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THE DEVELOPMENT OF COST-EFFECTIVE METHODS FOR ANALYSING SOIL INFORMATION TO DEFINE CROP MANAGEMENT ZONES

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THE DEVELOPMENT OF COST-EFFECTIVE METHODS FOR ANALYSING SOIL INFORMATION TO DEFINE CROP MANAGEMENT ZONES

by

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ABSTRACT

Yield maps of winter-sown cereal crops were obtained from five sites in England for two or more seasons. These sites contrasted strongly with respect to the underlying geology and the resulting soil variability. All sites had been previously investigated by soil surveyors and/or agronomists. The yield maps were analysed in two ways:

i). **Spatially** (by computing multivariate variograms). These indicate how great the spatial variability of the yield actually is, and the spatial scales at which it occurs over all available seasons. If all of the yield variation occurs over very short intervals, then the possibility of mapping underlying causes and responding to them by precision farming is probably limited.

ii). **By continuous classification** (fuzzy c-means). This technique sub-divides the fields into regions within which the pattern of season to season variation was similar. It is postulated that similar factors are likely to be limiting to crop yield within a region of the field which has shown similar season-to-season variation in yield.

The information on the spatial variation of crop yield and the classifications were then considered, in the light of existing knowledge about soil variation in the fields, and some additional field sampling was conducted to aid interpretation.

It was found that the extent to which yield is spatially variable differed substantially between sites, and this was well described by the multivariate variogram of the yield maps. Sites which appeared uniform by this descriptor were also those which the detailed soil investigations had shown to lack soil variability.

At the most variable sites there was a clear relationship between the variability indicated by the analysis of the yield maps and that found in field investigations of the soil. The soil series classification used in the soil surveys did not always account for the important yield variations. However, there was evidence that single soil properties, particularly physical properties, were related to the yield variation. At one site, for example, where the Available Water Capacity of the soil had been estimated at a number of sample points, the classes defined from the yield maps accounted for a substantial proportion of the variation of this soil property. Soil series will be useful in accounting for within-field variation of yield where they differ substantially with respect to soil physical properties.

It was concluded that yield map analysis can aid investigations of soil variability at within-field scale; firstly by indicating the fields where such investigation is justified by the magnitude and spatial scale of the variation and secondly by providing a framework for a cost effective sampling strategy, since the classes defined from the yield maps appear to be related to underlying soil variation. The classes might be used as strata for sampling individual soil properties, or to guide initial investigative sampling to identify the principal soil types in the field. It was proposed that information from yield maps, and other sources such as digital elevation data or remote sensor data might be integrated in order to make best use of a limited number of costly soil samples. A rational procedure for using yield map data to proceed step by step from initial, low-cost assessments of spatial variation to more costly but clearly justified and directed sampling of individual soil properties is proposed.

Given these conclusions, what are the implications for precision farming ?

i). While all fields are variable, some are clearly more variable than others. Farmers would be advised to take a step-wise approach to investigating variation within their fields, rather than paying immediately for sampling and mapping of soil properties. Analysis of yield maps is proposed as a starting point. Firstly, farmers and their advisors may ask whether the yield variation within the field is substantial. Secondly, whether it occurs at a manageable spatial scale or is too intricate to manage. If it is concluded that variability is significant, and can be resolved and managed at a workable scale, then investment in some soil investigations may be justified. Our work in this report provides some standards for comparison in the analyses of yield maps from fields with differing levels of soil variability, but further research could enhance this.

ii. Any soil investigations should be carefully planned to be as cost effective as possible, making maximum use of all existing information. Thus rather than immediately paying for a grid survey of a spectrum of soil variables, none or few of which may emerge to be important, the farmer with his advisor could use the partition of the field using yield maps as an initial stratification. Each sub-region can then be investigated in turn, and the properties investigated within each sub-region could be carefully targeted. If, for example, a particular sub-region generally does well in all but dry years, then there is no point in looking for acidity or compaction problems, but an assessment of the risk of drought may be relevant.

iii. Having decided which soil properties are worth investigating and where in the field, then sampling should be planned to map properties at appropriate scales. Thus an estimate of the mean value of the property within one sub-region might be satisfactory in some cases, while other properties need to be mapped in more detail. In future it is to be hoped that maximum use will be made of remotely sensed information, data on topography, and other variables which can enhance the value of soil measurements and observations. Further research is needed to establish robust methods for doing this.

CONTENTS

1. INTRODUCTION

There is considerable interest in the possibility of responding to the familiar variability of soil conditions and crop performance within fields by spatially variable application of inputs such as fertilizer (site-specific management). Considerable effort has been and is being devoted to understanding the critical relationships between soil conditions and crop performance which might allow spatially variable rates of inputs to be prescribed. However, as was highlighted at a recent conference on precision agriculture by McBratney and Pringle (1997), the most likely limitation on a practical response to within-field variation is the cost of obtaining adequate information about soil properties.

The premise of the study reported here was that variation in soil properties, such as those which an experienced soil scientist could identify by auger or pit observations, and possibly some other soil properties such as pH, will be of fundamental importance in site-specific management. The question to be addressed is how can the variation of such properties be most efficiently mapped ? It is proposed that prior information on variability of the field could be used to direct the effort required for soil sampling and mapping to greatest effect. One such source of information may be the maps of spatial variation in yield which can be collected for combinable crops.

Work at Silsoe Research Institute (SRI) has shown how a sequence of yield maps can be used to subdivide a field into regions. These regions correspond to distinct patterns of season to season variation in yield (Lark and Stafford, 1997; Lark, 1998). There is some evidence (Lark *et al.*, 1997) that different regions within a field correspond to different potential limitations on crop yield (e.g. droughty soils, shallow soils or areas with high weed populations).

Can the stratification of fields by analysis of sequences of yield maps provide a useful framework for the collection, interpretation and organisation, by an advisor, of soil information for site-specific management. This could be done in the following way.

Step 1. Pre-survey planning. The yield map data indicate the magnitude of within field variation. The map produced by analysis of the sequence of data indicates:

i. Regions which appear to perform consistently well in terms of yield.
ii. Regions which appear to perform consistently poorly (this would be consistent with the effects of soil compaction, acidity or nutrient deficits).
iii. Regions where the season-to-season pattern of yield might be related to differences in seasonal weather, (so indicating where droughtiness or poor establishment in a wet autumn may be limiting on yield) or to other factors such as rotations.
iv. The spatial distribution of these regions.

The advisor therefore has prior knowledge as to whether the variability of conditions in the field is great or small, whether the spatial patterns are complex (requiring a lot of survey effort) or relatively simple, and clues as to where certain factors may be limiting.

Other sources of information are likely to be useful at this stage, including topographic maps of the field (particularly in digital form as Digital Elevation Models DEM), air photographs and possibly remote sensor images.

Step 2. Field Investigation. In the field the advisor's activities can be directed, at least initially, to investigating the regions identified from the yield map analysis and attempting to identify factors which account for the differences between them. This is likely to be a more efficient use of the advisor's time than a strict grid survey, whilst the way in which the regions are defined means that the sites visited should exemplify the soil variation in the field that is practically important. Having identified the potentially limiting factors within each region, the advisor may refine the boundaries derived from the yield map analysis. Sampling to identify nutrient deficits or pH problems may be focused on estimating mean values of these properties within the regions.

Step 3. Data interpretation and application. The results of the field investigation would be a (possibly modified) version of the map derived from yield data, along with information obtained from field work on the important soil properties within each region. The general knowledge available from agronomic research (Cranfield University and other sources), in combination with the particular information on soil conditions within the field, will allow recommendations to be made for different rates of inputs within each region. Information from the yield map analysis will aid this process.

This project set out to test the validity of the procedure outlined above as far as was possible using available data within a short time frame. All the fields used in this project had been the subject of intensive prior study by soil scientists from SSLRC and/or by soil scientists/agronomists from ADAS. The existing information on these fields was therefore substantial, and was supplemented at some sites during the course of the project by further investigation. Because this work was conducted in a short time frame, and was based in part on previous studies, there is some variation in the approaches taken at the different sites which is reflected in the different site reports.

Yield maps of all these fields were available for at least two seasons. These were subjected to the analytical procedures referred to above, to generate maps showing regions of the field distinguished on yields in the available maps. These maps, and information on the distinctive patterns of season-to-season yield variation to which each sub-region corresponds, were made available to the SSLRC and ADAS. They then overlaid the analysed yield maps with available information on the fields, in order to see how far the partition of the yield maps corresponded to soil variations of which they were aware. Further field investigations were conducted at a number of the sites. The objective of this was to attempt to ascertain how far the analysis of the yield maps identifies the key variations within the field with respect to soil.

This allowed an *a posteriori* evaluation to be made of the utility of the analysed yield map as an aid to investigation of the soil variability of the field.

The next chapter of this report outlines the methods used to analyse yield maps from these study sites, and presents the results of the analysis. In subsequent chapters, each site is described in turn. The key causes and patterns of soil variation are described, and are related to the results of the yield map analysis. The implications of these results, in the light of the approach outlined above, are then discussed and general conclusions are drawn.

2. ANALYSIS OF YIELD MAPS AND DIGITAL ELEVATION DATA

Introduction.

This chapter gives an account of the methods by which sets of yield maps were analysed prior to interpretation. The following paragraphs are offered as a non-technical summary.

The objective of the classification method is to divide each field into regions *within* each of which the pattern of yield variation over the seasons considered is similar. Thus, we might identify regions within which the yields are consistently high, or within which yield was high in all but one season. This is done, because it is thought reasonable that regions within which broadly similar factors are limiting on yield are likely to show similar patterns of season to season variation in yield. Thus, if parts of a field are potentially droughty, then they should form a distinct class characterised by low yields in drier years. Similarly, parts of the field with a significant nutrient deficiency may show consistently low yields. The classification thus simplifies all the complex information in a sequence of yield maps (typically 10,000 yield measurements) to a few basic patterns. This should aid the interpretation of the data.

The classes are recognised automatically by a clustering procedure. This generates as output the 'cluster centres' which may be regarded as representing the typical season-to-season fluctuation of yield for each class. Each site in the field will resemble each of these patterns to a greater or lesser degree, it is said to have 'maximum membership' in the class which it most closely resembles. We can plot the class of maximum membership at each site to show how the yield patterns represented by the cluster centres are distributed in space.

Usually the map showing cluster of maximum membership has a certain amount of short range 'speckle'. This detailed variability is unlikely to be of interest, and hinders interpretation. A smoothing method is applied to the map. This uses the 'multivariate variogram' which identifies the distance over which the important variations in yield occur, and maximises the smoothing effect at shorter distances. The variogram is a useful general measure of spatial variability, and its potential is discussed.

Data and analysis methods

Yield maps.

The yield data available are summarised in Table 2.1. Most were generated by the Massey Fergusson yield mapping system, but two fields were mapped using the RDS system. The reference number given in the Table is used to refer to the fields in Figure 2.13.

The raw data comprised point observations of GPS (Global Positioning System) latitude/longitude, yield and system-specific information. These were converted from latitude/longitude to Ordnance Survey co-ordinates. The data from Boxworth and Chicksands were processed by the VOYD system at ADAS Wolverhampton, which aims to identify data points which are low due to artefacts of the data collection process. Artefacts in the case of the other sites were identified statistically. Arbitrary limits were determined according to either Tukey's outer fences (Tukey, 1977) or to the Massey Fergusson (MF) trimming criteria where the lower limit is two thirds the average yield and the upper limit is twice the average yield. The MF criteria were used for the data sets generated by the Massey Fergusson system, and Tukey's criteria were invoked for the data generated by RDS. All data outside these limits was discarded, along with any data generated by the Massey Fergusson system where the nominal ground speed determined from GPS was greater than 10 metres per second since this suggests GPS error. This is standard practice in Massey Fergusson's software.

Table 2.1

Ref no.	Field	Harvest Years	Crop	Yield Mapping System
1	Easton Farms: Packway	1995	W.Wheat	
	Field	1996	W.Wheat	RDS
		1997	W.Wheat	
2	Easton Farms: Holly Field	1995	W.Wheat	
		1996	W.Wheat	RDS
		1997	W.Wheat	
3	Cirencester	1995	W.Wheat	Massey
		1996	W.Wheat	Fergusson
4	Andover	1995	W.Barley	Massey
		1997	W.Barley	Fergusson
5	Boxworth: Knapwell Field	1995	W.Wheat	Massey
		1996	W.Wheat	Fergusson
		1997	W.Wheat	
6	Boxworth: Top Pavements	1995	W.Wheat	Massey
		1996	W.Wheat	Fergusson
		1997	W.Wheat	
7	Chicksands: Shagsby Field	1996	W.Wheat	Massey
		1997	W.Barley	Fergusson
8	Chicksands: Shagsby 4 field	1996	W.Wheat	Massey
		1997	W.Wheat	Fergusson
9	Chicksands: Antenna/Bush	1996	W.Wheat	Massey
	Close	1997	W.Wheat	Fergusson

Sequences of yield maps for each field were overlaid. In some cases, however, the correspondence of Ordnance Survey co-ordinates between successive seasons was not good. This may be due to GPS errors, e.g. because of changes in base station settings. In these cases one of the yield maps was selected as a reference and the offset between the reference and each of the remaining yield maps was estimated, on the assumption that it consisted of a simple shift in the eastings and northings. In call cases data coverage across the field was reasonably uniform, so the offset could be estimated by comparing the mean x and y co-ordinates for the complete data set in each year.

Trimmed and offset yield values were then overlaid and yield estimates for each of the seasons were extracted for sites across the field.

Fuzzy classification was conducted on the yield data having first standardised the yield within each season to zero mean and unit variance. Details of the classification procedure are given by Lark and Stafford (1997). The classification was carried out to identify 2,3 ....8 classes. In summary for a specified number of classes (*g*), the procedure searches the data for the *g* most distinct groups of observations in terms of standardised yield in the different seasons. Each observation (*i*) has a membership in each class (*j*) denoted $\mu_{i,j}$ which is subject to the following constraints:

$$\sum_{j=1}^{k} \mu_{i,j} = 1, \quad \forall\, i \qquad (2.1)$$

$$0 \leq \mu_{i,j} \leq 1 \quad \forall i, j \qquad (2.2)$$

Thus an observation may have membership 1 in one class (complete resemblance to that class) and therefore zero membership in all other classes to which it is held to have no resemblance, or it may have partial membership in two or more classes.

The centre of a class, *j*, defines its typical member and is, effectively, the set of mean (standardised) yield values for all the data weighted by their memberships in class *j*.

The normalised classification entropy, NCE (see McBratney and Moore 1985) was then calculated to describe the 'distinctness' of the clusters which had been identified in each classification.

Because the classification procedure can "stick" at locally optimum solutions, the classification was repeated several times for each number of classes and that with the minimum NCE was selected. This minimum NCE was then plotted against the number of classes, and a local minimum in the plot was identified. The corresponding classification was selected for further consideration. Where a distinct local minimum was not seen, the plots sometimes showed a distinct break at g classes such that NCE (g -1) > NCE(g)   NCE (g+1), NCE (g+2).

In this case g classes were selected where the NCE plot declined exponentially with g there is weak evidence of clustering in the data and an arbitrary number of clusters were selected (usually 4).

The raw map of maximum membership often shows a good deal of short range "speckle". This was removed by smoothing the membership values using the procedure of Lark (1998). The membership values at each site were replaced by weighted averages of the membership values within different neighbourhoods of the site. The weights are determined according to the multivariate variogram (Bourgault and Marcotte, 1991) of the standardised yield data such that distant points have lower weight. Neighbourhoods were defined by radii of 5,10,20,30 and 40 metres and a smoothed map of maximum membership was obtained for each radius. Lark's (1998) coherence index was then calculated for each smoothed map and the map with a maximum index was selected. This index ensures that smoothing of local intricacy in the cluster map is maximised without creating larger scale changes in the relative frequency of the classes

Digital elevation model.

A digital elevation model of Knapwell field was available. This was analysed using SURFER software to extract attributes of the landform:

i. Slope. This is the slope, measured in degrees, in the direction of steepest ascent or descent from the node considered. It is thus a first-order derivative of the terrain surface.

ii. Profile curvature. Curvatures are rates of change of slope (units of degrees per unit distance). The profile curvature at a node of the DEM is the rate of change of slope in the direction of steepest ascent or descent from that node. Since curvatures are second-order derivatives, positive values indicate a locally concave surface.

iii. Plane curvature. This is the curvature of the surface in the horizontal plane. Negative values indicate convexity in this plane (and hence divergence of paths of surface water flow).

These three attributes were then used for cluster analysis in the manner described above for yield maps in an attempt to identify regions of similar land form.

Results

NCE plots for the analyses are presented in Figure 2.1, and the cluster centres are shown in Figure 2.2. Figures 2.3 - 2.12 show the class of maximum smoothed membership at sites across the field.

Easton Farms.

The NCE plot (Figure 2.1a) for Packway field indicated 4 distinct clusters. However, when these were investigated it appeared that three of them represented outlying data (not necessarily artefacts) scattered sparsely throughout the field. Most of the field was allocated to a single class. All data with maximum membership in this dominant class were analysed separately and the NCE plot indicated two classes (Figure 2.1b), denoted Class 1 and Class 2. These occurred in different parts of the field (Figure 2.3). Thus, the field seems to correspond primarily to two regions, although these are not strongly distinct with respect to yield.

A similar procedure was followed in Holly field. Three classes were indicated originally (Figure 2.1c), one of which was dominant. Analysis on data with maximum membership in this dominant class indicated another three classes (Figure 2.1 d). However, among these a single class was dominant, and the others showed limited spatial cohesion. Thus the original classification into three classes was used for interpretation. This field appears to be uniform with respect to yield potential, with some limited variability which may be artefactual.

Cirencester and Andover.

Three classes were defined in each of these fields on the basis of the marked initial drop in the NCE plot. In both fields the classes show a distinct spatial structure.

Boxworth.

Yield maps. In neither field does the NCE plot show distinctive structure, and the numbers of clusters were selected more or less arbitrarily. However, the maps (Figures 2.7, 2.8) show that the clusters have quite distinct spatial distributions.

Digital elevation data. The NCE plot indicates 4 distinct clusters. However, two of these occur at very few sites, and the spatial smoothing procedure actually eliminates them altogether (Figure 2.12). When the cluster centres are considered it is seen that the two dominant clusters are only distinctive on slope, and are indistinguishable on the two curvature variables.

Chicksands.

In Shagsby and Shagsby 4 fields, the NCE plot had distinct minima at 3 and 4 classes respectively. In Antenna/Bush Close field the NCE plot showed a marked initial drop to 3 clusters. All these classes had a distinct spatial distribution within their fields.

Multivariate variograms.

The methods section above referred briefly to the multivariate variogram of Bourgault and Marcotte (1991) which was used for spatial smoothing of the classified maps. This function describes the spatial variability of yield in the fields over time, it corresponds to the mean sum of squared differences in yield, for all seasons in the data, between two points separated by a given distance (called the *lag*). The multivariate variogram models for the yield data sets used in this study are presented in Figure 2.13. Since the multivariate variogram will increase with the number of variables, the variogram models have been adjusted by dividing by the number of yield maps available for each field. It should also be noted that while the multivariate variograms used for smoothing the maps were computed for the standardised data, these have been transformed back to the original units (variance of yield in t/ha).

The multivariate variogram might not be immediately meaningful to the non-statistician, but it is a very valuable tool for quantifying the degree of variability of yield in a field, and the spatial scale(s) at which it operates. Figure 2.14 shows some pairs of hypothetical variograms to illustrate this.

The overall height of the variogram is a measure of the overall variability of yield in the field. Thus field 2 in Figure 2.14a is much more uniform than is field 1, with respect to yield over the period for which the variograms have been calculated. The value to which the variogram rises is called the *sill.*

Variation in yield occurs because of factors which operate at different spatial scales. For example, there may be differences in the available water capacity of soil in a field which are due to changes in underlying solid geology which occur every 200m on average. The important variations may occur over much smaller spatial intervals, for example, patchy deposits of sandy drift 25m across on average. In the former case it may be feasible to map the underlying variation and respond to it. In the latter case it may not be possible. Figure 2.14b shows variograms like those which we might expect in the case of (1) yield variation dominated by long-range processes, and (2) variation dominated by short-range processes.

