in each landscape unit.

The soil maps also agree on some of the boundaries between soils on 'solid' clays and soils on clayey or silty drift, which 63API did not distinguish. These are presumably boundaries with clear or fairly clear external expression. One part of the solid/drift clay boundary

TABLE 7

The effect of increasing survey effort

		No. of mapping units		*No. of separate occurrences*		*Boundary length km/km²*		*Per cent purity**	
Area	*Map*	*Series*	*Series and phase*	*Series*	*Series and phase*	*Series*	*Series and phase*	*Series*	*Series and phase*
1	63SS	5	..	8	..	4·0	..	62·7	..
	25SS	5	..	10	..	4·6	..	86·5	..
2	63SS	4	..	11	..	6·0	..	51·0	..
	25SS	4	..	19	..	9·1	..	65·0	..
3	63SS	3	..	3	..	1·6	..	44·5	..
	25SS	3	4	7	12	4·5	6·3	78·5	59·5

* Purity as per cent of grid points in each special area at which series (or phase) found is that predicted by the 63SS or 25SS maps.

had been mapped by the surveyor with a dotted line, to indicate uncertainty: this is also the part of it to which 25SS and BPM made most corrections.

The extra observations for 25SS corrected the wrong identification of an area of Mead (calcareous clayey alluvium) series as Ford End (calcareous silty drift) series. They also identified some Fladbury (clayey drift) series within an area tentatively mapped as Denchworth (solid clay) series, and an unmapped inlier of the Fernham series within a mapped area of Uffington series. The extra observations for BPM further modified the Denchworth–Fladbury boundary already improved in 25SS, and located another inlier of the Fernham series. Apart from these BPM modified 25SS very little. The areas involved in most of these changes are small.

Though not identical, the boundaries on 63SS and 25SS, can clearly be seen to be successive approximations to BPM; they are *consistent*. This seems to be characteristic of boundaries which separate discrete and coherent soil bodies.

It seems that the purity of 63SS is greatest for area 1 because much of the boundary mapped there had some external expression. Some boundaries lacked sufficient external expression to be located by the relatively sparse observations of 63SS, or to be correctly interpolated between observations. Nevertheless the soil bodies were coherent enough to be mapped *consistently* as the density of observations was increased from 63SS to BPM; the purity of 25SS confirms their coherence.

Area 2 is quite different. There is some agreement (Fig. 4) on the location of the main boundary between Coombe (Ct) series and the rest, on the soil maps, and to a lesser extent on 63API, but the correspondence is poor in detail. Clearly, even the Coombe boundary has inconsistent external expression, and the others little if any.

Most other boundaries, especially between Icknield, Ilsley, and Charity, are not consistent between 63SS, 25SS, and BPM. Some new boundaries or inliers appear; as in area 1, but some disappear. A group of Ia–Is boundaries in the centre of the area change their direction by 90° in passing from 25SS to BPM. All this strongly suggests that there is a short-range soil pattern too fine to be shown by the small number of boundaries that can be represented at the scales employed. This was confirmed (Burrough, 1969): in many places soil variations within short distances are as great as the differences between series, and areas occupied only by single series are too small to be mapped at the scales compared here. So, while there is a large proportionate increase in the number of soil bodies and length of boundary mapped on passing from 63SS to 25SS, the soil bodies mapped on 25SS are only slightly more uniform than those on 63SS; there is only a small increase in their purity.

Area 3 is intermediate in character. One boundary, between the Carswell (clayey drift over gravel) and Kelmscot or Radley (calcareous loamy drift over gravel) series, is reasonably consistent on all three soil maps and on 40API, presumably because it has adequate external expression. The remaining boundaries between the series on the gravel have little external expression, so 63SS has the smallest purity of the three areas.

But, though tortuous in outline, the series boundaries on 25SS and BPM are more or less consistent, suggesting that the occurrences of Kelmscot and Radley series (differing in drainage) are coherent. Thus the purity of 25SS is quite high. In contrast, the phase boundaries on 25SS and BPM are inconsistent, and the purity of phases in 25SS is small, because the difference between the two phases of Kelmscot series (separated on depth of loam over gravel) proved to be no greater than that commonly occurring over short distances (Burrough, 1969) within the area of the series.

Thus, over all three areas soil boundaries that could be mapped on 25SS by their external expression could almost certainly have been mapped on 63SS, and some of them by API too, especially with good quality photographs. Where most boundaries are of this kind extra survey effort improves the map very little. Conversely, if the soil bodies are coherent but lack external contrasts (area 3 and parts of area 1), extra observations may be expected to produce a better map.

But maps can only record the distribution of soil bodies which are coherent at the scale of the map. If the soil bodies are too small to be mapped (as soil series in area 2 and phases in area 3), extra survey effort may be fruitless until the map scale is sufficiently increased for the soil bodies to be coherent.

Discussion

The soil map at 1:63 360 is typical of soil maps widely produced by conventional or free survey. The complexity of the soil patterns is comparable to that in many other parts of the world.

The number of observations per km² found necessary by the soil surveyor, in different parts of the area, depended partly on the complexity of the soil pattern: there is some association between the length of boundary mapped per km² and the density of observations. But a given length of boundary could be mapped with fewer observations per km^2 in some landscape units than in others. And the effort per observation required to identify a profile class at a point, or to move about, also differed between landscape units. Even so the survey effort needed (h/km^2) was roughly proportional to the density of observations and to the length of boundary mapped per km^2.

