CHAPTER 3

MEASUREMENT OF SOIL PROPERTIES IN VERTISOLS

3.1 INTRODUCTION

The physical behaviour of vertisols is governed by swelling, which in turn affects the measurement of many physical properties. To account for the effects of swelling in the measurement of these properties, it is necessary to understand the mechanism of swelling, its magnitude, and the range of water contents over which swelling occurs. These factors are outlined in following sections.

Variability in soil properties is a widely recognized problem. Cracking in vertisols leads to large short range variability. A knowledge of the influence of this short range variability on measurements taken over an experimental site is important when interpreting the measurements and extrapolating experimental findings to commercial farms. The increase in the power of computers available to researchers has permitted mathematical description of soil variability. Recently developed techniques for describing soil variability are outlined in Section 3.3, together with methods of assessing optimum sample size, and statistical techniques for summarizing profiles of soil properties.

3.2 SOIL SWELLING AND MEASUREMENT OF SOIL PROPERTIES

In measurement of soil properties, the solid phase is conventionally used as a rigid frame of reference. In swelling soils, this frame of reference is not rigid. Relative movements within swelling soils lead to measurement errors, especially when factors such as water and nitrate content are integrated over the profile.

3.2.1 Mechanism of swelling and its relationship to sampling

The plate-like crystals (lamellae) of most clay minerals in soils are arranged in packets or domains (Marshall and Holmes, 1979). Swelling of these clay domains does not contribute greatly to swelling of agricultural importance. For example, the maximum expansion of Ca-montmorillonite domains to a lamella separation of 2 nm is completed at low water potentials of between -2000 and -3000 kPa (Norrish, 1954). McIntyre *et al.* (1982) postulated that swelling at potentials above those for maximum inter-lamellar separation is due to association of water with cations in force fields between clay domains. Swelling of soil aggregates is approximately isotropic as the clay domains, and thus inter-domain spaces, are randomly oriented in the soil (Quirk and Aylmore, 1971).

Normal swelling is defined as occurring when the change in soil volume equals the change in water volume (Figure 3.1). The nature of normal swelling is not affected by the type of soil cations (Yule and Ritchie, 1980a), but replacement of sodium by calcium will reduce unconfined swelling at very high potentials (Bridge and Tunny, 1973), as separation distance of sodium, but not calcium, saturated clay crystals at high water contents is unlimited (Quirk and Aylmore, 1971). This difference occurs as divalent, but not monovalent, cations are able to 'bridge' charges on two adjacent clay surfaces (Emerson, 1983), increasing the attraction between the clay crystals sufficiently to limit separation between them.