Yield variation may be influenced by processes at different scales in the same field. Of interest is the variation at such short range that the sampling has not resolved it. This is reflected in the so called *nugget* term of the variogram - the apparent value of the variogram at lag zero.

If the nugget is large relative to the sill, then this implies that a lot of the variation in yield is happening at very short spatial scales. Thus, while both variograms in Figure 2.14c show the effects of a comparable long-range process, variogram (1) with a very substantial nugget actually reflects a situation in which much of the variability is extremely intricate.

Nuggets are only comparable between variogram models if the sampling schemes on which they are based are comparable, at least for shorter lags. This is the case for the variograms in Figure 2.13.

The variograms for the fields studied here are instructive. Clearly Shagsby field at Chicksands (7) is the most variable, and most of its variation occurs at a range of around 70m, with a very small nugget component. By comparison, Top Pavements field at Boxworth is the least variable, and most of this variability is accounted for by the nugget term. We might conclude, tentatively that the variability in Shagsby field is (a) of sufficient magnitude and (b) manifested at a tractable spatial scale and so warrants further investigation. By contrast the variation in Top Pavements field is limited and spatially intricate.

Discussion.

The discussion here is limited to general observations on the variability of these fields. More detailed discussion of each field occurs in later chapters of the report. A general comment which must first be made is that the results of classification on fields using only two years worth of yield data may not be very robust. The wider the range of conditions for crop growth represented in the set of yield maps the more likely it is that meaningful sub-regions will be recognised, unless the variations within the field are likely to be very consistent from year to year. Unpublished work at Silsoe Research Institute on a field with strong but seasonally-dependent sources of variation suggested that at least three yield maps were needed to generate robust classifications.

Most fields in this study showed evidence in the NCE plot for some particular number of classes defined on standardised yields in the seasons analysed. The two fields at Boxworth showed no such evidence, but the classes which were defined (an arbitrary number) corresponded to a regionalisation of the field into spatially coherent classes. The NCE plot for Holly field at Eastons farm indicated the presence of distinct classes, but these did not correspond to coherent regions of the field. It is interesting to note that the fields at Boxworth and Holly Field have variograms with the lowest sills, and - particularly in Holly field - much of the variation is at very short spatial intervals.

The variograms in Figure 2.13 show that Shagsby and Shagsby 4 fields at Chicksands, and the field at Cirencester have the most pronounced yield variation, with much of it occurring at scales which are likely to be amenable to mapping and a management response. This is probably not the case at Top Pavements, Knapwell and Holly Field, where the variation is limited and spatially intricate. Intermediate behaviour is seen in the other fields. For example, Packway field shows rather more variation then most of the others, but a good deal of this is at very short spatial intervals (the nugget is large relative to the sill). It would be useful if this study, with more detailed follow up, could generate rules of thumb whereby the multivariate variogram of a number of yield maps of a field could indicate to the farmer the strength of evidence that there is spatial variability of significant magnitude, and at a tractable scale, which justifies the costs of more detailed investigation. The information on the classes identified in the data may be of considerable value in planning the sampling for such investigation.

Figure 2.1

Normalised Classification Entropy

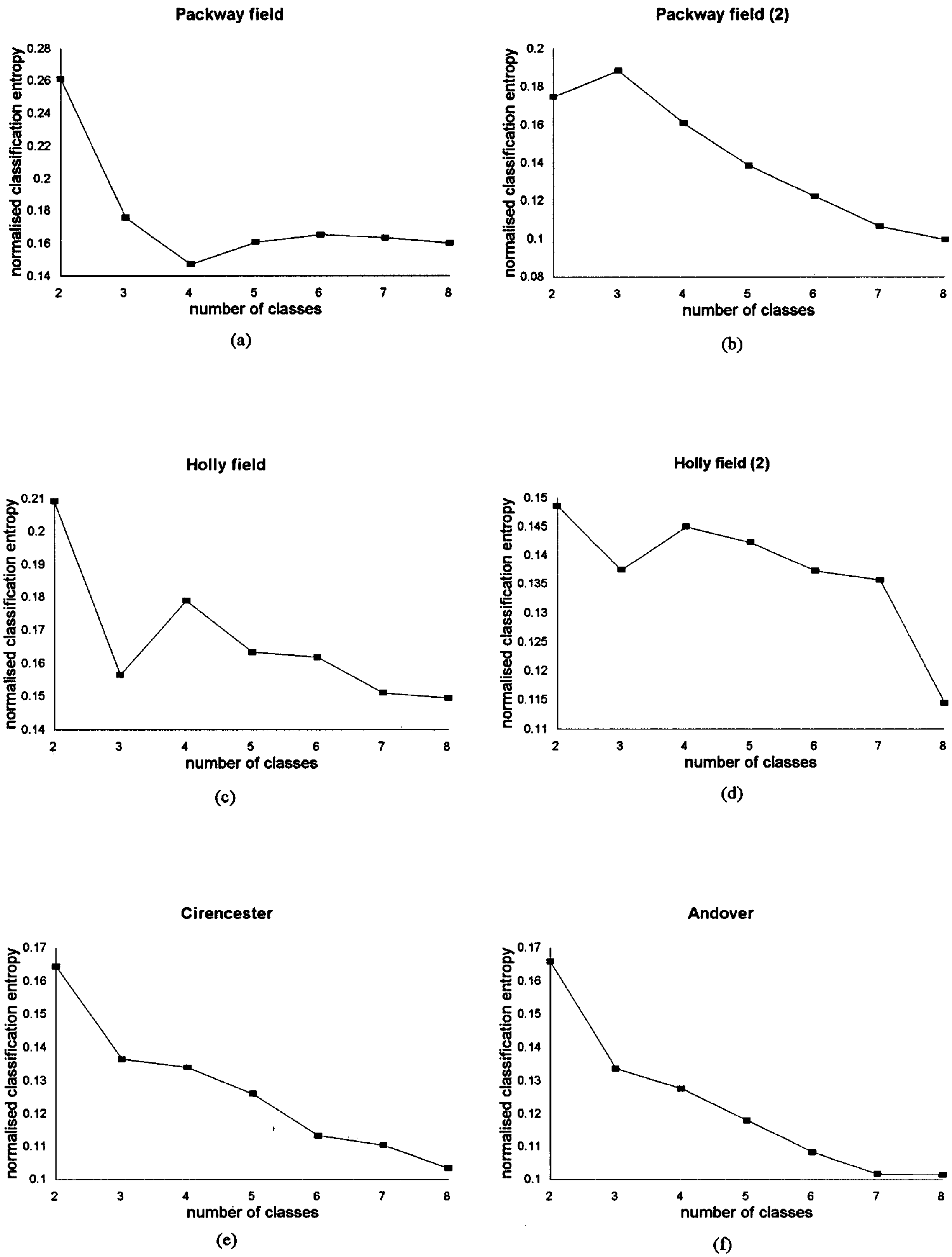
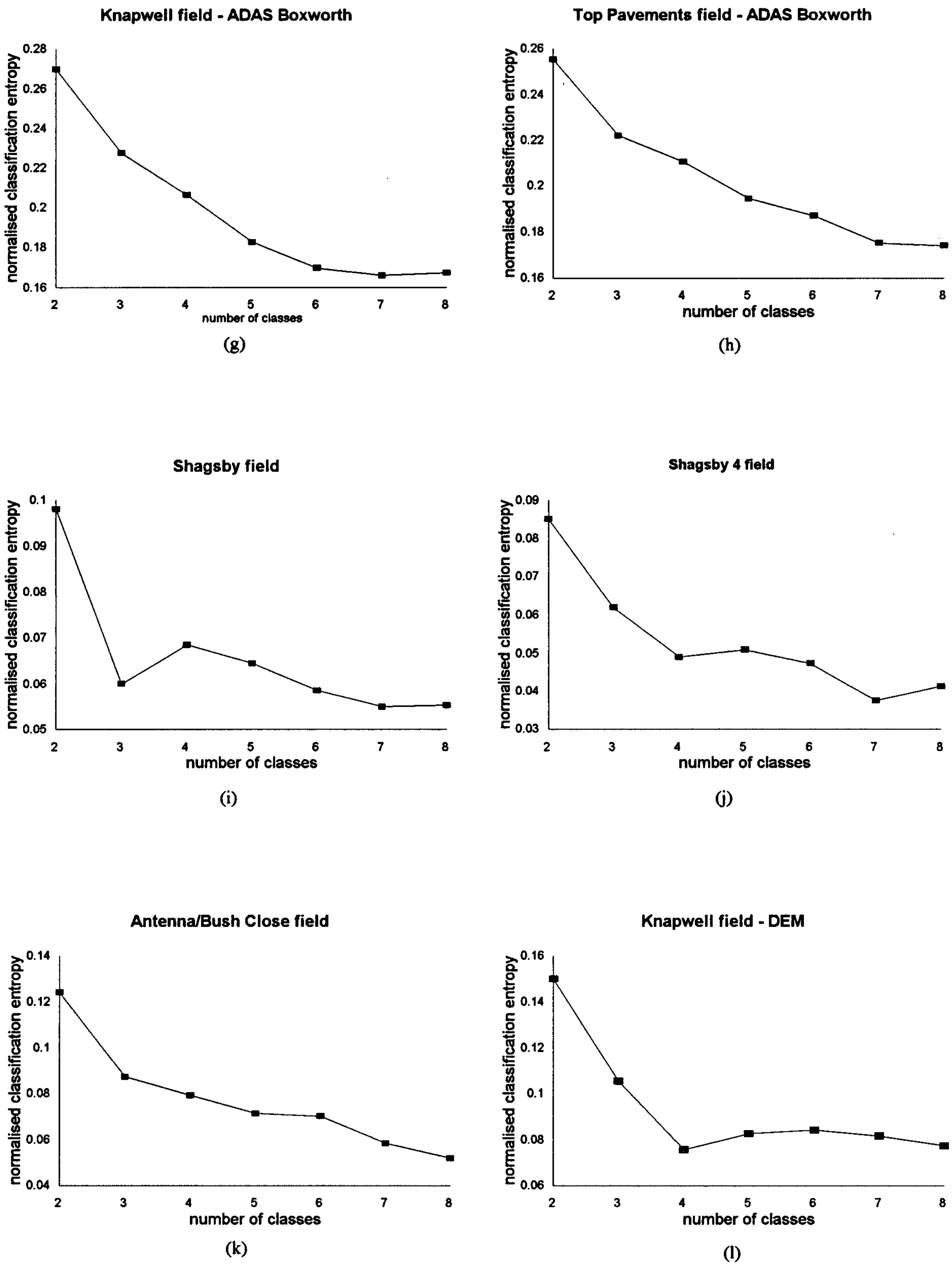


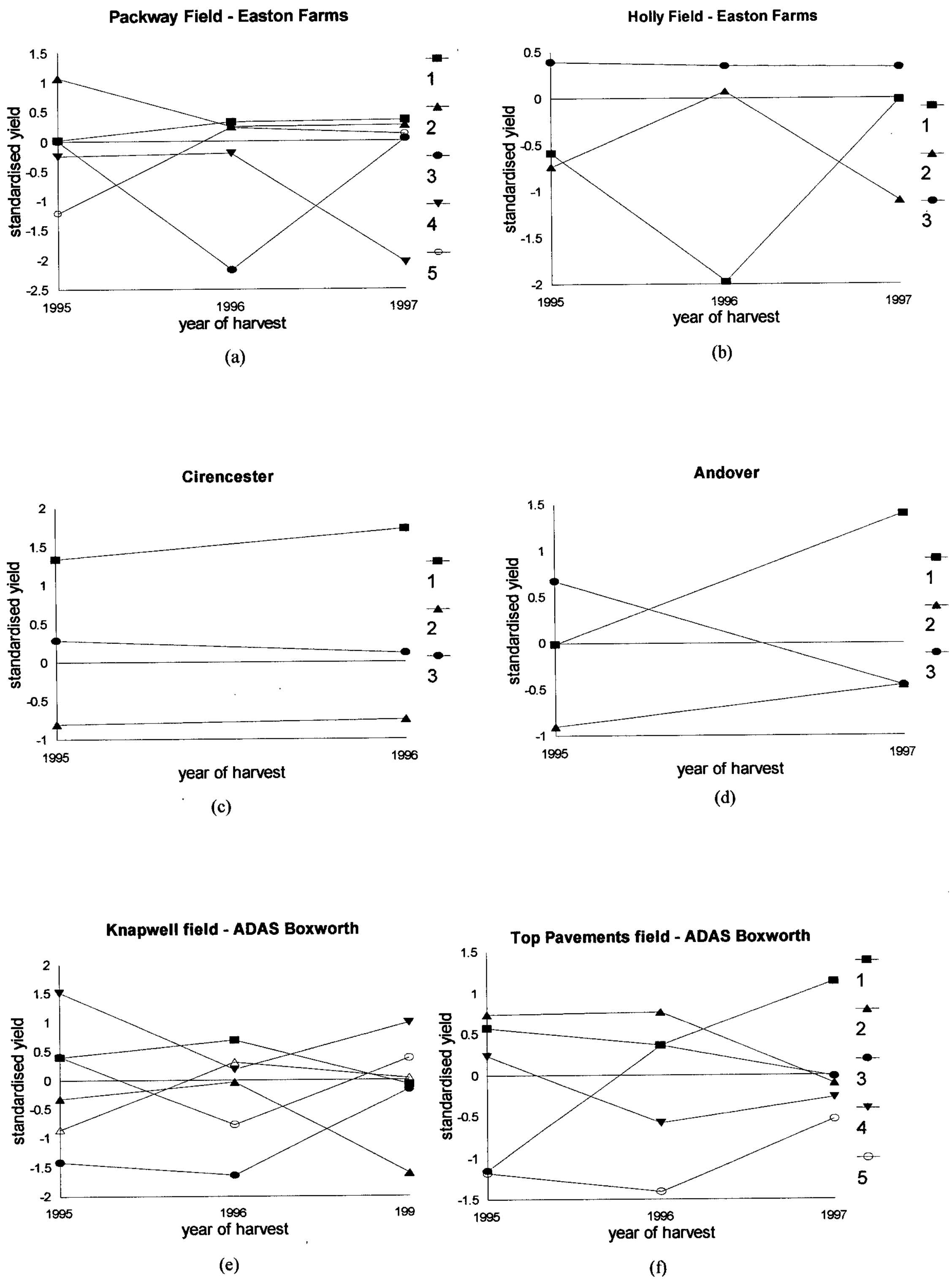
Figure 2.1

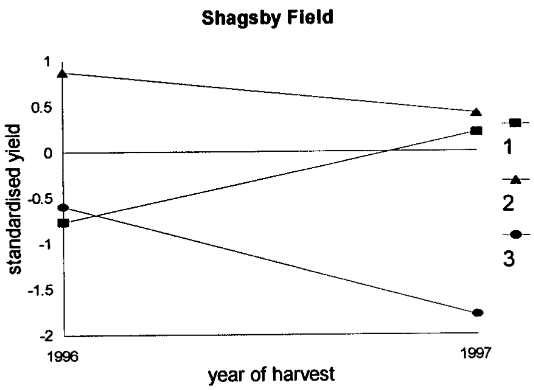


Knapwell field - ADAS Boxworth
normalised classification entropy
number of classes
(g)
Top Pavements field - ADAS Boxworth
normalised classification entropy
number of classes
(h)
Shagsby field
normalised classification entropy
number of classes
(i)
Shagsby 4 field
normalised classification entropy
number of classes
(j)
Antenna/Bush Close field
normalised classification entropy
number of classes
(k)
Knapwell field - DEM
normalised classification entropy
number of classes
(l)

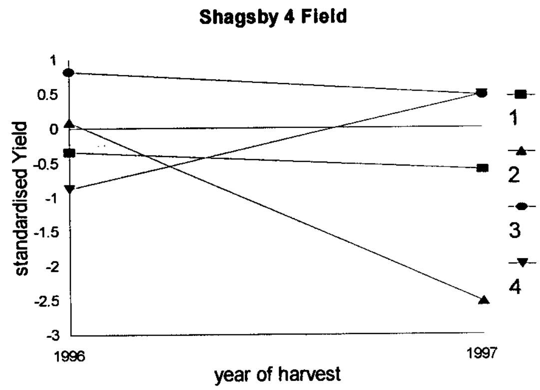
Figure 2.2

Cluster Centres

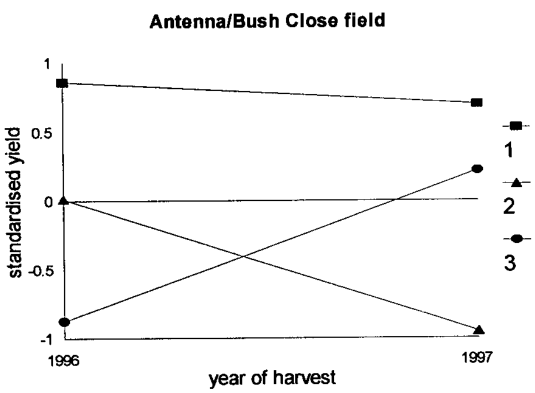



Shagsby Field
standardised yield
1
0.5
0
-0.5
-1
-1.5
-2
1996
1997
year of harvest
1
2
3

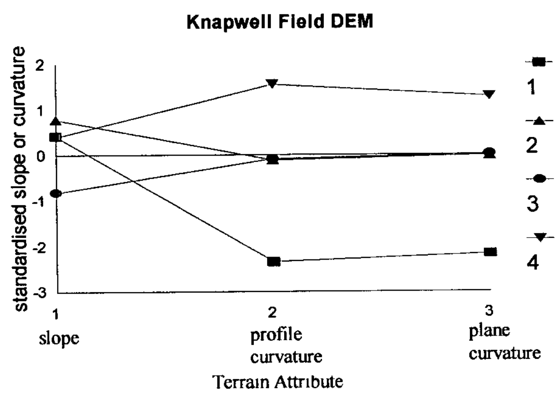
(g)


Shagsby 4 Field
standardised Yield
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
1996
1997
year of harvest
1
2
3
4

(h)

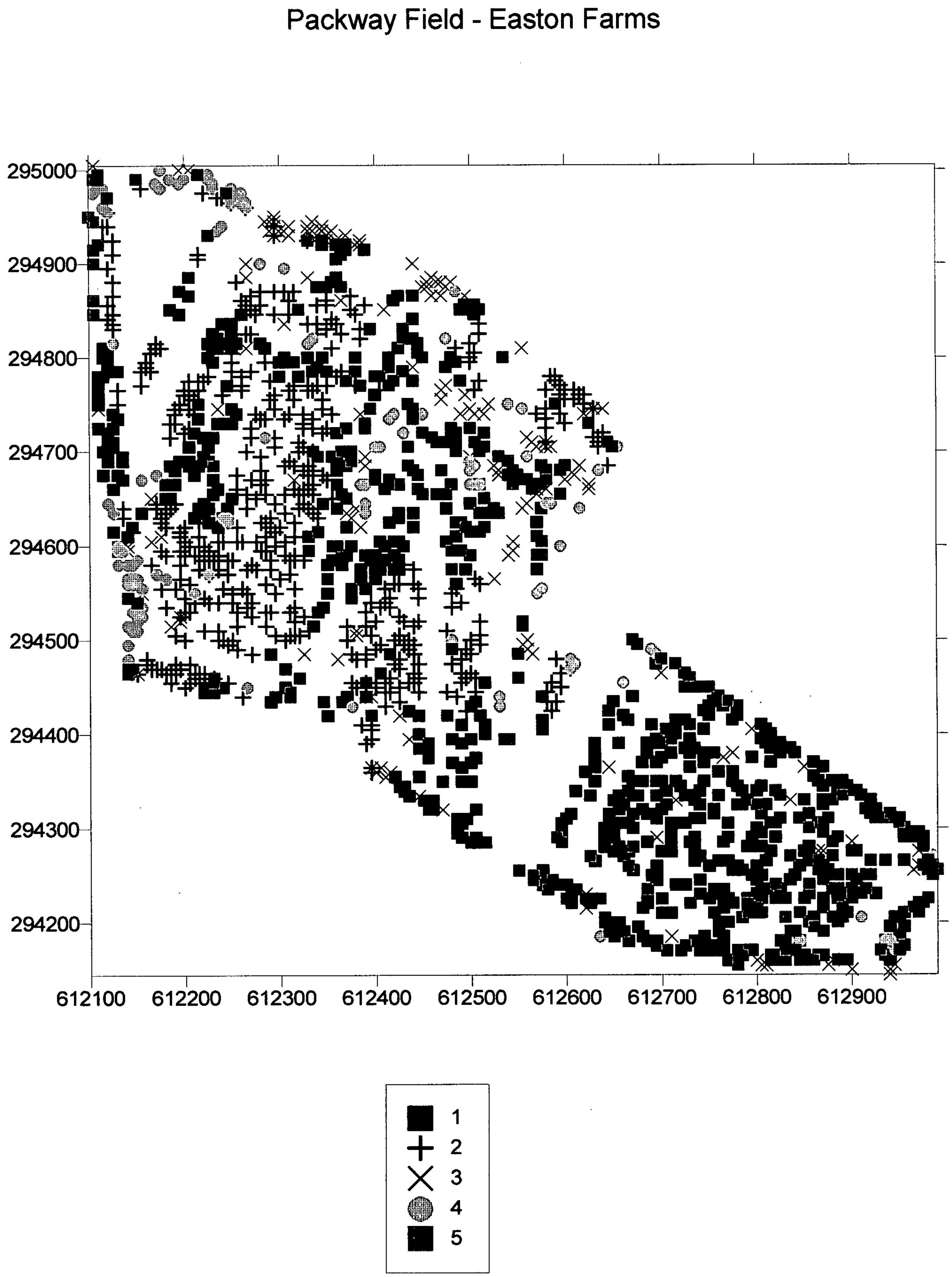

Antenna/Bush Close field
standardised yield
1
0.5
0
-0.5
-1
1996
1997
year of harvest
1
2
3