Observations (P. A. B.) on the surveyor (M. G. J.) at work confirmed how much the location of boundaries depended on their external expression. Only 30 per cent of soil observations by auger were to check boundaries. The study showed that few, if any, of the boundaries mapped at 1:10 560 (25SS) by their external expression had not already been mapped at 1:25 000 (63SS). Such units had purities of about 60 per cent on 63SS.

Extra survey effort and larger map scale is justified only in situations where discrete and coherent soil bodies remain unmapped, or erroneously mapped, at the smaller scale because of their lack of external expression. In these circumstances more detailed surveys achieved purities up to 85 per cent. Soils which show no differences in external expression may not differ significantly in their potentialities for agriculture or engineering (cf. Curtis, 1963).

Where the profile class changes so frequently over short distances, that few soil bodies are coherent at the map scale used, then even a ten-fold increase in survey effort will produce only small improvements in the map, to increase the purity of its mapping units from 40/50 to 60 per cent.

III. The Costs of Soil Survey

(P. A. Burrough and P. H. T. Beckett)

Introduction

Aim

This paper presents data on the direct costs, per unit area surveyed, of the soil maps already described.

Previous work

It is generally assumed that the cost per unit area of producing a soil map depends on the intricacy of the pattern of the soils which are to be distinguished, on the nature of the soil mapping units, on the survey procedure employed, and on logistic or other practical problems imposed by the terrain. But there are very few published studies on the costs of soil survey.

Part II has indicated how the field effort (in man hours/km^2) required to produce maps at 1:63 360 by *free survey* varies with the ease of access or cross-country movement, with the depth and tenacity of the soils to be distinguished, and with the length of soil boundary (km/km^2) to be mapped.

Bie and Beckett (1971) have related the overall effort of sixty-six Australian surveys (in man-days/km^2) to the length of soil boundary mapped (km/km²); the effort necessary to map unit length of boundary depended on the nature of the mapping units, and on whether the survey made use of air photograph interpretation (API) or not. They also related survey effort to map scale (1970), and indicated how optimum map scale depends on the intricacy of the landscape to be surveyed, and on the intensity of the land use to be served by the map. They related the overall costs (in U.S. dollars/km²), or effort (in man days/km²), of soil surveys from several countries to map scale. Both studies produced regressions of the form:

$$\log\begin{Bmatrix}\text{cost per km}^2\\ \text{or}\\ \text{man-days per km}^2\end{Bmatrix} = a+b\log(\text{map scale}) \qquad (2)$$

in which b had values of 1·76 and 1·57 respectively.

Veenenbos (1957) discussed soil surveys with and without API. His figures on cost and scale are related by log–log regressions with similar values of b. Beckett (1968) related survey costs to survey procedure and suggested that for any given survey procedure there is probably a range of map scale over which it gives the best value for money.

This Study

The trial area and the soil maps to be compared have been described. All maps (except those by API) were reduced to equivalent virtual scale (pp. 365–7).

Records were kept of time spent, and costs incurred, in all stages of the surveys. On average the surveyor spent about one-seventh of his working day travelling to and from the area being surveyed, and about one-tenth of his field time on visiting and talking to farmers, on moving from one part of the survey area to another, and on sheltering from showers or other adversities. This unproductive field time is excluded from our calculated costs, which include only the direct costs of soil survey, that is the costs and effort of productive field work, and of analyses, and the costs of compilation up to the production of the first manuscript copy of the soil map. The reconnaissance on which the map legend of the series maps was based had taken place three years earlier; no records had been kept and so no allowance could be made for it.

Apart from this we have excluded the costs of HQ or research overheads, and the editorial and cartographic costs of publications, which together may add as much as 30 to 70 per cent to the costs. We have also excluded the cost of the surveyor's own time on office administration, on travel to and from the survey area, on writing up a soil survey memoir, or on other duties not directly related to the survey.

General purpose soil maps

Soil series mapped by free survey. The effort (in man-hours per km²) of mapping soil series at two scales by free survey is given in Table 9. The effort for 63SS in area 1 was calculated indirectly (pp. 372–4); the figure given is the mean of two independent estimates.

Physiographically defined units mapped by API. No record had been kept of the time or effort required to produce 63API, but Wong (1967; see also Webster and Wong, 1969) had recently remapped an adjacent area, similar to areas 1 and 3, without prior knowledge, and his estimates are used in Table 9. The apparent reduction in survey effort compared to 63SS is of the same order as the 45 per cent reduction in total survey effort reported by Bie and Beckett (1971). Buringh (1960) reports 83–93 per cent reduction in *field* effort by using API to map soils at 1 : 50 000. None of these figures are exactly comparable.

40API of area 3 was produced by a special API survey without ground check but drawing upon extensive prior knowledge of the area; Table 9 gives the time spent on API.

Soil series mapped by grid survey. The effort of mapping soil series by grid survey comprises the time to lay out a predetermined grid and to visit every grid site, the time to identify the soil series at every grid site, and the time to compile a series map from the grid observations. The last was small, since the interpolation of boundaries was purely mechanical (p. 365); Table 8 gives the time required for the other

TABLE 8

Mapping effort, to lay out sampling grids and to identify series

	Density of sites/km²	*Area 1*	*Area 2*	*Area 3*
		(*a*) Times to lay out sampling grid and to visit sites (h/km²)		
100/100	100	10	6·7	4·2
140/140	50	5·9	4·2	3·3
300/100, 100/300	33·3	4·4	3·3	2·8
300/300	11·1	1·8	1·6	1·5
		(*b*) Average time to identify the soil series at a site (h/site)		
		0·113	0·076	0·049

operations. The effort to produce grid maps of soil series at different virtual scales may be estimated from these and from the observation densities of the different sampling grids. They are presented in Table 9.