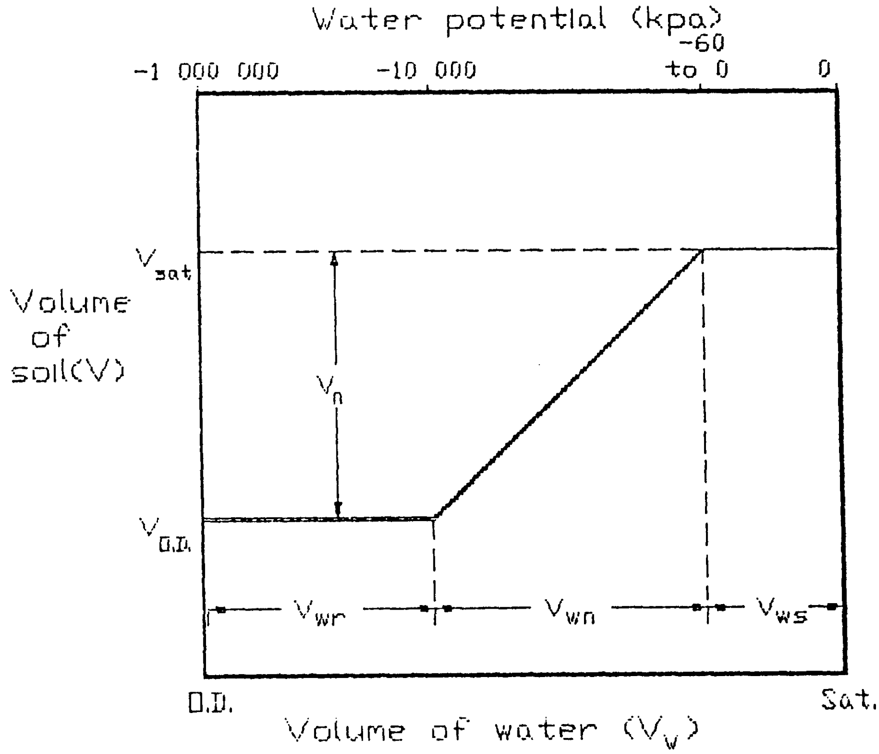

Figure 3.1 The stages of water gain and loss: residual (oven dry (-1 000 000 kPa) to shrinkage limit (-10 000 kPa)), normal (shrinkage limit to swelling limit (-60 to 0 kPa)), and structural (wetter than swelling limit) as postulated by Yule and Ritchie (1980a). (Shrinkage limit water potential from Holmes (1955), Swelling limit water potential range from Yule (1984); s = structural, n = normal, r = residual).

The swelling limit (Figure 3.1), above which Yule (1984) claimed that no swelling occurs, has been calculated by McIntyre (1984), and Yule (1984) to be -30 kPa. Bridge and Ross (1984) reported published values for the swelling limit to range from -60 to 0 kPa. At soil water potentials higher than the swelling limit (structural shrinkage phase), larger intrapedal, and particularly interpedal, pores begin to fill. The water in these larger pores, known as structural water, is not in the force fields arising from cations and clay surfaces, and does not cause any swelling (McIntyre and Sleeman, 1982). A more recent description by McGarry and Malafant (1987) (Figure 2.3) indicates that some volume change occurs in the structural shrinkage phase.

The relationship between field bulk density and gravimetric water content has been classified by Fox (1964) as being either three-dimensional or unidimensional. When a soil is undergoing three-dimensional swelling or shrinkage, soil movement occurs in both horizontal and vertical planes (three dimensions). However, sampling detects swelling or shrinkage only in the vertical plane, as the sample includes vertical fissures, but not the horizontal planar void created by changes of surface height with soil water content. In this case, Fox (1964) postulated that field bulk density (ρ_{b3D}) at a given water content θ_g is given by:

$$\rho_{b3D} = \rho_{bmin} / [(\rho_{bmin} / \rho_s) + (\theta_g * \rho_{bmin}) + \varepsilon_{amin}]^{0.33} \qquad 3.2.1$$

where ρ_{bmin} is the fully swollen bulk density, ρ_s is the particle density, and ε_{amin} is air filled porosity in the fully swollen soil.

Unidimensional swelling was said by Fox (1964) to occur when the soil could no longer expand horizontally, but only along the vertical axis (one dimension). In this case, ρ_{b1D} at a given θ_g is given by:

$$\rho_{b1D} = 1 / [(1 / \rho_s) + \theta_g + (\varepsilon_{amin} / \rho_{bmin})] \qquad 3.2.2$$

Any sample which contains no interpedal cracks or fissures will follow a unidimensional shrinkage/swelling curve.

Many researchers believe that normal shrinkage observed in the field is three-dimensional and equidimensional (Berndt and Coughlan, 1977; Yule and Ritchie, 1980a; McIntyre *et al.*, 1982; Bridge and Ross, 1984). Fox (1964) also invoked three-dimensional shrinkage for all but his wettest samples, for which he claimed the unidimensional shrinkage model was appropriate. The majority of evidence for three-dimensional shrinkage in the field comes from observation of a ratio of 3:1 of profile water loss to reduction of surface height. If the soil was shrinking unidimensionally, the ratio would be 1:1. Yule and Ritchie (1980b) acknowledged that the observation of the 3:1 ratio is confounded to some extent by the occurrence of structural water loss, during which shrinkage is less than normal, in some layers of the profile when surface height measurements are recorded.

A major problem in the sampling of swelling soils is whether or not a representative volume of cracks is included in the sample. The extent of crack sampling will have a large influence on values of volumetric measures, particularly in dry soils. Chan (1981) observed that 75 mm diameter core samples taken at depths greater than 0·3 m followed the unidimensional relationship, whereas samples from depths shallower than 0·3 m followed the three-dimensional relationship. He noted that structural units in the 0·3 to 0·5 m layer may be 0·3 m in any direction, implying that accurate samples from this layer would need to be of the order of 0·3 m diameter.