(i)


Knapwell Field DEM
standardised slope or curvature
2
1
0
-1
-2
-3
1
slope
2
profile curvature
3
plane curvature
Terrain Attribute
1
2
3
4

(j)

Figure 2.3



Packway Field - Easton Farms
295000
294900
294800
294700
294600
294500
294400
294300
294200
612100
612200
612300
612400
612500
612600
612700
612800
612900
1
2
3
4
5

Figure 2.4

Holly field - Easton Farms

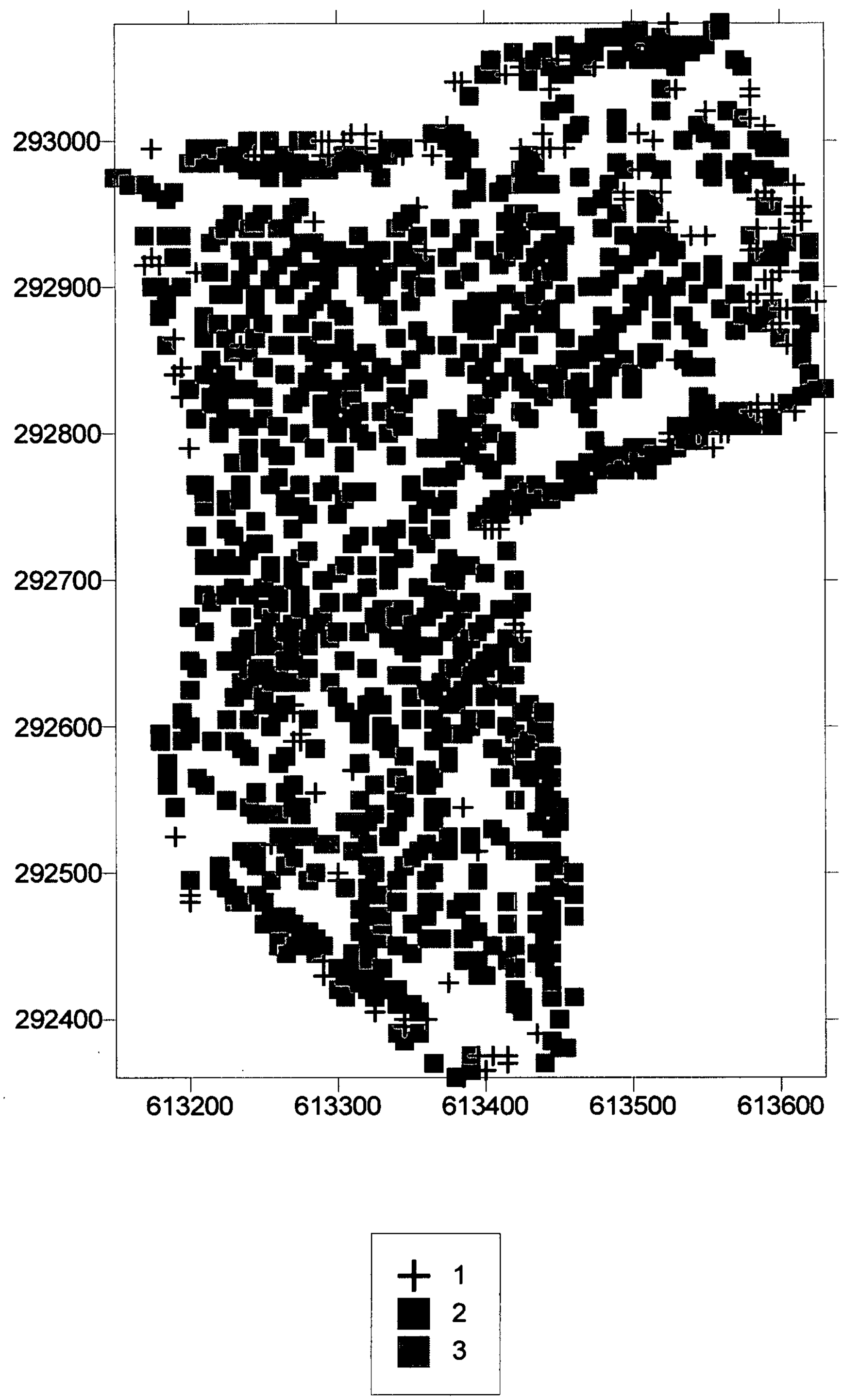


Figure 2.5

Cirencester

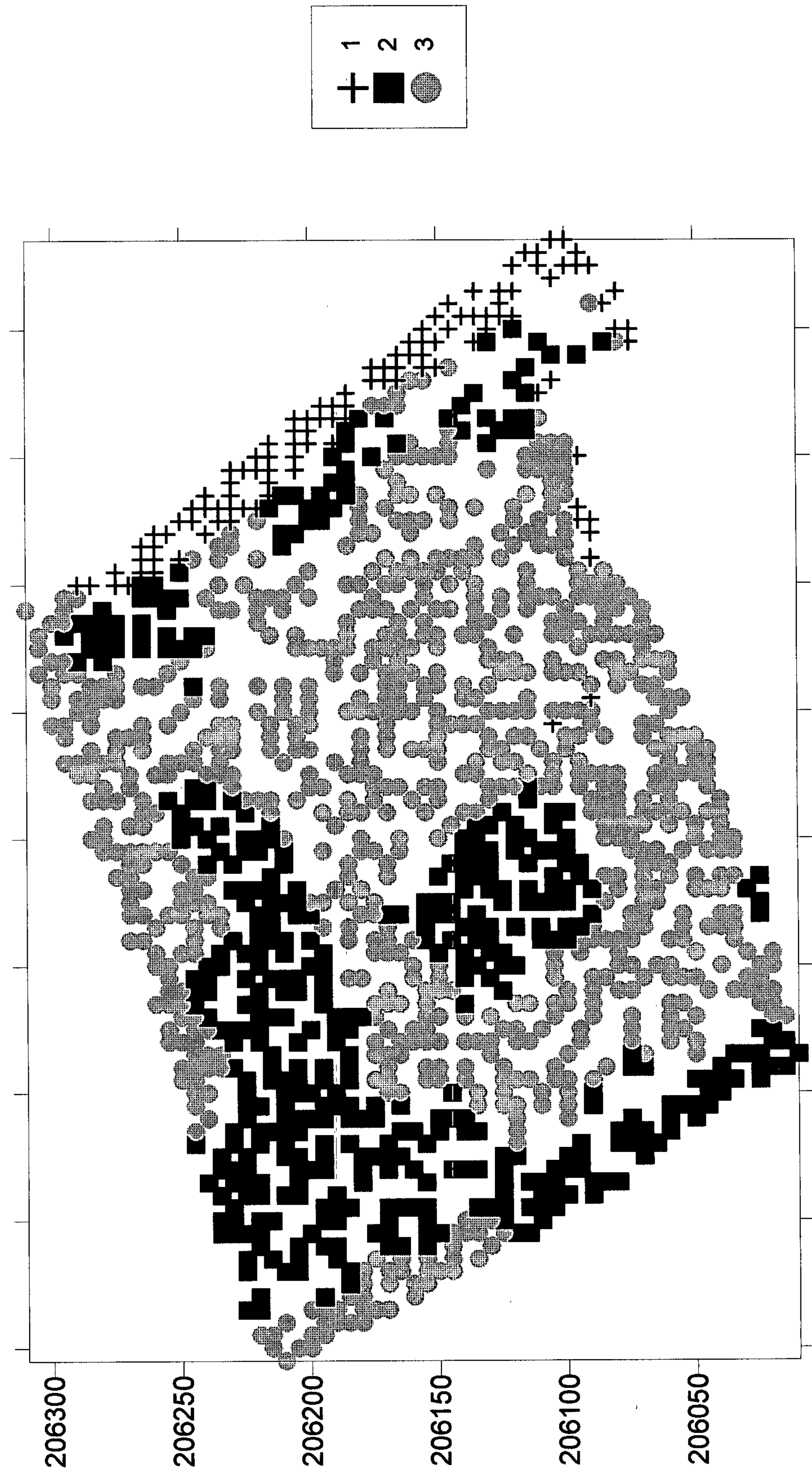


Figure 2.6

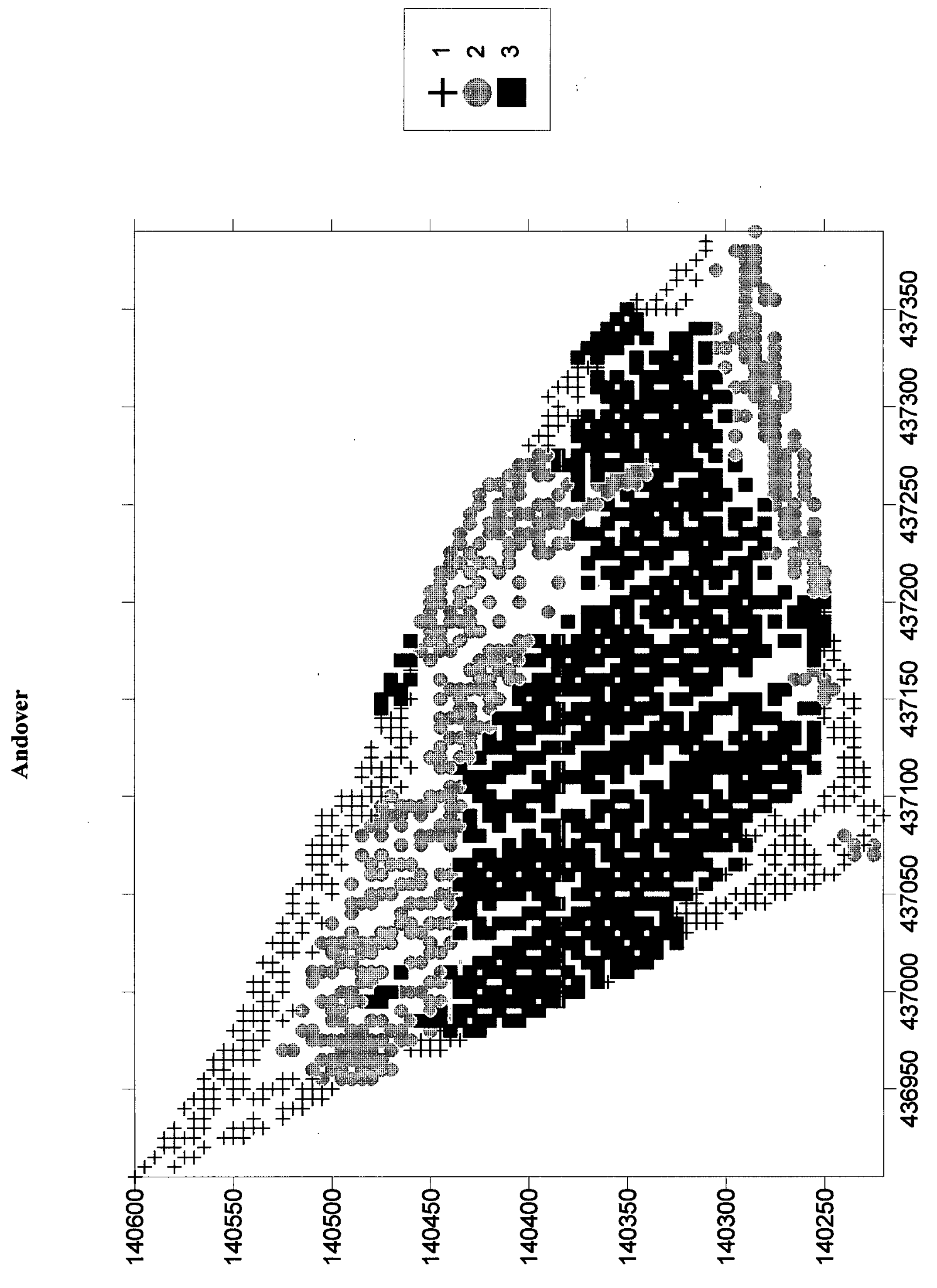

Andover
1
2
3
140600
140550
140500
140450
140400
140350
140300
140250
436950
437000
437050
437100
437150
437200
437250
437300
437350