At first sight there is an apparent discrepancy between these estimates and the average of twelve sites per day that are visited by a NAAS extension officer collecting soil samples for analysis. But his twelve fields are usually widely spaced and the extension officer probably spends some time at each site talking with the farmer, while the grid sites were relatively close, and the time spent by the soil surveyor talking with farmers is excluded from our calculations.

Comparison between free and grid survey. The data in Table 9 for grid maps give quite good log–log regressions, like equation (2) above, in which b has values of 1·7, 1·4, and 1·3 for areas 1, 2, and 3 respectively.

TABLE 9

Mapping effort, excluding unproductive field time, for soil series or API maps

Survey	Area 1 Virtual scale	Area 1 Density of obsvns./km²	Area 1 Length of boundary mapped km/km²	Area 1 Effort h/km²	Area 2 Virtual scale	Area 2 Density of obsvns./km²	Area 2 Length of boundary mapped km/km²	Area 2 Effort h/km²	Area 3 Virtual scale	Area 3 Density of obsvns./km²	Area 3 Length of boundary mapped km/km²	Area 3 Effort h/km²
Free survey 25SS	1:18 900	140·8	4·6	23·3	1:19 840	127·0	9·1	13·2	1:19 840	127·0	6·3	9·1
63SS	1:52 400	19·7	4·0	3·7*	1:63 500	12·3	6·0	2·5	1:68 000	10·9	1·6	2·1
Grid survey† 100/100SS	1:22 400	100	5·0	21·3	1:22 400	100	9·0	14·3	1:22 400	100	8·6	9·1
140/140SS	1:31 600	50	3·5	11·1	1:31 600	50	6·8	7·7	1:31 600	50	5·8	5·3
300/100SS }	1:38 800	33·3	3·3	8·3	1:38 800	33·3	6·3	5·9	1:38 800	33·3	5·2	3·7
100/300SS }			3·6				5·4				3·7	
300/300SS	1:67 000	11·1	1·9	3·2	1:67 000	11·1	3·6	3·1	1:67 000	11·1	3·6	2·2
API 40API		..	..			..	..		1:40 000	..	..	0·25‡
63API	1:63 360			1·2	1:63 360			1·2		..		

* See comments * Table 4 (p. 373). † To lay out sampling grid, visit sites, identify series present, and later to compile map.
‡ No ground check, but by a surveyor with local experience.