Large scale sampling with 0·3 m diameter cores is clearly impractical. Alternative methods of sampling and data manipulation will be considered in the following sections.

3.2.2 Accounting for swelling in measurement of soil properties

Yule (1984) and Bridge and Ross (1984) have demonstrated that errors of 30% and greater can occur in estimates of changes in integrated profile water contents if swelling is ignored. This error arises from failure to sample cracks in dry profiles, leading to overestimation of water content and soil density. To date, however, swelling has largely been ignored in measurements on swelling soils.

Correction to fully swollen density

In discussing methods of improving sampling techniques in swelling soils, Chan (1981) advocated, as an alternative to the use of very large samples, volumetric sampling only when the soil is in a fully swollen soil state. As a fully swollen soil contains no cracks, problems of crack sampling are avoided by this procedure.

Yule (1984) and Bridge and Ross (1984) extended the approach of Chan (1981) by taking volumetric samples from a fully swollen soil, then, using the three-dimensional shrinkage relationship of Fox (1964), calculated volumetric water content for drier soils corrected to fully swollen density from measured θ_g. Bridge and Ross (1984) presented five methods of estimating profile water content. In their preferred method, the fully swollen height equivalent to the dry height sampled for each depth increment is calculated using the three-dimensional shrinkage relationship of Fox (1964). The procedure, which aims at calculating water capacity for the same mass of soil in wet and dry profiles, is illustrated in Figure 3.2 and achieved by the following steps:

i) Sample a fully swollen core of wet soil (wet, Figure 3.2) to determine $\rho_{b_{min}}$, $\varepsilon_{a_{min}}$ and ρ_s.

ii) Sample a core of dry soil (dry sampled, Figure 3.2), section it into the the same lengths sampled in the wet soil and determine θ_g for each core sample.

iii) Calculate ρ_{b3D} for each section of the dry sampled core by substituting the values determined above into equation 3.2.1.

iv) Calculate the fully swollen height equivalent to the dry sampled core by multiplying the measured length of each core section by: $\rho_{b3D} / \rho_{b_{min}}$. This gives the adjusted dry core of Figure 3.2.

v) Calculate water capacity of each adjusted core section by multiplying the adjusted height by θ_v corrected to fully swollen density ($\rho_{b_{min}} * \theta_g$).

vi) Calculate corrected profile water capacity by accumulating water capacity of equal heights from the surface in the wet and adjusted dry profiles, and discard excess soil from the base of the adjusted dry core (Figure 3.2).

A limitation of the method recommended by Bridge and Ross (1984) is that it ignores the structural shrinkage phase (Figure 3.1). This is despite the evidence of structural shrinkage presented by Smith (1959), Berndt and Coughlan (1977), Yule and Ritchie (1980a), Chan (1982) and McIntyre *et al.* (1982). If the water content range contains the structural shrinkage phase, failure to account for structural shrinkage will lead to an overestimate of the difference in water content between corrected and uncorrected profiles. The size of this error will depend on the slope of the shrinkage during the structural shrinkage phase, which can vary from 0·1 to 0·8 (McGarry and Malafant, 1987a).

Ross (1985) attempted to overcome this limitation by developing a relationship between density of soil sampled between cracks (ρ_{ba}) and shrinkage assuming three-dimensional, but not necessarily normal shrinkage. This relationship is given by:

$$\Delta x / \Delta X = (\rho_{b_{min}} / \rho_{ba})^{0.33} \qquad 3.2.3$$

where Δx and ΔX are dry and fully swollen heights of the layer being sampled respectively, and $\rho_{b_{min}}$ is the fully swollen reference density. However, this relationship assumes that no shrinkage cracks are sampled in wet or dry samples, which is in contrast to the observations of Chan (1981) for depths shallower than 0·3 m (Section 3.2.1).