Figure 2.7

Knapwell field - ADAS Boxworth

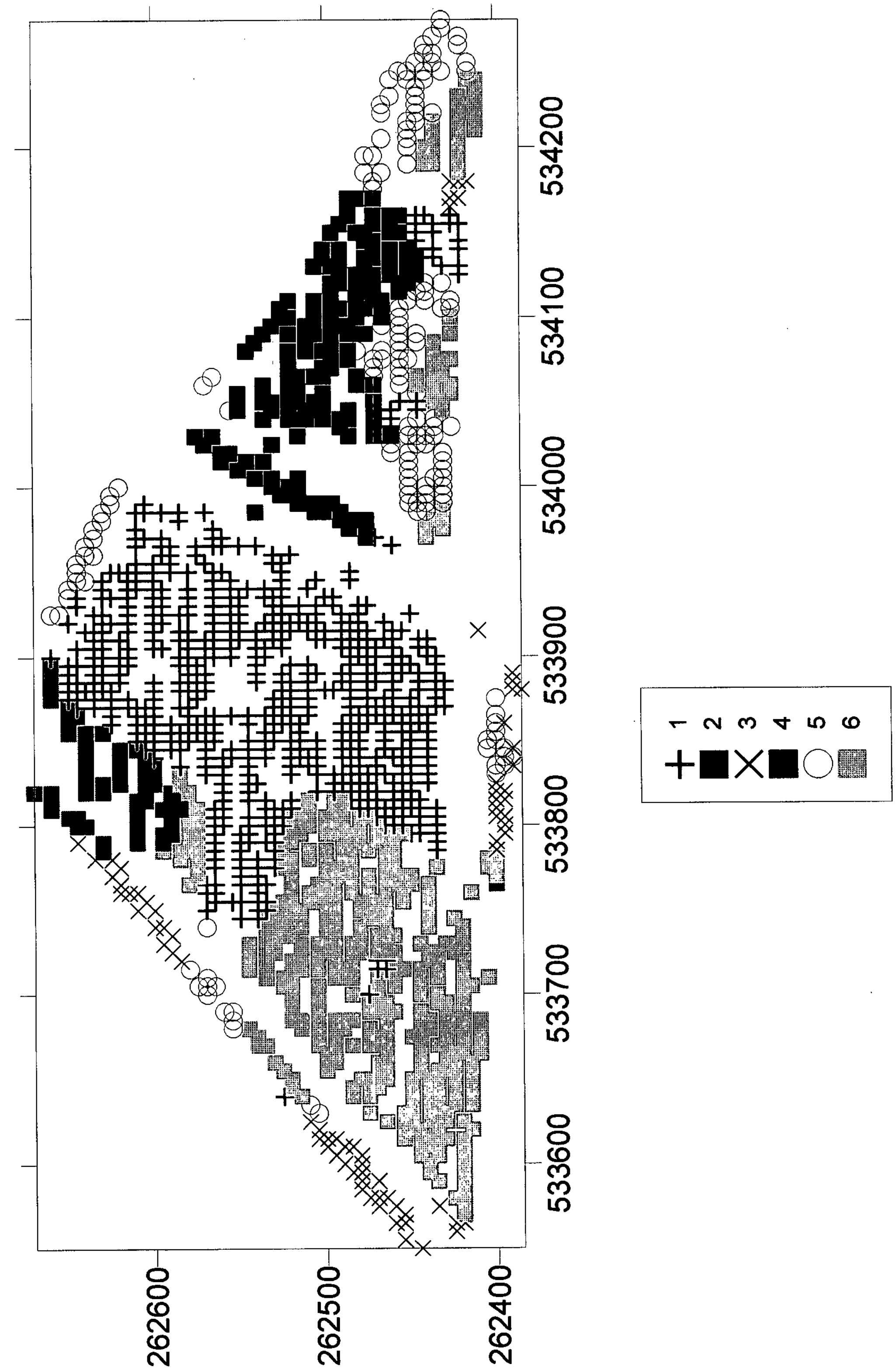


Figure 2.8

Top Pavements field - ADAS Boxworth

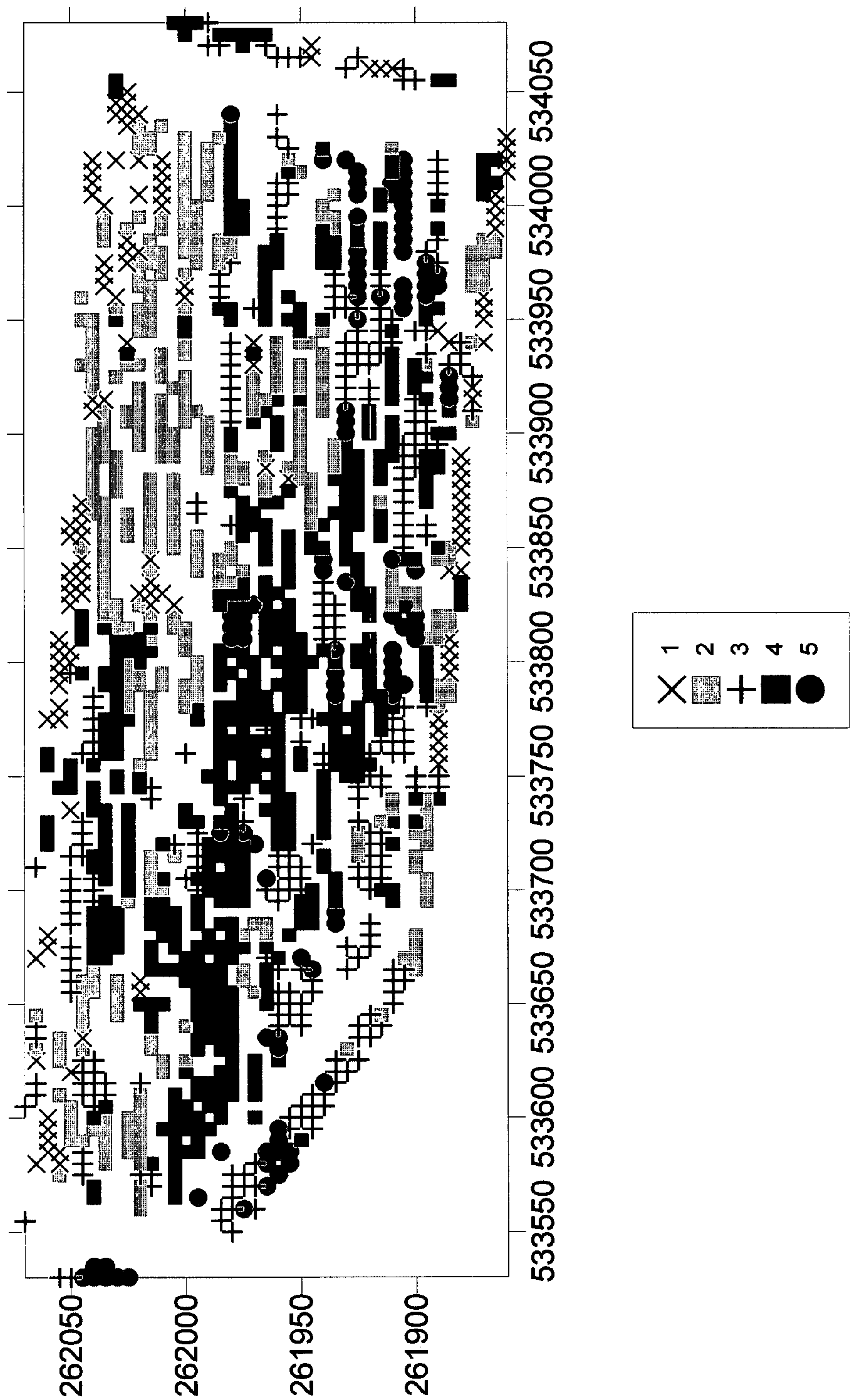
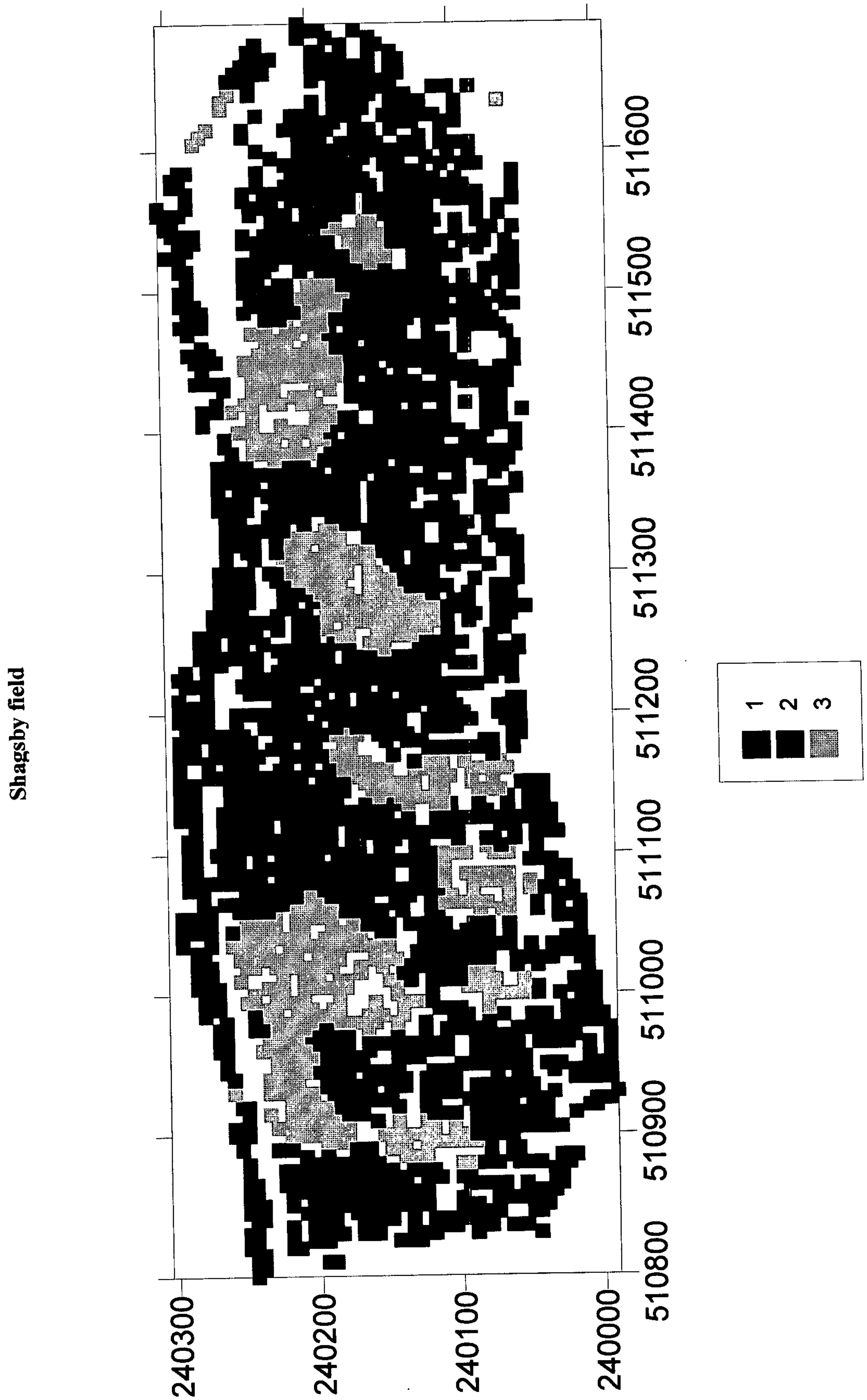


Figure 2.9


Shagsby field
240300
240200
240100
240000
510800
510900
511000
511100
511200
511300
511400
511500
511600
1
2
3

Shagsby 4 field

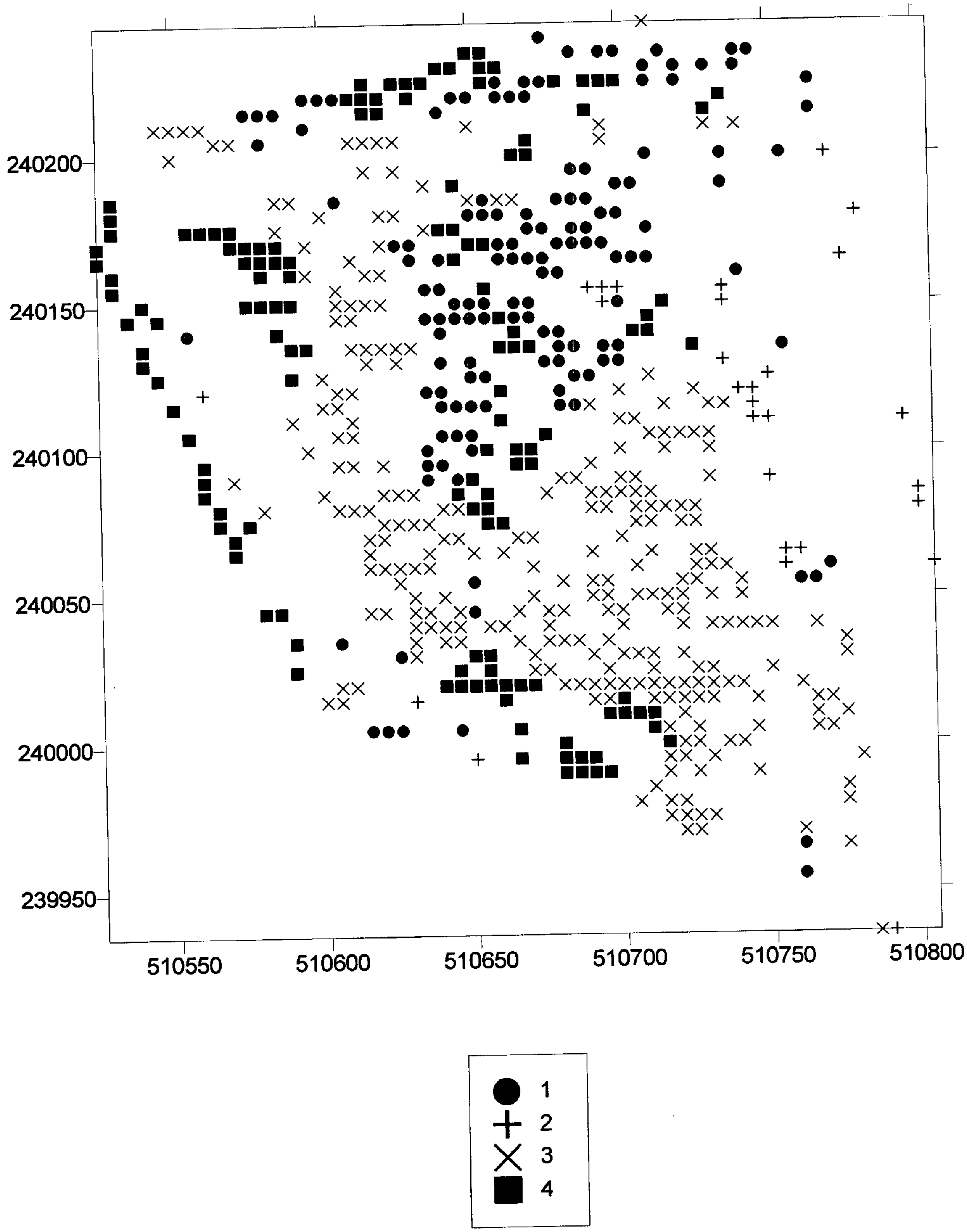


Figure 2.11

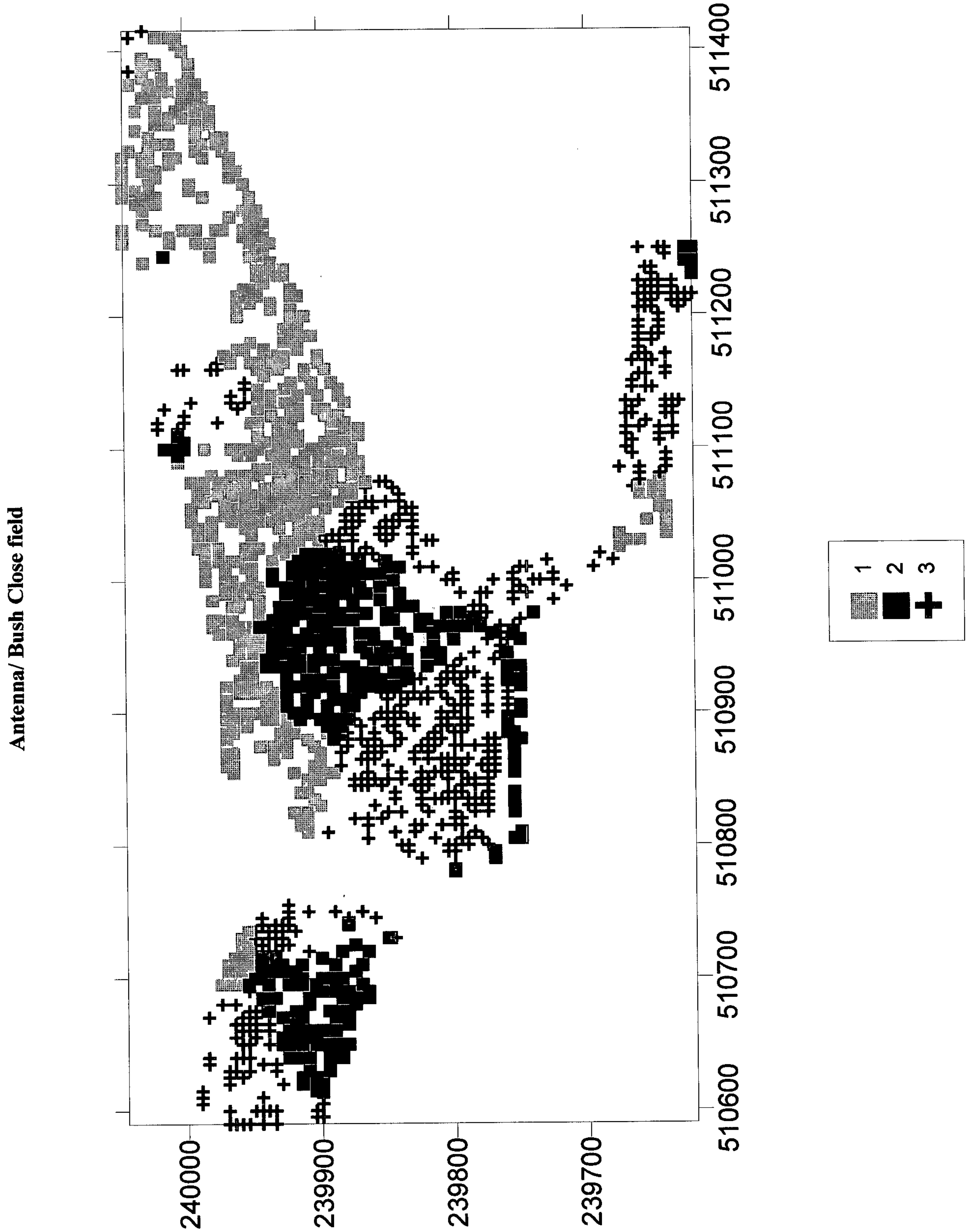

Antenna/ Bush Close field
240000
239900
239800
239700
510600
510700
510800
510900
511000
511100
511200
511300
511400
1
2
3

Figure 2.12

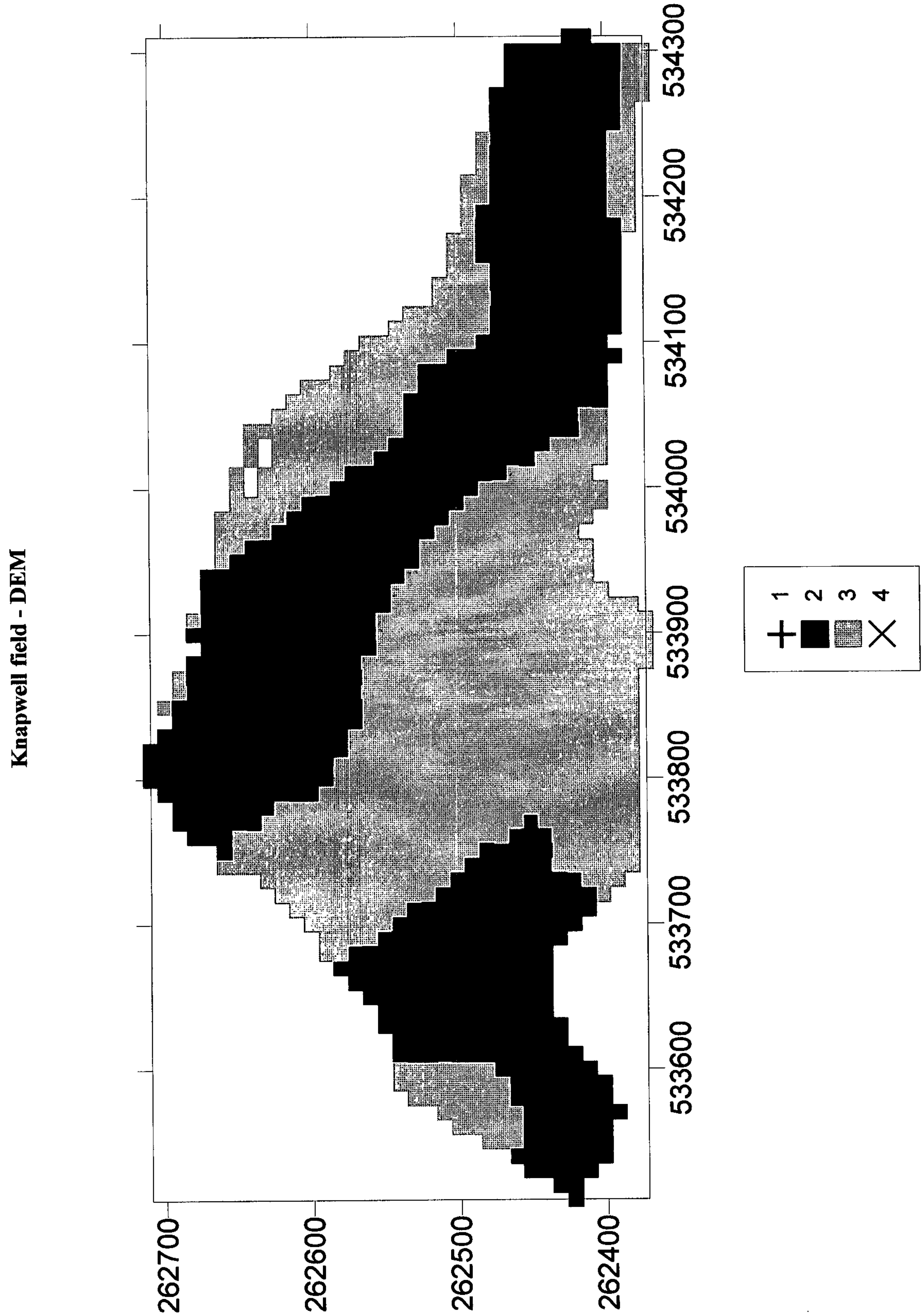
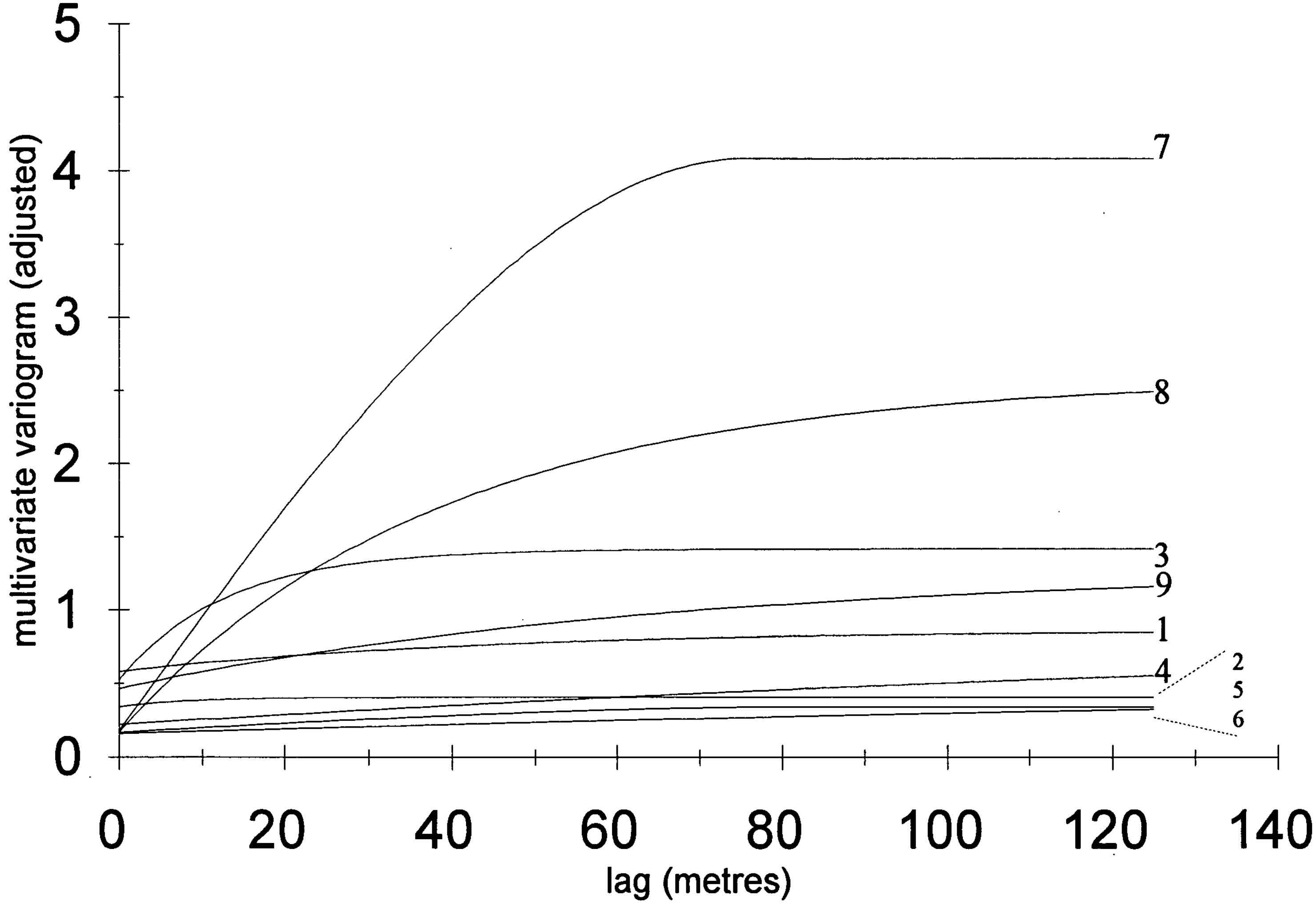
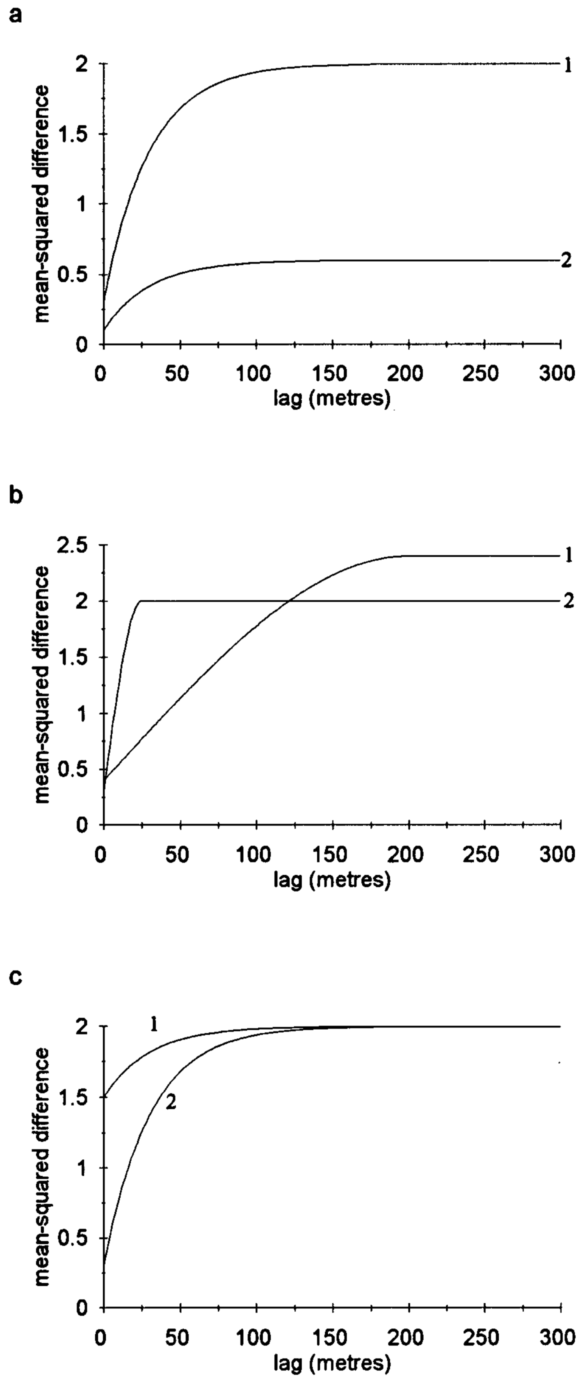