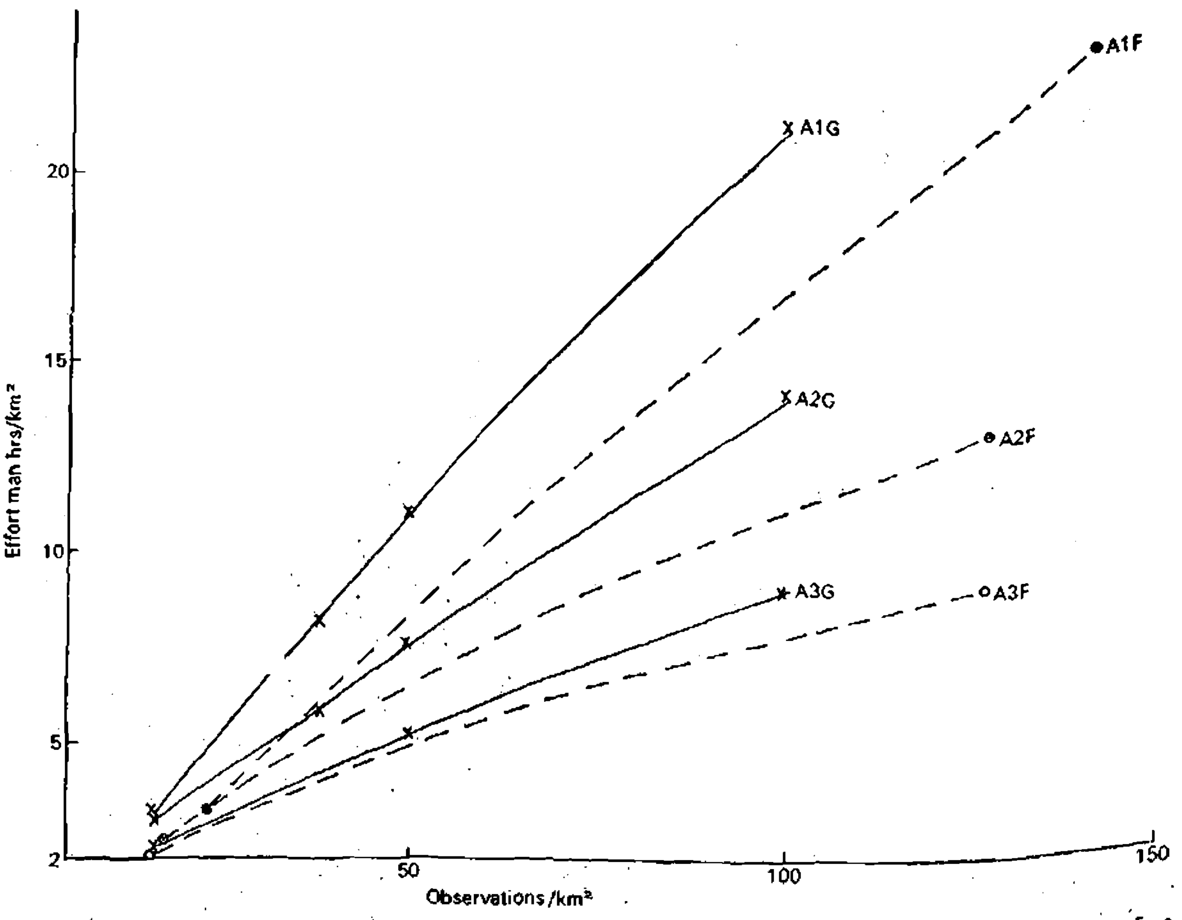


FIG. 7. The effort required to map soil series, in relation to observation density; three areas A1, A2, A3, by free (F) and grid (G) survey.

Fig. 7 relates productive field time (man hours/km^2) to the observations/km^2 of all series surveys; the curves for the free surveys are from a log–log interpolation between the two recorded values. Fig. 7 indicates how survey effort increases slightly less in proportion than the density of observations: when observations are more closely spaced, less time is spent on moving from one observation point to another. For reasons already stated the comparison is biased against free survey. Even so, and except in area 3 (fewest restrictions on access), free survey required some 20–30 per cent less effort than grid survey; for a given effort free survey could produce a map at a scale at least 20–30 per cent larger. The differences between the survey efforts required in the three special areas are mainly (Part II) due to differences in ease of access and in the soils to be separated, and to a lesser extent to differences in the length of boundary to be mapped per unit area in each. Fig. 8 relates field effort to virtual map scale. As expected, the effort required per unit area mapped rises increasingly sharply as virtual scale increases, but less sharply than the true parabola (i.e. $b = 2$ in eqn. (2)) necessary if the cost of survey per cm^2 of published map were to be independent of map scale (e.g. Beckett, 1968).

The costs of series surveys. The direct survey costs per km^2 may be simply calculated:

$$\text{survey costs/km}^2 = \text{man-hours/km}^2 \times \text{salary of surveyor/h.} \qquad (3)$$

From the basic salaries (including welfare contributions and pension rights) for a scientific officer (lowest grade for a good Honours graduate) in the Soil Survey of England and Wales in 1969 (K. E. Clare, personal communication), and for a scientific assistant (neither graduate nor diplomate), we estimated personnel costs at approximately £1 3*s.* (£1·15) and 7*s.* (£0·35) per hour respectively.[1] The following comparisons depend mainly on the ratio of these two figures, which are roughly comparable to similar ratios in other national soil survey organizations (Bie and Beckett, 1970), and on their ratios to the costs of analyses. We assume that a scientific assistant (or comparable) is not capable of independent free survey, which is not always true, but that he is capable of identifying series at pre-determined sites, as on a grid, once a skilled pedologist has shown him the diagnostic features of the soils to be distinguished (e.g. Morgan, 1965; Stoneman, 1968). To the extent that a soil surveyor spends some of his time unproductively or on administration, his time in the field costs his organization more than this: we continue to omit all expenses other than direct survey costs.

Figure 9*a* averages the costs of soil survey, thus calculated, over the three special areas.

Free survey (curve 5) is cheaper than grid survey at comparable observation density by the same surveyor (curve 4). Grid survey by a scientific assistant (curve 7) is cheaper than free survey by a scientific officer, at comparable observation density. This difference would be a little but not much smaller if allowance were made for the cost of a

[1] All costs relate to 1969.