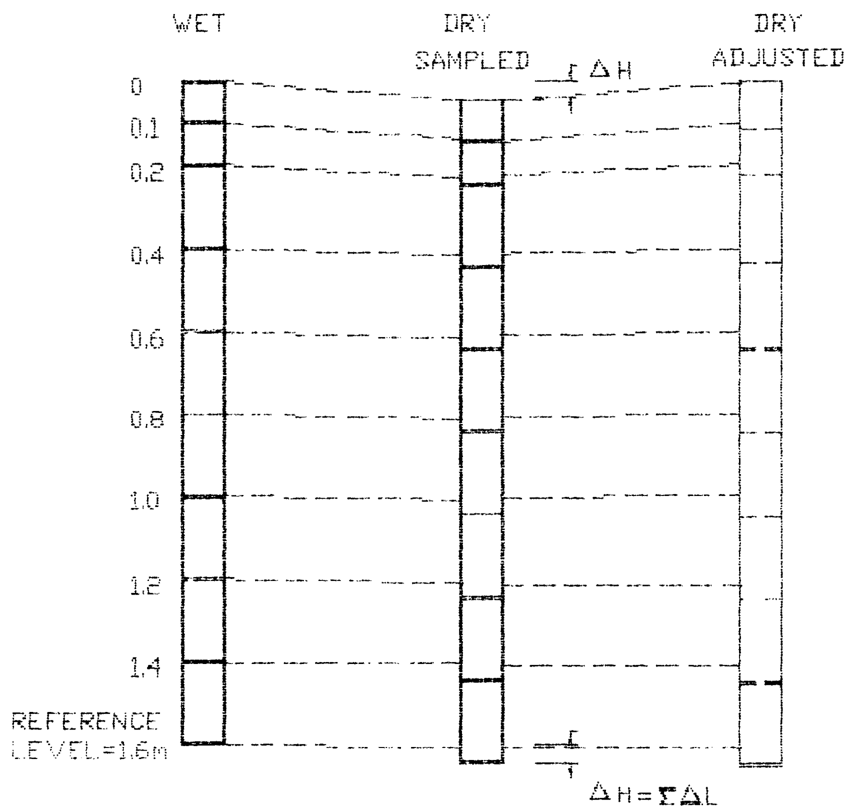

Figure 3.2 Changes in soil height (ΔH) between wet and dry profiles of Cunnanurra clay, together with soil height adjusted from dry sample to fully swollen height according to the preferred method of Bridge and Ross (1984). Dashed lines show layers of the same soil mass (after Bridge and Ross, 1984).

The difficulty in defining fully swollen density limits the application of both methods outlined above. Talsma and van der Lelij (1976) and McIntyre *et al.* (1982) have independently shown that swelling at 0·8 m is not complete after 120 days continuous ponding. However, Ross (1985) stated that it is important that fully swollen density and water content be measured in the field, as overburden pressure constrains swelling of deeper soils, leading to the possibility of erroneous results from samples wet up in the laboratory.

Correction of soil measurements to fully swollen density will improve the accuracy of measurements in swelling soils over those measurements for which no corrections are made. However, uncertainty about the precise relationship between water content and shrinkage, particularly at water potentials above -50 kPa, limits the reliability of the corrected measurement.

Material coordinates

The occurrence of swelling implies that a conventional linear depth scale does not include a constant mass of soil as water content varies. Consequently, a new physical scale of depth measurement has been developed. Smiles and Rosenthal (1968) used a material coordinate, m, which defines planes between which the mass of the solid phase is conserved. They expressed m as the integral:

$$m = \int_0^x (1 / (1 + e))dx \qquad 3.2.4$$

where e is the void ratio, and x is the conventional scale of physical length.

McGarry and Malafant (1987b) have modified the material coordinate of Smiles and Rosenthal (1968) by scaling it using particle density, to give a mass coordinate M(z). Their material coordinate is defined by the integral:

$$M(z) = \int_0^z (m_s)dz \qquad 3.2.5$$

where m_s is the mass of solids for each depth interval, and M(z) is the accumulated mass of solids per unit area. This mass coordinate was used to describe changes in soil water profiles by McGarry (1987).

The material coordinate system of Smiles and Rosenthal (1968) has been criticized by Sposito *et al.* (1976) who claimed that the assumption of constant particle density for all depths is inapplicable to field profiles. Sposito *et al.* (1976) preferred the material coordinate system of Raats and Klute (1969), which uses the state of porosity of the soil at some arbitrary time for a material coordinate. Although reservations regarding constant particle density at all depths are valid in many soils, use of an arbitrary value as scale of reference limits application of the material coordinate system proposed by Sposito *et al.* (1976).