Knapwell field - DEM
262700
262600
262500
262400
533600
533700
533800
533900
534000
534100
534200
534300
1
2
3
4

Figure 2.13 Multivariate variograms for yield maps of all fields in this project. The numbers indicate the Fields (see Table 2.1)



Hypothetical multivariate variograms

Figure 2.14



3. TWELVE ACRE FIELD, GLEBE FARM, HATHEROP, CIRENCESTER

Introduction

The farm was originally mapped as part of the SAFE HGCA project in 1997. An additional survey has been undertaken in 1998 as part of this project to obtain data on the spatial distribution of soil physical characteristics as well as to improve on the spatial distribution of the identified soil series.

Site

The field is at 115 to 120 m above sea level to the east of the village of Hatherop in the Cotswolds (SP1705 0630) (Figure 3.1 and 3.2). Most of the field is level with a short 5 to 6° slope trending north west to south east below which is a linear hollow running along the eastern margin of the field. The parent material is Cotswold Brash, overlain in the very east of the field by a thin layer of colluvium. The cropping history is continuous winter wheat.

Soil types and distribution

Three soils were mapped as part of the Cranfield University HGCA project "Management Guidelines for Precision Farming" - Sherborne, Moreton and Didmarton, based on observations at 17 auger bores located approximately 50 m apart in a grid pattern (Cosser et al. 1997) (Figure 3.3). In addition six pits were dug to approximately 1 m depth, sampled and the particle size distribution, pH, and organic carbon contents measured in the laboratory. The field has been sampled at a further 37 locations using a tractor mounted corer as part of the current project targeted to examine the relationship between yield and the underlying soil.

Sherborne

Typical profiles consist of a calcareous topsoil to between 25 and 35 depth over a thin yellowish brown subsoil that quickly passes to brashy Oolitic limestone. The textures are clayey throughout the profile. Stones that are common to many in the profile are usually platy in shape.

Moreton

These permeable clayey soils are similar to the Sherborne soils but they are deeper to limestone, usually 50 to 60 cm. The yellowish brown subsoil is moderately to very stony with small angular and platy limestone stones.

Didmarton

These are deep soils that have formed at the bottom of slopes and dry valley bottoms in colluvium. They are clayey throughout the profile, sometimes, as here, becoming less clayey with depth. They are well drained and characteristically stoneless to depth.

All the soils are wetness class I. (Hodgson, 1997)
Topsoil pH varied from 7.9 to 8.1 and topsoil organic carbon from 2.3 to 2.5%.

Discussion

The field is uniform in topsoil and subsoil texture (clay) and shows only small variations in topsoil thickness and profile stoniness. Therefore if soil factors are affecting the yield pattern in the field they must be related to depth to rock, which is the soil parameter that varies the most in the field. There were no signs of compaction.

The information from all the point information has been collated in a Geographic Information System to aid in the analysis of the point data and to produce maps of some of the soil parameters (Figure 3.4 and 3.5).

Cluster analyses

In this paragraph the yield cluster map obtained in Chapter 2 (Figure 2.5) was related to soil physical properties obtained during the field work.

Yield class 1	Consistently above average yield
Yield class 2	Consistently below average yield
Yield class 3	Close to average yield

The relationships between yield classes and soil series are shown in Table 3.1 and between yield classes and soil physical parameters in Tables 3.2 and 3.3.

Table 3.1 Relationship between soil series at sample points and yield class

YIELD CLASS	SHERBORNE (%)	MORETON (%)	DIDMARTON (%)
1 (N=4)	0	50	50
2 (N=20)	45	35	20
3 (N=30)	80	10	10

This table shows how sample sites within each class defined from the yield maps are divided among the soil series. The underlying contingency table was analysed and a null hypothesis of random association between the yield map classes and the soil series was rejected ($p < 0.01$).

Table 3.2 Relationship between yield and soil parameters at Hatherop
(based on 37 targeted soil cores and 17 auger bores on grid)

YIELD CLASS	TOPSOIL DEPTH		SOIL DEPTH		AWC	
	MEAN (cm)	SD	MEAN (cm)	SD	MEAN (mm)	SD
1 (N=4)	22.8	1.7	80.7	12.4	106.5	7.7
2 (N=20)	22.1	6.4	49.5	23.9	87.9	18.6
3 (N=30)	22.7	7.5	36.7	21.8	79.1	17.1

Profile available water capacity for winter cereals (AWC) was calculated to a depth of 120cm for each profile using data held in the SSLRC's information system (LandIS) (Figure 3.6). The AWC calculation takes into account water held in the porous limestone. Evidence from the soil pits suggests rooting to at least 60 cm, i.e. the roots are exploiting moisture within and between the limestone fragments (mean rooting depth 75 cm).

Table 3.3 Relationship between yield classes and profile available water capacity

YIELD CLASS	**MODELLED AWC (mm)**				
	<60	**60-80**	**80-100**	**100-120**	**%**
1	0	0	0	100	100
2	0	45	20	35	100
3	3	57	27	13	100

LandIS provides an assessment of the qualitative suitability of a soil for growing a wide range of crops including winter cereal (Jarvis et al. 1984). The results for the soils at Hatherop (suitability for winter wheat) were: Sherborne series - marginally suited, Moreton series - moderately suited, Didmarton series - well suited.

Statistical analyses

(i) Regression of soil properties on (transformed) memberships.

Multiple regression analyses were carried out for the full data set with each soil property in turn as the dependent variable, and the membership values in the three classes defined from the yield maps as the independent variables. The membership values were transformed to their log-ratio values before the analysis (Aitchison, 1986). The regression function was estimated by a maximum likelihood method, rather than ordinary least squares, on the assumption that the errors are spatially dependent with a stationary exponential covariance function which is estimated at the same time.

There was no significant linear relationship between the transformed membership values and any of the soil properties (Adjusted R^2 values of 0.01 (Top soil depth), 0.08 (soil depth) and 0.07 (AWC) respectively). This is disappointing, but the potential of this general approach should not be dismissed purely on the grounds of one study based on two season's yield maps. The results using the classes as categorical variables (below) show that the variability in these soil properties is at least partly expressed in the yield maps.

(ii) Analysis of variance on differences between the classes (maximum membership) with respect to soil properties.

The class of maximum membership was known at each site. The mean value for each property could thus be estimated, and the differences tested by a (random effects) one-way analysis of variance.

The class means and standard deviations are shown in Table 3.2. There were significant differences between the classes means for soil depth (p=0.001) and available water capacity (p=0.01), but not for topsoil depth (p=0.96). The difference between classes 2 and 3 with respect soil depth was significant (p=0.026) as was the difference with respect to available water capacity (p=0.047).

The intraclass correlation (Webster and Oliver, 1990) was computed for soil depth and for available water capacity. This indicates the proportion of variation in the property explained by differences among the class means as estimated in a random effects analysis 30% of the variation in soil depth was explained by differences among the classes, and 21% of variation in AWC.

(iii) Discriminant analysis.

The smoothed and transformed memberships of the classes defined on yield were used to estimate quadratic discriminant functions to separate the three soil series. Figure 3.7 shows the two canonical axes and each datum labelled according to the soil series. The canonical axes represent a transform of the three-dimensional space defined by the membership values in the three classes. This soil series are distinguished as clearly as possible in this transformed space. As might be expected from the soil series map and map of classes, the soil series were not effectively separated by the discriminant analysis.

Conclusions

Traditionally soil series have been used as a key to soil variability. However the series concept includes a variety of soil physical and chemical parameters that are usually found together over a particular parent material.

One of the conclusions from this and related studies into the management of soil variability is that the farmer/land manager needs to consider single feature maps of his field to express the physical variability and then to relate these maps singular or in combination to the yield maps.

In the case of 12 acre field it is clear that the soil depth and available water capacity explain many of the patterns shown in the yield cluster map. The conclusion is therefore that the underlying soil pattern has a considerable effect in determining yield at 12 acre field, and that the analysed yield map would be a useful tool when planning field investigation of this pattern.

Figure 3.1 Hatherop site looking from gate towards south east corner.

Figure 3.2 Digital air photograph of 12 acre field in May 1998

Figure 3.3 Soil map - Hatherop

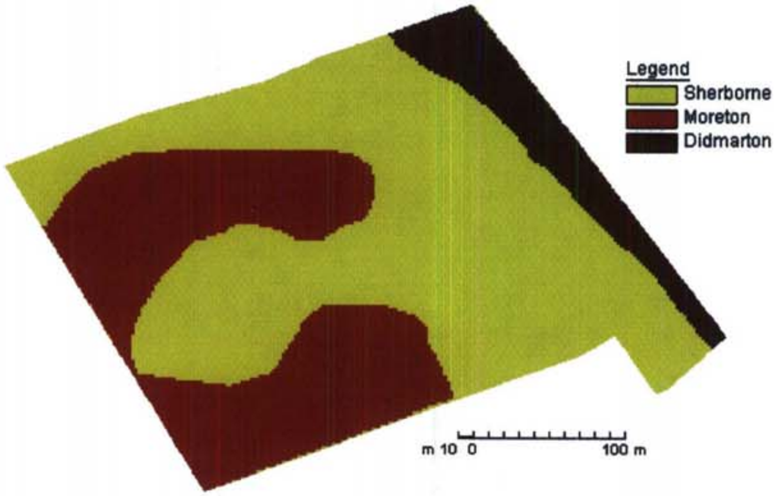


Figure 3.4 Modelled topsoil thickness map - Hatherop

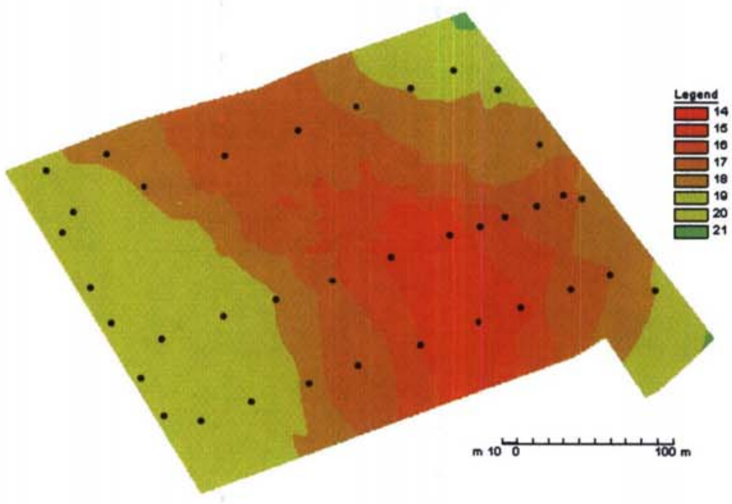


Figure 3.5 **Modelled depth to rock - Hatherop**

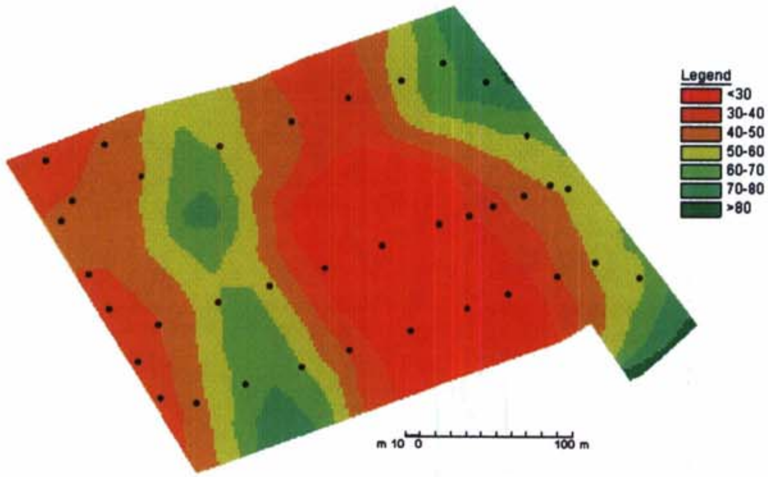


Figure 3.6 **Modelled profile available water capacity for winter sown cereals - Hatherop**

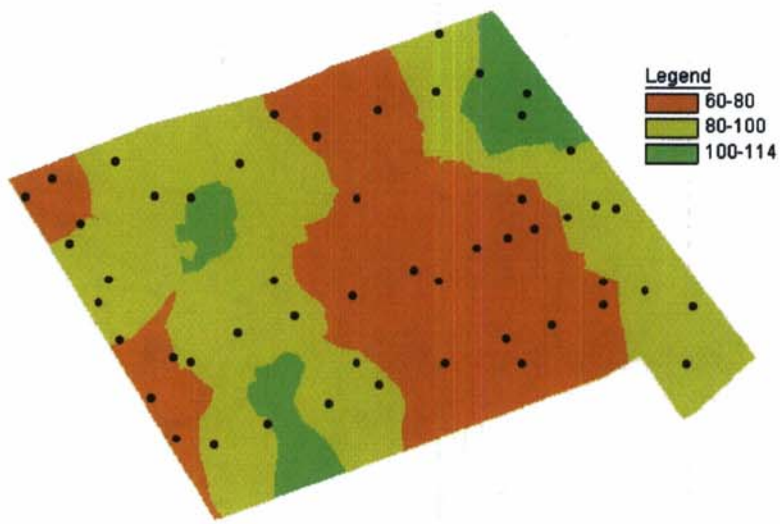
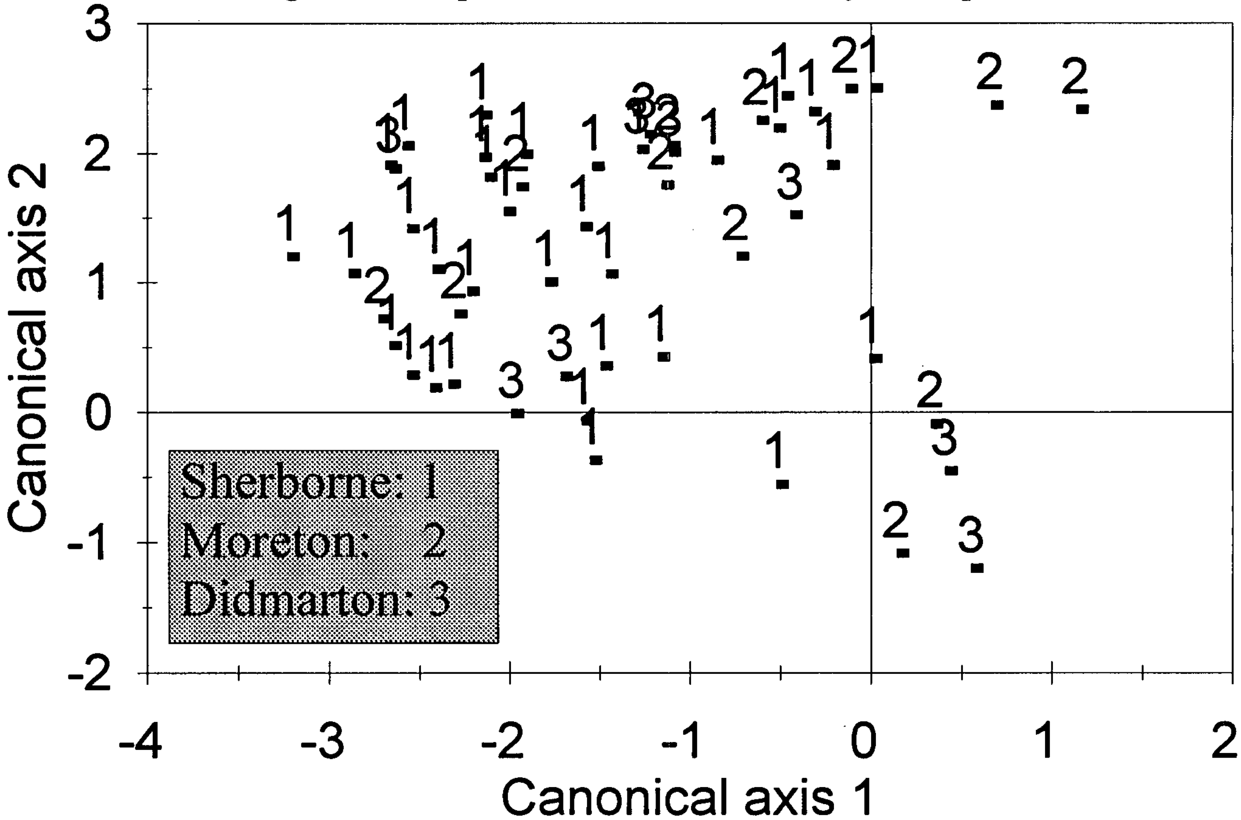


Figure 3.7

Canonical variates derived from discriminant analysis of three soil series using membership values for classification of yield maps



4. TRENT FIELD, WESTOVER FARM, WHERWELL, ANDOVER

Introduction

The farm was originally mapped as part of the SAFE HGCA project in 1997. An additional survey has been undertaken in 1998 as part of this project to improve our understanding of the spatial distribution of soil physical characteristics as well as the spatial distribution of the identified soil series.

Site

The field is at 50 to 70 m above sea level to the south of the village of Goodworth Clatford (SU3705 4045) (Figure 4.1). The field slopes from south west to north east with a maximum slope of about 7°. The underlying geology is Upper Chalk. The cropping history is continuous barley.