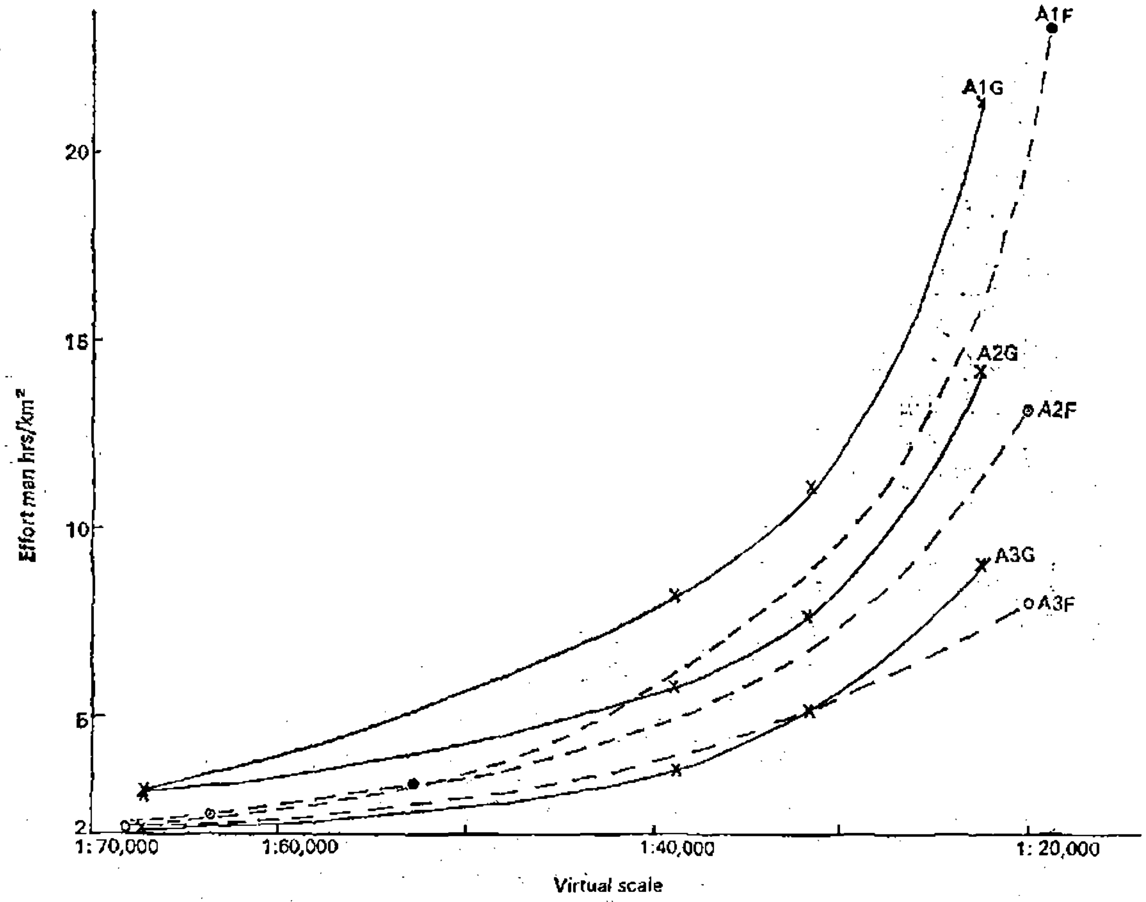


FIG. 8. The effort to map soil series, in relation to 'virtual' map scale; three areas A1, A2, A3, by free (F) and grid (G) survey.

scientific officer supervising the assistant, which is extra to the cost of the senior soil surveyor or correlator supervising both.

Special purpose or single-property maps

Excluding, as above, non-productive field time, the cost of producing single-property isoline maps of soil morphological properties from grid observations may be calculated as the effort of laying out the grid and visiting all the grid sites, of recording a morphological property at each site, and of preparing an isoline map of the values recorded. For soil properties determined by laboratory analysis the cost comprises the effort of laying out a grid and visting all the grid sites, of collecting a bulked sample for analysis from each site, the cost of its analysis, and the effort of preparing an isoline map from the analyses.

The effort of laying out sampling grids and of visting each site is given in Table 8. On average it took 0·017 h per property per site to record a morphological property. It took 0·135, 0·117, and 0·100 h to collect and bulk 15 topsoil samples per site in areas 1, 2, and 3 respectively. The compilation of isoline maps from tabulated data took on average 1 h/km^2 for the 100/100 and 140/140 grids and 0·5 h/km^2 for the 100/300 and 300/300 grids, at approximately £1/h.

The costs of soil analysis vary greatly with the equipment and motivation of the organization doing the work. We have used a 1969 estimate by the National Agricultural Advisory Service (L. J. Hooper, T. R. Williams, personal communication) of £0·875 per soil sample for simultaneous analyses for available Mg, P, K, and pH and organic matter. This is expected to fall by at least one-third when the analyses are fully automated. These figures are low; some organizations quote costs of over £5 for similar analyses.

Maps of soil series are intended to provide information about many soil properties. In order to make a fair comparison we have calculated the direct costs per km^2 of preparing sets of isoline maps of four and of eight soil morphological properties, recorded by a scientific assistant on one visit; or the costs per km^2 of a set of isoline maps of four properties (Mg, OM, pH and CEC), and of eight properties, all from analyses of a single bulked sample from each site collected by a scientific officer or by a scientific assistant.

For this purpose we have assumed that the cost of determining CEC is equivalent to that for available P and K together; and that the cost of determining eight properties is twice that of these four. We have also compared the costs of the maps if the analyses of the samples collected by the assistant are carried out manually as at present, or automatically. All costs are averaged over the three special areas and presented in Fig. 9.

Physiographically defined units mapped by API

It is not possible, from our data, to calculate comparable costs of soil survey by API. Veenenbos (1957) and Vink (1963) present figures on

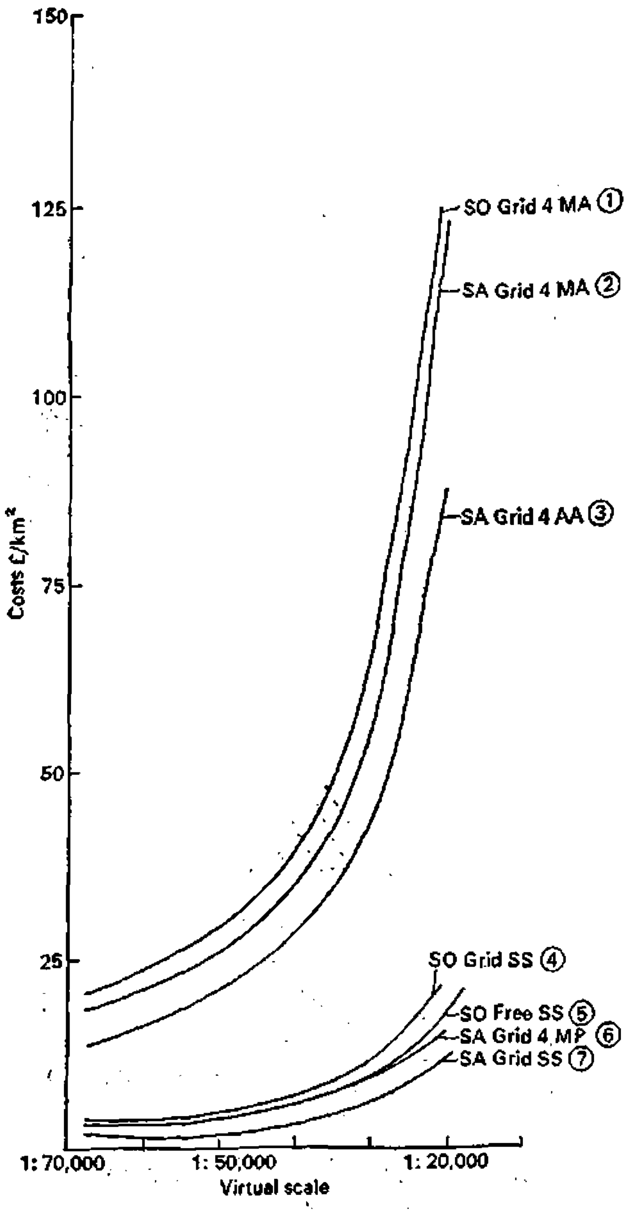


FIG. 9*a*. The costs of soil survey in relation to virtual map scale. SO and SA indicate survey or collection of samples by scientific officer or scientific assistant; 'free' and 'grid' describes irregular or regular location of observation points; SS indicates maps of soil series; MP indicates isoline maps of morphological properties; MA, AA indicate isoline maps of chemical properties determined in the laboratory by manual or automated analysis; 4, 8 indicate the cost of sets of 4 or 8 maps; $\frac{1}{4}$ or $\frac{1}{8}$ indicate the cost of one map from a set of 4 or 8.

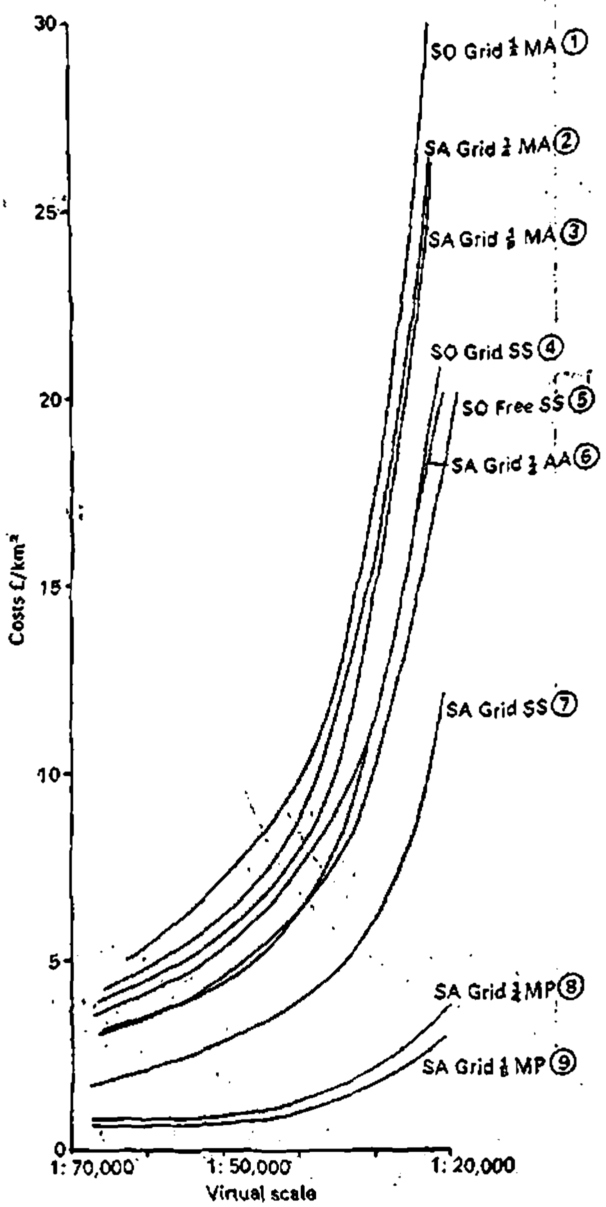


FIG. 9*b*. The costs of soil survey in relation to virtual map scale. SO and SA indicate survey or collection of samples by scientific officer or scientific assistant; 'free' and 'grid' describes irregular or regular location of observation points; SS indicates maps of soil series; MP indicates isoline maps of morphological properties; MA, AA indicate isoline maps of chemical properties determined in the laboratory by manual or automated analysis; 4, 8 indicate the cost of sets of 4 or 8 maps; ¼ or ⅛ indicate the cost of one map from a set of 4 or 8.

the benefits of API, from which we have derived a very approximate figure of 30 per cent for the ratio of $\frac{\text{costs of survey using API}}{\text{costs of free survey without API}}$.