Soil types and distribution

Two soils were mapped as part of the Cranfield University HGCA project "Management Guidelines for Precision Farming" - Andover and Panholes, based on observations at 15 auger bores located approximately 50 m apart in a grid pattern (Cosser et al. 1997) (Figure 4.2). There is also an area of disturbed soils in the north west corner of the field. In addition four pits were dug to approximately 1 m depth, sampled and the particle size distribution, pH, and organic carbon contents of each soil horizon measured in the laboratory. The field has been sampled at a further 87 locations using a tractor mounted corer as part of the current project targeted to examine the relationship between the yield and the underlying soil. The depth to chalk was observed at each location, and the soil series identified.

Andover

These are shallow freely draining silty clay loam soils over chalk. Topsoils are 25 to 35 cm thick, slightly or moderately stony with flint and chalk stones.

Panholes

These freely draining soils are similar to the Andover soils but deeper. Topsoils are brown, stony silty clay loams with chalk and flint stones. Subsoils are similar in texture but browner in colour and overlie shattered chalk at 40 to 60 cm depth.

Disturbed soil

The small area mapped as disturbed has a very deep greyish brown silty clay loam topsoil overlying a layer of mixed origin. It is thought that the soils could result from levelling of a previous hollow.

All the soils are in wetness class I. (Hodgson, 1997)
Topsoil pH varied from 6.9 to 7.9 and topsoil organic carbon from 1.5 to 3.3% (the lowest values for pH and organic carbon were found in the south east corner of the field).

Discussion

The field is uniform in topsoil and, where present subsoil, texture (silty clay loam) and shows only small variations in topsoil thickness and profile stoniness. Therefore if soil factors are affecting the yield pattern in the field they must be related to depth to the chalk, which is the soil parameter that varies the most in the field. There were no signs of topsoil compaction, but some of the subsoil layers above the chalk were compact and flinty.

The information from all the point information has been collated in a Geographic Information System to aid in the analysis of the point data and to produce maps of some of the soil parameters (Figure 4.3 and 4.4).

LandIS provides an assessment of the qualitative suitability of a soil for growing a wide range of crops including winter cereal (Jarvis et al. 1984). The results for the soils at Wherwell indicated that all three soil series were well suited for winter barley.

Cluster analysis

In this paragraph the yield cluster map obtained in Chapter 2 (Figure 2.6) was related to soil physical properties obtained during the field work.

Yield class 1	at or above average yield
Yield class 2	consistently below average yield
Yield class 3	highest yield in 1995, below average in 1997

Profile available water capacity for winter cereals (AWC) was calculated to a depth of 120 cm for each profile using data held in the SSLRC's information system (LandIS) (Figure 4.4). The AWC calculation takes into account water held in the porous chalk. Evidence from the soil pits suggests rooting to 60 to 65 cm, i.e. the roots are exploiting moisture within the chalk rock.

The relationships between yield classes and soil series are shown in Table 4.1 and between yield classes and soil physical parameters in Tables 4.2 and 4.3.

Table 4.1 Relationship between soil series at sample points and yield class

YIELD CLASS	ANDOVER (%)	PANHOLES (%)	DISTURBED SOILS(%)
1, (N=24)	50	17	33
2, (N=37)	62	38	0
3, (N=26)	82	18	0

Table 4.2 Relationship between yield and soil parameters at Andover
(based on 87 targeted soil cores)

YIELD CLASS	SOIL DEPTH		AWC	
	MEAN (cm)	SD	MEAN (mm)	SD
1 (N=24)	36.1	14.3	120.9	5.6
2 (N=37)	31.5	14.8	118.5	5.4
3 (N=30)	25.4	9.7	116.2	4.7

The "disturbed soils" were difficult to classify and quantify in terms of their behaviour and particularly their AWC. Because of the large number of stones seen in some profiles the calculated AWC are probably over- rather than under-estimates.

Table 4.3 Relationship between yield classes and profile available water capacity

YIELD CLASS	MODELLED AWC (mm)				
	<115	115-120	120-130	>130	%
1	22	30	48	0	100
2	35	38	22	15	100
3	53	32	15	0	100

Statistical analyses.

(i) Regression of soil properties on (transformed) memberships.

The same regression procedure discussed in the previous Chapter was applied here to see if any relationship could be identified between the transformed membership values and soil depth and AWC.

There was no significant linear relationship between the transformed membership values and either of the soil properties (Adjusted R^2 values of 0.09 (depth to chalk), and 0.1 (AWC) respectively). The results of the analyses using the classes as categorical variables (below) show that the variability in these soil properties, as at the Cirencester site, is at least partly expressed in the yield maps.

(ii) Analysis of variance on differences between the classes (maximum membership) with respect to soil properties.

The class of maximum membership was known at each site. The mean value for each property could thus be estimated, and the differences tested by a (random effects) one-way analysis of variance.

The class means and standard deviations are shown in Table 4.2. There were significant differences between the classes means for soil depth (p=0.02) and available water capacity (p=0.01).

The intraclass correlation (Webster and Oliver, 1990) was computed for both properties. 10% of the variation in soil depth was explained by differences among the classes, and 12% of variation in AWC. This is a smaller proportion of the variability than was accounted for at the Cirencester site. However, the overall variance of depth to parent material was 617.0 at Cirencester, and 190.0 at Andover. The variance of AWC at Cirencester was 344.5, but only 30.2 at Andover. The Andover site shows markedly less variability than Cirencester, at least with respect to these two soil properties.

(iii) Discriminant analysis.

The smoothed and transformed memberships of the classes defined on yield were used to estimate quadratic discriminant functions to separate the three soil series. Figure 4.5 shows the two canonical axes and each datum labelled according to the soil series. The disturbed soil is distinct from the two series, but this is unlikely to be of significance as the mapped disturbed soil only occupies a small part of the field. There is some difference between Andover and Panholes series on this plot, with the latter series tending to the bottom left quadrant although there is a good deal of overlap between the series. This, not very strong, discrimination might be enhanced by adding additional information - for example on land form, or from remote sensors.

(iv) Spatial analysis.

Yield values were extracted from the 1995 and 1997 maps, which corresponded to each of the 87 soil samples. Each yield value was the average of all data in the map within 10m radius of the sample location. Since there were 87 locations, it was feasible to estimate the semivariograms and cross-semivariograms for these properties, at the scale of resolution permitted by the sample grid (which is rather coarser than the resolution of the multivariate variograms). It should be noted that the number of data available for computing variograms of the soil properties is somewhat less than ideal, so the estimates will have a good deal of error.

The semivariance of a variable z is estimated, for a distance h, by

$$\gamma(h) = \frac{1}{2n_h} \sum \left(z(i) - z(i+h)\right)^2 \qquad (4.1)$$

where *z(i)* and *z(i+h)* are, respectively, the value the property takes at location *(i)* in the sample and at location $(i + h)$. The sample contains n_h data separated by this distance. The semivariogram is a plot of the semivariance against distance. As the distance increases the semivariogram rises, until a distance is reached beyond which observations of the property are effectively independent.

The cross-semivariance for two properties z and u is estimated by

$$\gamma_{z,u}(h) = \frac{1}{2n_h} \sum \left(z(i) - z(i+h)\right)\left(u(i) - u(i+h)\right). \qquad (4.2)$$

While the semivariance must always be positive, the cross-semivariance may be negative if the two properties are negatively correlated.

Figure 4.6 shows the variograms which were computed. It is interesting to note the difference between the two semivariograms of yield (Figure 4.6 b and c). In 1995 yield was less variable than in 1997 (compare the scales of the graphs), and the semivariogram does not rise appreciably beyond a distance of 150m or so. In 1997 the semivariogram rises continuously to distances of 250m and possibly more. This variogram is similar to that for AWC (Figure 4.6a). Furthermore, the cross-semivariogram for 1995 yield and AWC takes negative values, implying a negative correlation between the properties, while the AWC/ 1997 yield cross-semivariogram takes positive values, and is broadly similar to the semivariograms for the two properties. This suggests that AWC or some correlated soil property might have limited yield more markedly in 1997 than in 1995, but given the limited available data, this can only be speculative. However, the semivariograms and cross-semivariograms do suggest that the yield map data could be used to improve the precision with which AWC may be mapped from soil samples, using the procedure of co-kriging.

4.5 Conclusions

Depth to chalk in isolation did not give a fair reflection of the pattern of yield zones. This is confirmation that the crop exploits resources, particularly water, from the chalk itself. The model used to generate the AWC map takes into consideration water held in the chalk to 140 cm depth, hence small variations in topsoil thickness, as on the western margin of the field, are not reflected in either the AWC or yield maps. However, this assumes homogeneous chalk material throughout the field with consistent water retention characteristics which might not be the case.

The patterns of all the variable studied in the northern part of the field are complicated by the area of disturbed soils where former boundaries and embankments has been levelled. AWC and soil thickness can only be estimates in this area because of the very variable mixture of flint stones, chalk fragments and soil particles

Figure 4.1 Andover site looking north west.

Figure 4.2 Soil map (based on 1997 survey) - Andover

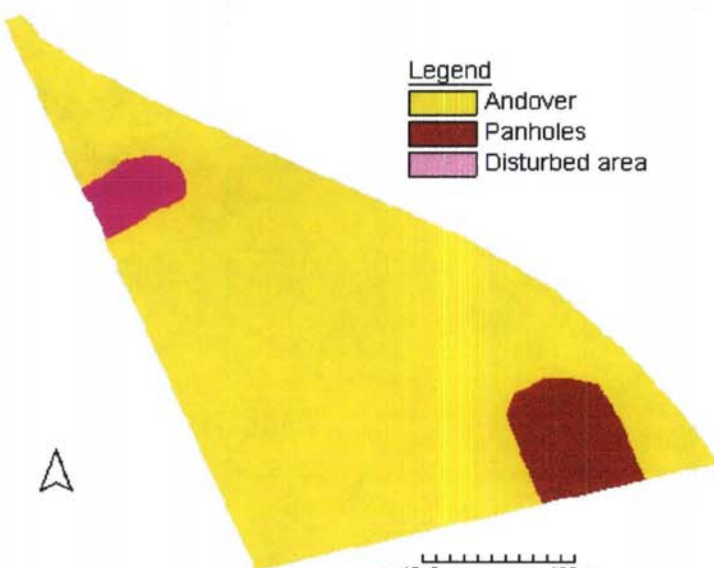


Figure 4.3 Modelled depth to chalk - Andover

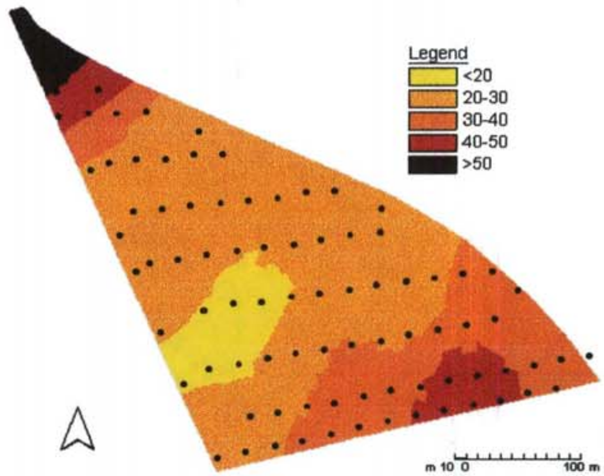
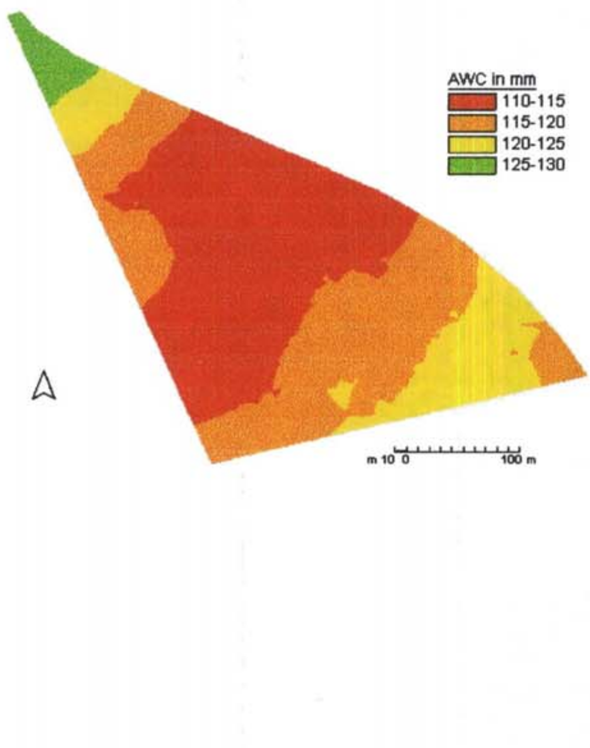


Figure 4.4 Modelled profile available water capacity for winter sown cereals - Andover



53

Figure 4.5

Canonical variates derived from discriminant analysis of three soil series using membership values for classification of yield maps (Andove site)

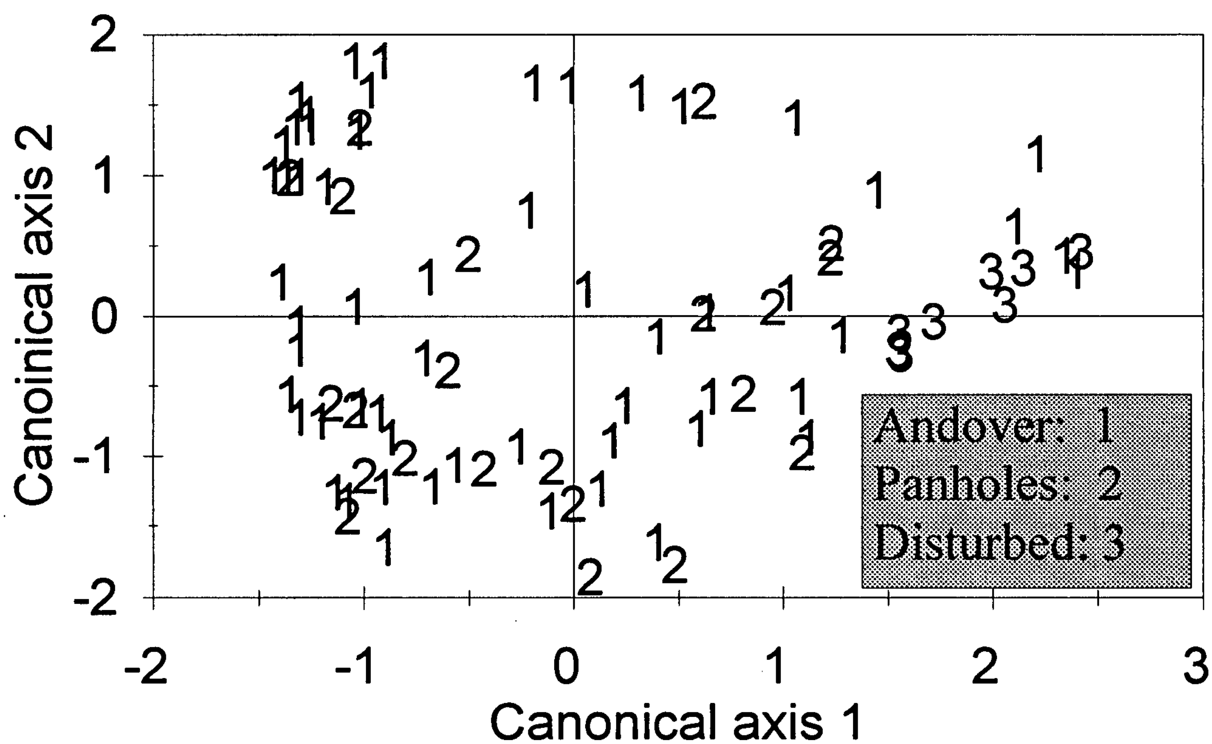
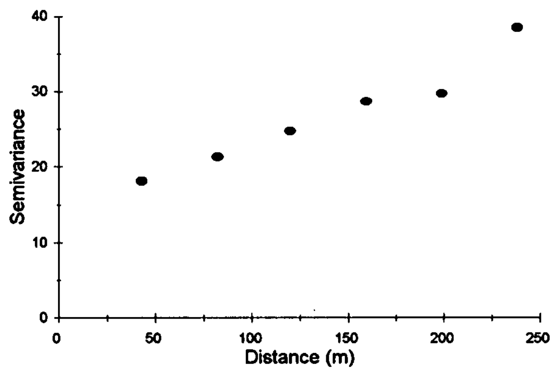
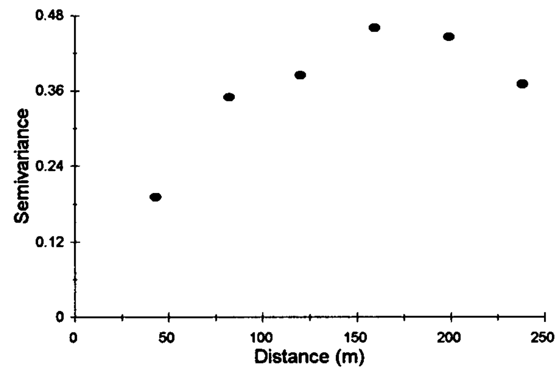


Figure 4.6

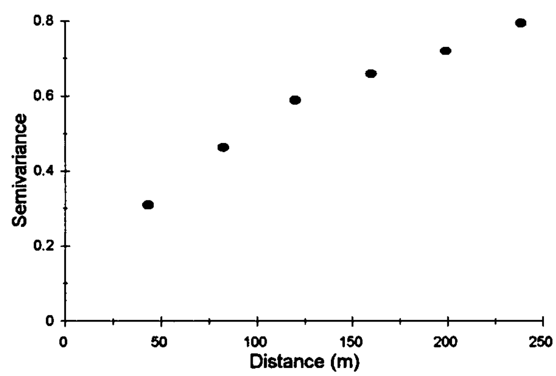
a). semivariogram for AWC



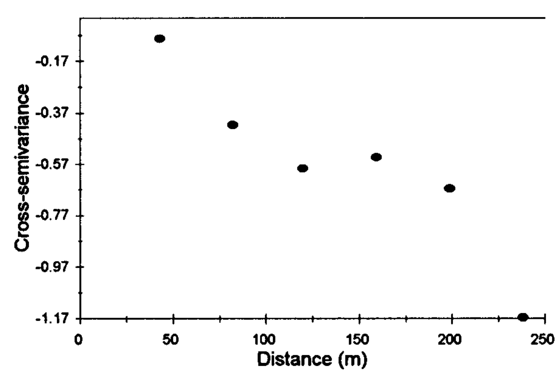
b). semivariogram for Yield (1995)



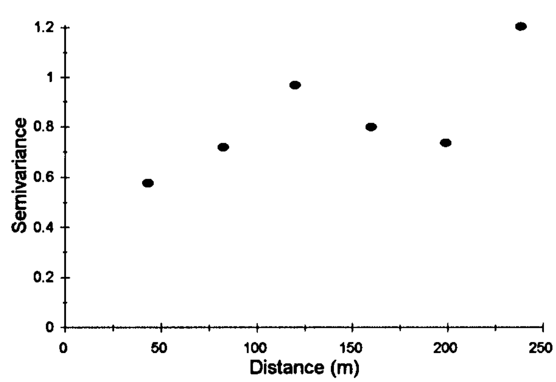
c). semivariogram for Yield (1997)



d). cross-semivariogram for AWC , Yield (1995)



e). cross-semivariogram for AWC , Yield (1997)



5. HOLLY & PACKWAY FIELDS, BUNWELL, NORFOLK

Introduction

Two fields were studied at Villa Farm, Bunwell, Norfolk (grid ref. TM 123 925), on the extensive East Anglian boulder clay plateau 12 miles south-west of Norwich. The soils on the 600-ha farm had already been examined and mapped, with emphasis placed on soil structure, topsoil pH, and implications for yield mapping and precision farming. This initial survey included soil investigation at the intersects of a 200-m grid. At each site properties such as texture, colour, the presence of calcium carbonate (free lime), stones and topsoil pH were recorded. An additional survey in May 1998 concentrated on identifying the soil characteristics that could distinguish the smoothed three-year yield clusters (Figure 2.3 & 2.4).