Discussion

There are a few considerations which affect the comparisons offered in Fig. 9. 'Virtual scale', calculated from observation density, is somewhat unjust to free survey procedures which, other things being equal, can achieve more detailed boundaries from a given density of observations than grid survey. Against this, our estimates of the costs of free survey and of series maps by grid survey, should have been slightly higher by a share of the time of the original reconnaissance, while the compilation times for isoline maps included some time on the definition of isoline classes which would have been applicable to larger areas. The 10 per cent of unproductive field time, if it had been included, would have increased the costs of all the series maps and the isoline maps of morphological properties in proportion, but the maps of chemical properties rather less. The cost of supervision would also have slightly reduced the difference between the costs of surveys by scientific officers and assistants.

None of these factors alters the relative positions of the graphs of Fig. 9 by very much.

Figure 9*a* emphasizes how the mapping of series by free survey (curve 5) is cheaper on average than by grid survey (curve 4); but an assistant can produce a grid map of soil series more cheaply than a scientific officer can by free survey, or at 70–100 per cent larger scale at the same cost. How much more cheaply depends directly upon the ratio of their salaries. The cost of sets of four isoline maps of chemical properties (from grid samples) depends on the grade of personnel (curves 1 and 2) but it depends even more on the costs of analyses (curves 2 and 3): at £4–£5 a sample curves 1 and 2 would be five to seven times higher. Beckett *et al.* (1967) indicate how the quality of a soil map is likely to be affected by the cost of mapping the units chosen. Sets of four isoline maps of morphological properties (curve 6) are more expensive than a grid series map, but mainly by the cost of defining isoline classes and interpolating isolines. Probably it is quicker, on average, to identify series (on two to four properties) than to observe and record four of their differentiating features.

Figure 9*b* compares the costs of individual isoline maps from sets of four and eight. It shows (curves 2 and 3, 8 and 9) how the cost of one isoline map is indeed less when it is one of eight from the same set of samples than when it is one of four, but not by very much. Again the relative positions of the curves depend very much on the costs of analysis. But even when the costs of analysis are as low as the figure assumed for automatic analyses, and the costs of collecting samples are divided between the four or eight maps in a set, an isoline map of one chemical soil property still costs 1·5–2 times more than the corresponding series grid map (curves 6 and 7). As the former attempts to provide information about one property only while the latter attempts to do so for several, the isoline map will have to do so with considerably greater precision to justify the extra cost.

Acknowledgements

We are most grateful to Mr. K. E. Clare (Head of the Soil Survey of England and Wales) for allowing M. G. J. to take part in a joint study; Mr. P. H. Nye for his supervision during the middle year of this study; Dr. F. Marriott for statistical advice during the planning and the writing up of the trials; Dr. R. Webster for the air photo map of area 3; Messrs. K. E. Clare, L. J. Hooper, T. R. Williams, I. Wong, S. W. Bie for the information on which our estimates of cost are based; the Science Research Council for a student grant; the Vaughan Cornish bequest for a special grant; the farmers and landowners who allowed access to their land; and to Mr. Clare, Dr. Webster, Dr. M. J. Mulcahy, and Mr. Bie for criticizing drafts of this paper. We are responsible for errors and misinterpretations.

Two of us (P. A. B., P. H. T. B.) particularly wish to record our appreciation of our co-author's co-operation and tolerance: not every soil surveyor will expose himself to such persistent observation and yet, as the various regressions suggest, maintain such a consistent rate and standard of survey. We are most grateful.

REFERENCES

ARKELL, W. J. 1939. A map of the Corallian beds from Marcham to Faringdon, Berkshire. Proc. Geol. Ass. **50**, 487–509.

—— 1941. A map of the Corallian beds around Highworth, Wilts. Proc. Geol. Ass. **52**, 79–109.

—— 1947. The Geology of Oxford. Oxford, Clarendon Press.

AVERY, B. W. 1955. The Soils of the Glastonbury district of Somerset. Mem. Soil Survey Gt. Br., H.M.S.O.

—— 1964. The Soils and Land Use of the District around Aylesbury and Hemel Hempstead. Mem. Soil Surv. Gt. Br., H.M.S.O.

——, STEPHEN, I., BROWN, G., and YAALON, D. H. 1959. The origin and development of brown earths on clay with flints and coombe deposits. J. Soil Sci. **10**, 177–95.

BECKETT, P. H. T. 1966. Some consequences of periglacial processes and post-glacial adjustment in Southern England. Biul. peryglac. **15**, 165–74.

—— 1967. Lateral changes in soil variability. J. Aust. Inst. agric. Sci. **33**, 172–9.

—— 1968. Method and scale of land resource surveys, in relation to precision and cost, in Stewart, G. A. (ed.), Land Evaluation. Macmillan, Australia, 51–63.

——, BURROUGH, P. A. and WEBSTER, R. 1967. The cost of soil survey in relation to the classification criteria employed. J. Indian Soc. Soil Sci. **15**, 187–92.

—— and WEBSTER, R. 1965. A classification system for terrain. Rep. **872**. Military Engineering Exptl. Establishment, Christchurch, Hants.

——, —— 1971. Soil variability—a review. Soils Fertil. **34**, 1–15.

BIE, S. W., and BECKETT, P. H. T. 1970. The costs of soil survey. Soils Fertil. **33**, 203–17.

—— —— Quality control in soil survey. II—The costs of alternative survey procedures and mapping units. J. Soil Sci. **22** (in press).