Sites

Holly Field (TM 134 928) falls from 58 m above sea level (O.D.) on the plateau in the west, where the gradient is negligible, to 45 m O.D. towards the stream in the east, with gentle to moderate slopes of 3 to 4½ degrees in the north-east. The field (Figure 5.1) was in four separate parcels before amalgamation, with the southernmost field under grass and with a distinctly more organic-rich topsoil. A total of 16 investigations were made with some being double bores 1 metre apart.

Packway Field (TM 124 946) is an amalgamation of 11 smaller fields (Figure 5.2). The land falls gently from 66 m O.D. on the plateau in the west to 54 m O.D. along the stream in the south-east. Maximum slopes are of 1½ to 2 degrees. Some of the former field boundaries were clearly visible as lines of taller, darker green growth in winter wheat. Organic matter in the bottom of infilled ditches provides additional moisture and nutrients for more vigorous growth. The soil profile was investigated at a total of 19 sites.

Geology and soil parent materials

The Bunwell district consists of a dissected plateau formed from glacial drift deposits resulting from one or more advances across East Anglia of a large ice sheet. All soil profiles at Bunwell display a distinctive two-layer sequence of deposits, the parent materials from which the soils have developed. There is an *upper loamy layer* (commonly 30–60 cm thick on slopes to more than a metre thick on the plateau) of light loams (sandy loam texture) or medium loams (sandy clay loam and clay loam textures) derived from glacial outwash and/or deposition by wind. Below this occurs one of two similar but distinctive deposits left behind as ground moraine (termed 'till') upon decay of the ice sheet.

Over much of East Anglia the lower layer consists of till, known commonly as *Chalky Boulder Clay* (*CBC*). It consists of a dense grey, weathering to brown, calcareous clay containing common small chalk stones and some larger flints. It is usually fissured down to 1.5 m and below but becomes impermeable at depth. Of critical importance to farming the land, the upper few cm of the boulder clay are usually leached of lime and chalk.

A similar but less heavy glacial deposit known as *Loamy Chalky Till* (*LCT*) forms the subsoil through most of the land at Bunwell. The matrix is paler in colour than the CBC as it contains a larger proportion of fine chalk and resembles a marl. It has a finer, more strongly developed structure and is generally more permeable than the clayey subsoil, but becomes impermeable at depth.

The junction between the upper loams and LCT or CBC below can be undulating with irregularly shaped pockets of sand.

Shallow valleys contain infills of loamy material that has moved down from the adjacent slopes. In geological terms this is classed as either '*Head*' (from glacial permafrost times) or '*colluvium*' (derived from more recent erosion and slopewash of the loamy plateau cover in post-glacial times).

Soil types and distribution

Ashley series (map symbols As and As*, Figure 5.1 & 5.2)

This soil is typical of slopes in boulder clay country in mid-Norfolk and mid-Suffolk and on better drained plateaux there. The usual sequence is of medium loams (clay loam and sandy clay loam) over calcareous chalky clay but at Bunwell a *loamy subsoil phase* of this (As*) occurs with a very chalky loamy lower subsoil.

The topsoil is usually a sandy clay loam, naturally non-calcareous. The upper subsoil is a non-calcareous sandy clay loam of variable thickness, with faint ochreous mottling and structure only weakly developed. The lower subsoil is either (i) clayey, non-calcareous with weak coarse structure at first but then chalky within 80 cm depth with moderately to strongly developed prismatic structure, passing downwards to dense, slowly permeable Chalky Boulder Clay, or (ii) a deep, very calcareous clay loam or silty clay loam (Loamy Chalky Till), with strongly developed medium blocky or prismatic structure. Although soils with the LCT seem to be at an advantage in management terms over the CBC, this is something of an unknown factor. The soil becomes slowly permeable at depth with mottling due to slight seasonal waterlogging usually evident.

Honingham series (HG)

This soil is the light loamy equivalent of Ashley series and is typical of slopes and better drained plateaux in boulder clay country in Norfolk and Suffolk around the eastern edge of Breckland where the influence from the local sandy deposits is quite strong. The sequence is of a sandy loam topsoil over a sandy loam upper subsoil passing to sandy clay loam, but in many places the topsoil is directly over sandy clay loam textures. There is some faint mottling in these loamy layers indicating intermittent waterlogging in winter and early spring. Water draining through the soil profile is held up by the clay-layer sequence of non-calcareous over calcareous chalky clays.

All of the upper loamy layers and the non-calcareous clay in Ashley and Honingham soils are potentially acid, but this has been overcome by surface applications of lime.

Cannamore series (Cmr)

This soil is common on sloping ground that has shed any loamy covering through soil erosion. As a result, the clay loam textured LCT can occur immediately below the plough layer, or there may be an intervening brownish clay loam or sandy clay loam. Where the pale-coloured chalky material is incorporated into the surface the topsoil can be sticky and smear easily. The whole soil profile is calcareous and the LCT is very calcareous with more than 10% of the soil being calcium carbonate. Faint mottling in the upper subsoil intensifying with depth suggests that the soil is moderately permeable with intermittent wetness during winter and early spring.

Hopsford series (HP)

In Packway field an accumulation of medium loamy soil more than a metre thick occurs along a narrow, shallow valley.

In all of the soils, the thickness of the respective layers is very variable over short distances of a metre or less, typical of patterned ground deformation under glacial or periglacial environmental conditions. There are irregularly-shaped pockets of sandy material commonly occur at the junction of the loamy layers and the underlying clay/clay loam.

Discussion

The soils across the two fields have strong similarities and change gradually across the landscape rather than abruptly. There is a tendency for the chalky lower subsoil to occur at a greater depth beneath a thicker loamy covering on the plateau portion of each field compared with the gentle slopes. These gentle slopes aid the natural lateral drainage of the soils. Ashley and Honingham soils respond well to drainage and the water regime is readily improved, although problems with the effectiveness of the drainage in the northern corner of Packway Field have been recognised by the farmer.

There is a narrow range of soil moisture available to a winter wheat crop (AP) and of total available water capacity of the soil to 1 metre depth (AWC), as indicated in Table 5.1, with the calculated distributions shown in Figure 5.1 & 5.2. The available water is smallest where sand pockets are extensive in the lower subsoil, or compaction is pronounced in the topsoil and/or upper subsoil.

Table 5.1. The range of soil moistures calculated for the investigation sites.

	AP winter wheat mm		AWC mm	
	min	max	min	max
Holly Field	123	146	137	155
Packway Field	121	147	131	157

Although most topsoils and upper subsoils have the potential to become acid, the lime status at every investigation site was adequate for a cereal crop (pH>6.5). Topsoils in Holly Field were mainly calcareous and in Packway Field non-calcareous, with the lowest recorded pH value of 6.9.

Cluster analysis

The yield cluster maps obtained in Chapter 2 (Figure 2.3 & 2.4) were related to soil physical properties obtained during the field work.

Holly Field

Cluster 1, with depressed yields in 1995 and particularly 1997, to some extent preferentially occupies field margins. The three sites investigated in May 1998 clearly had a larger number of more durable cobbles of soil evident on the surface in the sugar beet crop. Two of the sites were on headlands, and soil wetness and its associated compaction were recognised by the farmer in these places. The generally heavier sandy clay loam textures of Ashley series topsoils compared with the sandy loam of Honingham series could also be detected across the field by the more cobbly surface soil structure. Cluster 1 also occurs within the sandy loam part of the field without explanation.

Cluster 2, with relatively depressed yields in 1996, a dry year, occurs mainly in the area of Honingham series. The coarser sandy loam textures may induce a slight drought effect although this is not shown by the calculated values for available water (Table 5.2), although the moisture retentive till (LCT or CBC) was found at slightly greater depth in the three investigation sites (Table 5.3).

Cluster 3, mean standardised yield consistently positive, occurs throughout the field and is the dominant grouping. Overall, the depth to moisture retentive chalky subsoil was found to be generally shallower at the seven sites studied (Table 5.3).

No clear effect can be seen from the enhanced organic matter content of topsoils in the former pasture in the southernmost part of the field.

Table 5.2. The range of soil moistures by yield-cluster groupings.

	AP winter wheat mm			AWC mm			Sample
	min	max	mean	min	max	mean	size
Holly Field							
cluster 1	140	146	143	142	155	149	4
cluster 2	139	145	141	148	154	150	3
cluster 3	123	145	140	137	153	148	7
Packway Field							
cluster 1	128	143	138	145	150	148	5
cluster 2	132	142	136	135	157	147	4
cluster 3	–	–	144	–	–	152	1
cluster 4	128	128	128	131	135	133	2
cluster 5	121	140	132	136	153	144	3

Packway Field

Clusters 1 and 2 share the bulk of the field's yield characterisation, with the main difference attributable to the relatively enhanced yield of cluster 2 in 1995. Cluster 1, with just above the mean standardised yield in all three years, is dominant in the south-east part of the field, with smaller delimitations in the north-west part. Cluster 2 is complementary with two large blocks in the north-west and an absence from the south-east. These two clusters appear to represent the typical yield potential for the soils of Packway Field where particular constraints are avoided. At the few sites investigated, the upper loamy layers are thicker over the chalky subsoil for cluster 2 soils (Table 5.3), but calculated moisture availability is similar for both (Table 5.2).

Cluster 3 has a severely depressed yield in 1996, a dry year, and is commonly associated with field margins.

Cluster 4 has slightly below average yields in 1995 and 1996, but yields were particularly poor in 1997. Moisture retentive chalky subsoil was found at depths greater than a metre (Table 5.4), but the block in the south-west can be attributed to weed infestation of wild oats (*Avena fatua*) and brome-grass (*Bromus*) in 1997. A similar infestation was seen to persist there in May 1998, when further weed occurrences were noted along some of the old infilled field boundary ditches. Persistent poor drainage has been notified by the farmer in the northern corner of the field.

Cluster 5 shows below average yields in 1995, a good year for winter wheat, and just above average yields afterwards. The concentrations are in the south-east portion where the farmer recognised slug-infestation problems in 1995, and linear occurrences in the north-west part of the field that he attributed to serious weed infestation in the same year along old field boundaries.

Table 5.3. The range of depth to CBC or LCT subsoil by yield-cluster groupings.

	Depth in cm to LCT							Depth in cm to CBC		Mean depth
Holly Field										
cluster 1	33	44						79	119	69
cluster 2	78	100	100							93
cluster 3	39	50	58	59	68	72	96			63
Packway Field										
cluster 1	48	55	75	95				76		70
cluster 2	>110 x 3							74		–
cluster 3	62									–
cluster 4	>110 x 1							105		–
cluster 5	78	>110 x 1						39		–

Conclusions

The soils of both Holly and Packway fields are sufficiently similar throughout each field with regard to rooting depth, water availability and the potential to become compacted that consistent yield differences that can be ascribed to soil differences are not readily apparent, compared with the contrasting soil types studied by Stafford *et al.* (1996). Although the farmer recognised an overall yield advantage when rainfall was plentiful (1995) and lower yields when soil moisture deficits were larger (1996 & 1997), no within-field pattern can be detected from individual yield maps or from the three-year summaries. Mean yields, after removing outliers, for the two fields are given in Table 5.4.

Table 5.4. Mean yields for Hereward milling wheat in t/ha.

	1995	1996	1997
Holly Field	9.3	8.7	7.3
Packway Field	7.2	8.2	6.9

Instead, the farmer could recognise particular management problems that depressed yields, notably weed infestation, slug infestation, particular sites of compacted soil and inadequate drainage measures. None of these is dependent on soil type here.

With the narrow range of soils occurring at Bunwell and a characteristic undulation of the contact between upper and lower soil layers and irregular pockets of sand, small-scale yield differences are likely to occur in dry years. These may be visible as differential crop growth patterns, especially from the air, with close-interval variation, but detection of this phenomenon is beyond the precision of the yield recording equipment.

As topsoils and upper subsoils at Bunwell are non-chalky they display weakly developed soil structure and are thus particularly susceptible to compaction. This feature, however, is consistent throughout the two fields and as a factor affecting yields is largely dependent on management creating and alleviating the problem.

The implication of this conclusion is that over large parts of eastern England where chalky till is the substrate and moisture availability in the growing season is not restricting, i.e. areas with an average annual rainfall greater than approximately 650 mm, then yield mapping will not be as beneficial a tool as in areas of contrasting rooting depths in parts of the country where soil moisture is potentially limiting.

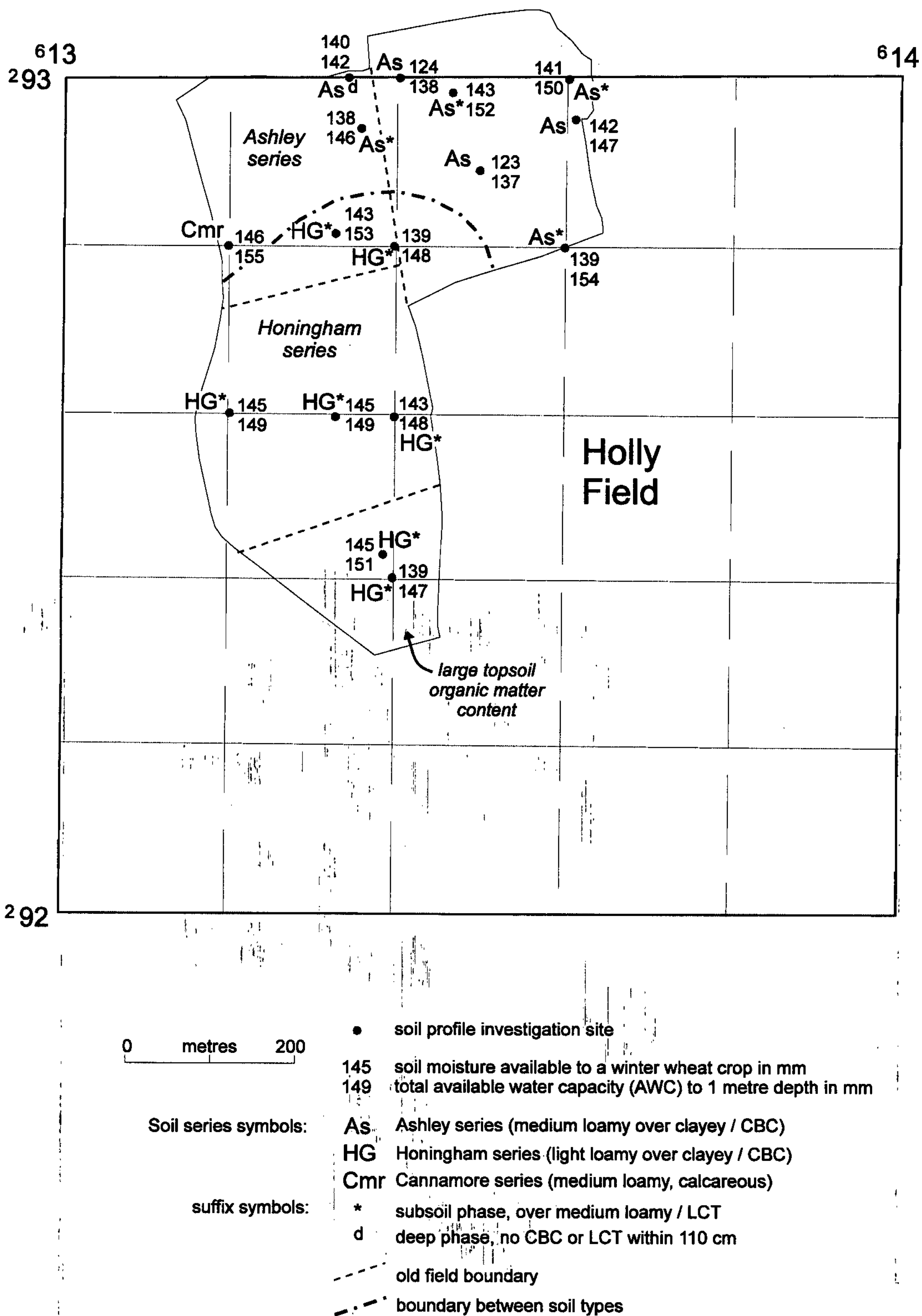
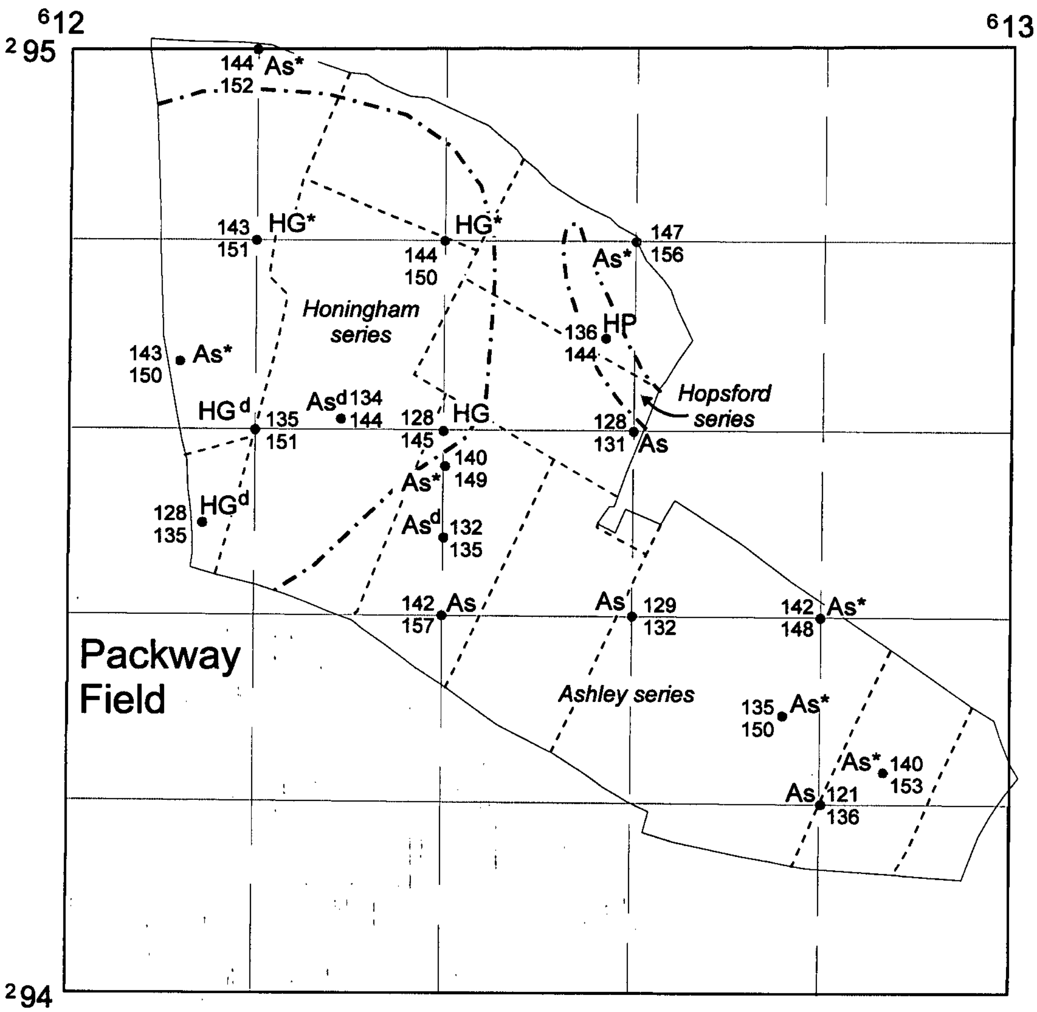


Figure 5.1 Soil profile investigation details Holly Field, Bunwell, Norfolk.



0 metres 200

• soil profile investigation site

145 soil moisture available to a winter wheat crop in mm
149 total available water capacity (AWC) to 1 metre depth in mm

Soil series symbols:
- As Ashley series (medium loamy over clayey / CBC)
- HG Honingham series (light loamy over clayey / CBC)
- HP Hopsford series (medium loamy)

suffix symbols:
- * subsoil phase, over medium loamy / LCT
- d deep phase, no CBC or LCT within 110 cm

- - - old field boundary
-·-· boundary between soil types

Figure 5.2 Soil profile investigation details Packway Field, Bunwell, Norfolk.