BOULAINE, J. 1966. Sur la precision des Cartes Pedologiques. Cahiers ORSTOM sér. Pedologique **4** (1), 3.

BURINGH, P. 1960. The applications of aerial photographs in soil surveys. In 'Manual of Photographic Interpretation', American Society of Photogrammetry, Washington, D.C. 633–66.

——, STEUR, G. G. L., and VINK, A. P. A. 1962. *Some techniques and methods of* soil survey in the Netherlands. Neth. J. agric. Sci. **10**, 157–72.

BURROUGH, P. 1969. Studies in Soil Survey methodology. D.Phil. thesis, Oxford.

CLARKE, G. R. 1957. The Study of the Soil in the Field. Oxford, Clarendon Press.

CUANALO, H. E. 1966. A study of the short range soil variation associated with intricate image patterns on air photographs. Dipl. thesis. Oxford, unpubl.

CURTIS, L. F. 1963. Soil classification and photo interpretation. Archives Internationales de Photogrammetrie, **14**, 153–8.

DAVIES, B. E., and GAMM, S. A. 1969. Trend surface analysis applied to soil reaction values from Kent, England. Geoderma, **3**, 223–31.

FINDLAY, D. C. 1965. The Soils of the Mendip District of Somerset. Mem. Soil Surv. Gt. Br., Harpenden.

GOOSEN, D. 1967. Aerial photo interpretation in Soil Surveys. Soils Bull. No. **6**, F.A.O., Rome.

HODGSON, J. M. 1967. The soils of the West Sussex coastal plain. Soil Surv. Gt. Br. Bull. No. **3**, Harpenden.

JARVIS, M. G. 1972. The soils of North Berkshire. Mem. Soil Surv. Gt. Br., Harpenden (in press).

KAY, F. F. 1934. A soil survey of the Eastern portion of the Vale of the White Horse. Univ. Reading, Dep. Agric. Chem. Bull. 48.

KERNEY, M. P., BROWN, E. H., and CHANDLER, T. J. 1964. The late-glacial and post-glacial history of the Chalk escarpment near Brook, Kent. Phil. Trans. roy. Soc. **248 B**, 135–204.

LOVEDAY, J. 1962. Plateau deposits of the southern Chiltern hills. Proc. Geol. Ass. **73**, 83–102.

MORGAN, J. F. 1965. The Surveyor and Land Development in Western Australia. Proc. 8th Survey Congress of the Institution of Surveyors, Canberra.

National Agricultural Advisory Service, 1967. Fertiliser Recommendations for Agricultural and Horticultural Crops. NAAS Advis. Pap. No. **4**, Minist. Agric. Fish. Fd. London.

OLLIER, C. D., and THOMASSON, A. J. 1957. Asymmetrical valleys of the Chiltern hills. Geogr. J. **123**, 71–80.

OSMOND, D. A., SWARBRICK, T., THOMPSON, C. R., and WALLACE, T. 1949. A survey of the soils and fruit in the Vale of Evesham. Bull. Minist. Agric. Fish. Fd. Lond., No. **116**. H.M.S.O.

REED, J. F., and RIGNEY, J. A. 1947. Soil sampling from fields of non-uniform and uniform appearance and soil types. J. Am. Soc. Agron. **36**, 26–40.

ROBINSON, K. L. 1948. Soils of Dorset. In 'A geographical handbook of the Dorset flora', ed. R. L. Good. Dorset Nat. Hist. Arch. Soc.

SANDFORD, K. S. 1924. The river gravels of the Oxford district. J. geol. Soc. Lond. **80**, 113–79.

—— 1965. Notes on the gravels of the Upper Thames flood-plain between Lechlade and Dorchester. Proc. Geol. Ass. **76**, 61–75.

SMALL, R. J. 1964. Escarpment dry valleys of the Wiltshire Chalk. Trans. Inst. Br. Geogr. **34**, 33–52.

Soil Survey Staff, 1951. Soil survey Manual. U.S. Dep. Agric. Handbk. No. **18**.

Soil Survey Staff, 1960. Field Handbook. Soil Surv. Gt. Br.

STEUR, G. G. L. 1961 Methods of Soil Survey in use at the Netherlands Soil Survey Institute. Boor Spade **11**, 59–77.

STONEMAN, T. C. 1968. The interpretation of Lands Dept. soil maps of the West Midlands area. J. Agric. West. Aust. **9**, 12–13.

TYURIN, I. V. *et al.*, 1959. Soil survey, a guide to field investigations and mapping of soils. Israel Programme for Scientific Translations. Jerusalem, 1965.

VEENENBOS, J. S. 1957. Methods and costs of soil and land classification surveys when using aerial photographs. Afr. Soils, **4**, 122–35.

VINK, A. P. A. 1963. Planning of Soil Surveys in Land Development. Publ. int. Inst. Land. Reclam. Improv. **10**.

WEBSTER, R. 1966. The Drifts of the Vale of the White Horse. Proc. Geol. Ass. **77**, 255–62.

——, and BECKETT, P. H. T. 1968. Quality and usefulness of soil maps. Nature, Lond. **219**, 680–2.

——, and WONG, I. 1969. A numerical procedure for testing soil boundaries interpreted from air photographs. Photogrammetria **24**, 59–72.

WONG, I. 1967. A numerical test of soil boundaries interpreted on air photographs. Dipl. thesis. Oxford, unpubl.

(Received 31 August 1970)