6. ADAS SITES: BOXWORTH AND CHICKSANDS

Knapwell and Top Pavements fields, ADAS Boxworth

Knapwell and Top Pavements fields have been closely studied between 1995-1997 since they have formed part of the MAFF LINK project 'Yield mapping as an aid to targeting fertiliser inputs in combinable crops'. In this project, winter wheat yield variation has been measured between 1995-97, and detailed soil and crop measurements taken at each of 21 permanent monitor points in each field for this period.

The soils in both fields are formed on chalky boulder clay and are mostly mapped as Hanslope series (calcareous clay loam topsoil overlying slowly permeable clay subsoil with chalk fragments). Although not forming part of the published Soil Survey classification, four phases of Hanslope series have been identified by Burton (1989) in his survey of the ADAS Boxworth farm. For many years, both fields have been managed as part of a rotation of combinable arable crops.

Phase 1 (very gentle slopes)	Calcareous clay topsoil, with few flints and hardly any chalk stones. Marked change to denser, distinctly mottled clay beginning at 40-50cm. Overall grey colours by 80cm.
Phase 2 (plateau sites)	Less calcareous surface horizons, greater depth to mottling than Phase 1.
Phase 3	Calcareous clay topsoil overlies distinctly mottled clay with common very small chalk stones.
Phase 4	Very chalky topsoils and subsoils.

Knapwell field

The majority of Knapwell field is Hanslope series but with a small area of Folksworth series (calcareous clay loam topsoil overlying weakly mottled sandy clay loam subsoil with impermeable clay at varying depths) mapped by Burton (1989). Folksworth soils are generally located in some of the lower lying dry valley features. Topographically, Knapwell is undulating with an altitude range of about 15 metres, and with some dry valley features in drainage receiving situations. A Digital Elevation Model (DEM) has been produced for Knapwell generated from three stereo aerial photographs, and the analysis of this was described in Chapter 2.

The Hanslope soils are generally poorer drained than in Top pavements field though a comprehensive field drainage system is in place and working. Of the 21 monitored points, phases of Hanslope series were recorded as follows:

Phase 1 - 11 points
Phase 2 - 5 points
Phase 3 - 5 points
Phase 4 - 0 points

The distribution of these soil phases was erratic though with a predominance of Hanslope phase 1 soils on the plateau area (area 3 in Figure 2.12) in the same approximate area as cluster 1. Cluster 6 contained a mixture of phases, but apart from 1995 (1.1 t/ha lower yield), cluster 6 performed very similarly to cluster 1. Over 50% of the field area consisted of these 2 clusters.

The best performing part of the field (cluster 4) was generally located in the low lying area adjacent to the open ditch on the north-eastern field boundary. The Soil Survey map also shows this area to contain a large proportion of the better drained and permeable Folksworth series soil. High yields would be expected in this area, since it is a drainage receiving site with a permeable soil suitable for deep and efficient rooting with minimal potential for moisture stress.

Clusters 2 and 3 cover only a small area but are known to be caused by rabbit damage and associated weed pressure. This was particularly severe in 1997. These clusters have no association with soil differences.

Comparison of the yield cluster maps with known soil and topographic factors, and other factors that are known to be influencing yield, indicates that:

- Some marked yield differences are due to rabbit and associated weed damage, and cannot be attributed to soil differences.
- Topographic information may be useful to help identification of subtle soil patterns and yield performance variation.
- Yield performance may be useful to identify the location of Hanslope soil phases, though small scale erratic variation in phase presence would be expected.

Top Pavements field

The whole of Top Pavements field is mapped as Hanslope series with little variation identified across the field. The field is mostly on a plateau site, gently and evenly sloping with an altitude range of no more than 10 metres. There is no DEM available for this field. Top Pavements field has generally been higher yielding than Knapwell field. One factor influencing this performance difference is considered to be the predominant occurrence of better drained phases of the Hanslope soil in this field (phase 2). The detailed soil studies as part of the MAFF LINK project have not identified any major soil differences. The soil at each of the 21 monitored points was classified as Hanslope series, with 18 of these classified as Hanslope phase 2. It can be concluded that the soil in this field is very uniform.

The cluster map shows an intricate pattern with no clearly defined zones of different yield performance history. Although the central field area might be considered for division into 2 zones (Figure 2.8, clusters 2 and 4), these are not well delineated and have a performance difference of less than 0.5 t/ha in 2 of the 3 years. Such small and erratic differences are unlikely to warrant consideration for adoption of precision farming methods.

The absence of clearly defined yield zones or large differences between the yield clusters in this field corresponds with the absence of any significant differences in soil type. It can be concluded that the yield cluster map has correctly indicated an absence of significant soil type variation in this field.

Lodge Farm, Chicksands, Beds

Yield map data from 1996 and 1997 are available for this farm. A soil survey (Wright 1984) showed a wide range of soil types present in these fields ranging from heavy clay soil (Hanslope and Evesham series) to deep sand soils (Cottenham series). These sand soils are very drought prone. Drought is a recognised problem on the farm with clearly visible effects of varying soil types in unirrigated crops. Wright calculated amounts of available profile water (APW) for the different soil series for cereal crops as follows:

Cottenham (slightly stony phase)	85 mm
Bearsted, Wick	85-120 mm
Hanslope, Evesham, Ashley	120 mm
Ludford	>125 mm

Separate cluster maps were produced for Shagsby field (1996 winter wheat; 1997 winter malting barley), Shagsby 4 (winter wheat in 1996 and 1997) and Bush Close and Antenna fields (winter wheat in 1996 and 1997) - see Figures 2.9, 2.10 and 2.11. There were clear correspondences between the cluster centres from these different fields - indicating similar patterns of season to season yield variation at sites within the fields. These are as follows:

Season-to season variation in yield		Field		
		Shagsby Field	**Shagsby 4 Field**	**Antenna/ Bush close**
A	Consistently above average yield.	Class 2	Class 3	Class 1
B	At or below average, lower relative yields in 1997	Class 3	Class 2	Class 2
C	Less than average in 1996, above average in 1997	Class 1	Class 4	Class 3
D	Consistently below average yield	-	Class 1	-

Figure 6.1 shows the classes derived from all three fields on the same plot, labelled according to the four common patterns described above. The spatial continuity of the distinctive yield patterns across field boundaries is seen.

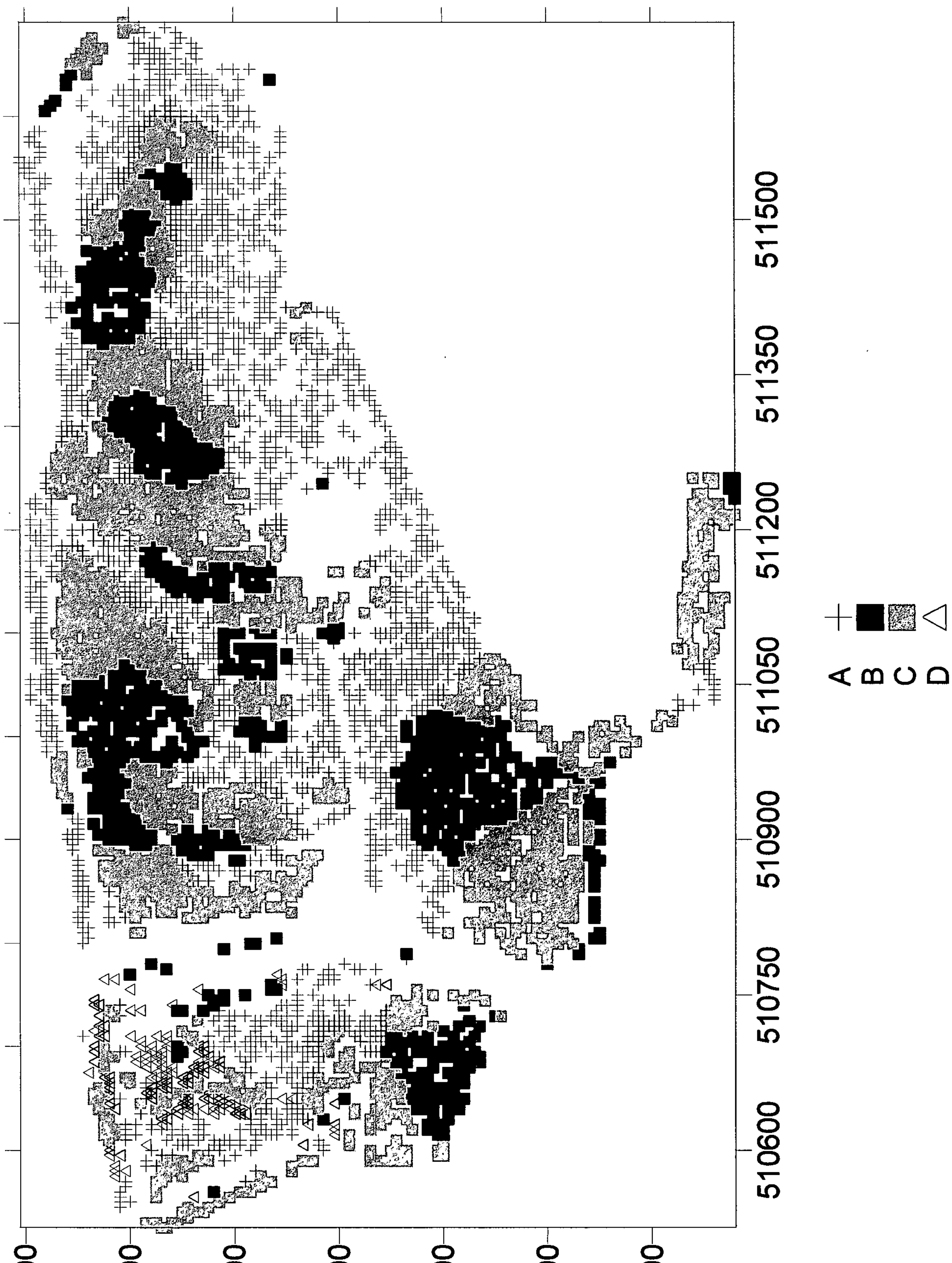
Yield clusters are closely related to soil series boundaries in these fields. In Shagsby field, three clusters were identified (Figure 3.9). The highest yielding areas (cluster 2) were located on Asfordby and Ludford series which have a high APW. These are generally located in the low lying valley areas. Areas of the Cottenham series are associated with low yields (clusters 1 and 3) due to the low APW of these soils and the occurrence of drought. Drought was clearly evident in 1996 and 1997 in these areas. It is interesting that there are 2 yield clusters within the single mapped area of Cottenham series. Cluster 3 is associated with flatter hill plateau areas, and cluster 1 with sloping valley sides. It is likely that there are differences in APW between these areas which are not mapped at the scale used for routine mapping by the Soil Survey. Soils of the Wick series are associated with the high yielding cluster 2 although this soil type is commonly regarded as having a low APW. The crop performance patterns described are clearly visible from aerial photographic evidence (June 1996).

In Shagsby 4 field, 4 clusters were identified (Figure 2.10). Cluster 2 was closely associated with the Bearsted series of low APW. This area had a very similar yield pattern to cluster 1 in Shagsby field (low yields in the drought year of 1997), suggesting that the Bearsted and Cottenham series in this area perform in a very similar way. Cluster 1 was associated with the Wick series and, as found in Shagsby field, yields were generally higher than in cluster 2 areas, indicating less drought restriction on the Wick soil type. Highest yields were produced in cluster 3 areas with much less evidence of any drought restricted yields in 1997. The soil survey map shows that the soils in this area are generally heavier textured clays of the Hanslope and Evesham series, both of which have a much higher APW than the other soils present.

Similar patterns can be seen in Antenna and Bush Close fields reflecting the situation that the soil types extend across the boundaries of the fields studied. Three clusters were identified in these fields (Figure 2.11). The cluster of high yielding areas associated with the Asfordby and Ludford soils in Shagsby field can be seen to extend into Bush Close field (cluster 1) but also associated with soils of the Evesham series in this field. The lower yielding clusters 2 and 3 are more closely associated with soils of the Hanslope series.

In conclusion, the yield cluster maps in these fields do strongly reflect soil type boundaries, and do provide a good measure of guidance for defining field zones of common performance.

Figure 6.1


240300
240200
240100
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510600
510750
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511200
511350
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A
B
C
D

7. CONCLUSIONS

The fields which were studied in this project represent interesting and contrasting situations. Some show very limited soil variability (Holly Field, Packway, Top Pavements). At others the soil variation is substantial (Chicksands, Cirencester, Andover). The results of analysis of yield maps from these fields, and their interpretation using existing and new soil information support the following conclusions.

1. While yield variability may occur which reflects non-edaphic factors (see discussion of Packway field in Chapter 3 and of Knapwell field in Chapter 5), it has been seen that within-field soil variations which correspond to significant, substantial changes in physical conditions for crop development, are related to the classes derived from the sequences of yield maps - even where the yield patterns are not consistent from one season to the next.

   1.1. This variability of the soil may be expressed in terms of contrasting soil series or phases within series or more subtle differences in topography as seen at Chicksands.

   Soil series may well express soil variation which is important for crop performance (e.g. Ogunkunle and Beckett, 1988; Lark *et al.* in press), although some studies have *not* found substantial yield variation explained by soil differences at this level of classification (Webster *et al.*, 1977). It may well be that the important soil variations within a field occurs within the series. From the fields observed here we would expect that a clear relationship between the classes defined by analysis on the yield maps, and soil series in a field will only occur when there are distinct differences between the series with respect to soil physical properties such as depth to bedrock or water retention characteristics.

   1.2. Variation in individual soil physical properties are reflected in the results of the yield map analysis.

At Cirencester there was not a simple correspondence between the classes defined from yield maps and soil series, but both accounted for significant variation in soil properties (AWC and depth to parent material). (Note that AWC gives a general indication of the soil's capacity to supply water to the crop, but does not necessarily represent the amount of water available to the crop during the critical periods of development).

2. Among the fields studied in this project, where yield variation is small and/or is limited to short spatial intervals, this is also true of the soil variability. It is interesting, for example, to contrast the sample variances of soil depth to parent material and available water capacity at the Cirencester site (617.0, 344.5 respectively), with the corresponding statistics for the Andover site (190.0, 30.2 respectively), and in the light of this difference to compare the multivariate variograms for their yield maps in Figure 2.13. The greater variability of the soil properties at Cirencester appears to be reflected in a markedly less flat variogram.

What are the implications of our findings for the practice of precision agriculture?

Firstly, in some conditions, soil and yield variation are either so limited or so spatially complex that a management respond to the variation is unlikely to be feasible. Uniform rates for inputs probably correspond to a risk-averse strategy.

Secondly, soil variation appears to underlie the important variations in crop yields, where these occur, but soil series are not necessarily the best means of describing this variation.

Thirdly, variation in soil properties - where this is substantial may be related to differences between the classes defined from yield maps (Chapter 2) or to topographic variation.

The rational farmer will therefore want to consider the possibility that his field has spatial variation which should influence its management but will not want to invest immediately in a detailed map of the field, examining a number of soil properties. He will proceed in stages, addressing successive questions about the variability, thus:

i) *Is there substantial variation in the yields from this field and does it occur at spatial scales at which a management response is feasible ?*

The multivariate variogram has been introduced in this project to quantify the magnitude and spatial scale of variation exhibited in a sequence of yield maps. If the information presented in Figure 2.13 can be added to in further research, then it may be possible to derive rules whereby analysis of one or more yield maps allows the field to be identified as "effectively uniform" or "variable but with an intricate short range pattern best regarded as uniform" or "significantly variable with variation at a scale which can be managed". This is done without any investment in soil surveying or analysis. If substantial variation occurs at a workable spatial scale, then it is worth proceeding to the next question.

ii) *Does this variation in yield reflect factors to which a response is possible*?

The classification approach to analysis of yield maps, described in Chapter 2, is relevant here. If the analysis generates distinct classes with a clear spatial structure then investigation of the causes of yield variation may be possible. Limited, targeted field work can be undertaken to try and identify the important soil factors which differ between the classes and which may explain their definitive season-to-season patterns of yield variation. This may involve some sampling and identification of soil type at locations within the classes. Non-soil causes of variation may also be identified at this stage, such as the spatial distribution of persistent weed patches, or evidence of grazing damage in particular parts of the field.

iii) *What information is needed to manage the variation in this field and how can it be collected most cost-effectively?*

The phase of investigation at (ii) above should indicate any factors (e.g. soil pH, available water) which appear to underlie the yield variation. It will also show whether soil series are a useful framework for collecting and interpreting information relevant to yield variation. It may be that certain factors need to be investigated with greater detail only in limited parts of the field.

Soil series might be mapped or, alternatively, edaphological classes corresponding to single or multiple soil variables which the investigations in (ii) suggest capture the critical soil variations from the point of view of crop production in that particular field.

It may also be necessary to map certain soil properties. To this end, the possibility of using predictive models based on yield or topographic data is worth considering in future research, since these may maximise the value of costly soil samples and analyses. Remote sensor data may also be useful. These methods can be used, in conjunction with geostatistical methods, to map specific soil properties. The spatial analysis of yield and available water at the Andover site has indicated one way in which yield data could be used to improve the precision with which particular soil properties are mapped. The important point is that, by the time the farmer is investing in this level of detailed soil information, he will be confident: a) that it is justified by the degree and scale of yield variation; and b) that there is good reason to investigate the particular soil properties which he is paying to have sampled and analysed.

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REFERENCES

Aitchison, J., 1986. *The statistical analysis of compositional data.* (London: Chapman and Hall).

Bourgault, G. and Marcotte, D., 1991. Multivariable variogram and its application to the linear model of coregionalization. *Mathematical Geology* **23,** 899-928.

Burton, R.G.O. 1989. The Soils of Boxworth Experimental Husbandry Farm. Soil Survey and Land Research Centre, Cranfield.

Cosser, N.D., Wood, G.A., Earl, R. and Godwin, R.J. 1997. *Management Guidelines for Precision Farming.* First Interim report to Home Grown Cereals Authority.

Hodgson, J.M. 1997. *Soil Survey Field Handbook.* Technical monograph No. 5, Soil Survey and Land Research Centre

Jarvis, M.G., Allen, R.H., Fordham, S.J., Hazelden, J., Moffat, A.J. and Sturdy, R.G. 1984. *Soils and their Use in South East England.* Soil Survey Bulletin No. 15.

Lark, R.M. 1998. Forming spatially coherent regions by classification of multivariate data. *International Journal of Geographical Information Science.* **12,** 83-98.

Lark, R.M. and Stafford, J.V. 1997. Classification as a first step in the interpretation of temporal and spatial variability of crop yield. *Annals of Applied Biology.* **130,** 111-121.

Lark, R.M., Stafford, J.V. and Froment, M.A. 1997. Exploratory analysis of yield maps of combinable crops. Precision Agriculture '97. Volume II: Technology, IT and Management. 887-894. BIOS Scientific Publishers Ltd,Oxford, UK

Lark, R.M., Catt, J.A. and Stafford, J.V. Towards the explanation of within-field variability of yield of winter barley: soil series differences. *Journal of Agricultural Science.* (In Press).

McBratney, A.B. and Moore, A.W., 1985. Application of fuzzy sets to climate classification. *Agricultural and Forest Meteorology.* **35,** 165-185.

McBratney, A.B. and Pringle, M.J. 1997. Spatial variability in soil - implications for precision agriculture. *Precision Agriculture '97. Volume I: Spatial Variability in Soil and Crop* pp. 3 - 31. Oxford, BIOS Scientific Publishers Ltd.

Ogunkunle, A.O. & Beckett, P.H.T. 1988. Combining soil map and soil analysis for improved yield prediction. *Catena* **15**, 539-553.

Stafford, J.V., Ambler, B., Lark, R.M. and Catt, J. 1996. Mapping and interpreting the yield variation in cereal crops. *Computers and Electronics in Agriculture* **14**, 101–109.

Tukey, J.W. 1977. *Exploratory data analysis.* Addisson Wesley, Reading MA.

Webster, R., Hodge, C.A.H., Draycott, A.P. & Durrant, M.J. 1977. The effect of soil type and related factors on sugar beet yield. *Journal of Agricultural Science, Cambridge* **88**, 455-469.

Wright, P.S. 1984. Soils of Lodge Farm, Chicksands, Bedfordshire. Soil Survey and Land Research Centre, Cranfield.