Philip and Smiles (1969) claimed that the material coordinate system of Smiles and Rosenthal (1968) can successfully describe structural, normal and residual shrinkage. However, Smiles and Rosenthal (1968) stated that their system describes a soil confined in the horizontal plane, but free to swell vertically. Consequently, sampling to define soil properties in this material coordinate system should be large enough to include a representative sample of vertical cracks. In the worst case, if the sample contained no shrinkage cracks, and the soil was shrinking normally, the material coordinate system would predict a surface height change according to a unidimensional shrinkage relationship, which is three times that measured by Yule and Ritchie (1980a), who invoked a three-dimensional shrinkage relationship.

Conclusions

Models of swelling behaviour outlined above have been developed mainly from laboratory studies. Little data have been collected measuring swelling behaviour of soil layers in the field, apart from that obtained by McIntyre *et al.* (1982), who measured swelling in a moderately swelling soil, and Aitchison and Holmes (1953), who measured the extent of swelling in a number of clay soils, but had only limited measurements of water content. Collection of further data would provide an objective basis for selecting swelling corrections, and improve confidence with which swelling corrections are used.

Bridge and Ross (1984) and Yule (1984) have demonstrated that large errors can occur if swelling is ignored. Therefore shortcomings in the current methods of correcting for swelling are insufficient reason to ignore swelling until a fully satisfactory method of sampling and correcting for swelling is developed and tested.

Correction for swelling is particularly important for integrated soil water capacity. Material coordinates, as outlined by Smiles and Rosenthal (1968) and modified by McGarry and Malafant (1987b), offer a coherent framework to which soil measurements can be related, and are theoretically the most sound procedure considered. However, the failure of material coordinates, in their present form, to resolve the problem of crack sampling limits the application of material coordinates when applied to field sampling.

Correction of soil measurements to a fully swollen profile, as applied by Yule (1984) and Ross (1985), implies the use of a material coordinate because the fully swollen (wet) and adjusted profiles should contain the same mass of soil (Figure 3.2). The material coordinate, on the other hand, uses the mass of soil in each sample as a frame of reference. Accuracy of correction to a fully swollen profile, either as outlined by Ross (1985) or by Yule (1984), and applied by Hodgson (1986), is limited by difficulties of determining the properties of a fully swollen soil, and uncertainty about the changes from the fully swollen state to the swelling limit. Despite these difficulties, it appears that correction to fully swollen density is the most appropriate of current theories, as errors introduced by them would introduce smaller errors than the crack sampling problems of the material coordinate approach.

Although swelling should be accounted for in measurement of profile soil water capacity , it may be safely be ignored when relating soil water content to some other soil physical measures. For example, measurement of penetration resistance is of little value if recorded from soil cracks. Consequently, it is more useful to relate penetration resistance to density and water content of the soil matrix than to properties of the soil as a whole.

A similar argument to that used for penetration resistance could be applied to soil water content and water potential measurements within a layer. For these measurements, the plant responds to conditions within the soil matrix rather than to a volume containing the macropores not included in small samples.

3.3 STATISTICAL METHODS USED IN DESCRIPTION OF SOIL PHYSICAL PROPERTIES

The presence of field variability in soil properties is a constant concern to those involved in soil research and soil management. Variability in experiments can be reduced by controlling the environment as closely as possible, to the extent that research is often conducted on carefully prepared soil in a laboratory or glasshouse. However, Trugdill (1983) pointed out that this reductionist approach to experimental work limits the application of the findings of that work in complex field situations. As the ultimate aim of most soil research is to either explain phenomena observed in the field, or predict the response in the field to a given set of circumstances, field variability is a problem we must account for, rather than one we should try to avoid.

The problem of variability of soil properties increases the importance of statistics in determining the reliability of measurements of these properties. Recent advances in solid state electronics have facilitated the ready collection of large data sets using instruments such as the recording penetrometer and the neutron moisture meter. At the same time, powerful computers are becoming more accessible to researchers, allowing use of statistical techniques previously inapplicable because of their complex and computationally inefficient nature. Techniques which are becoming more widely used include the description of spatial variability and multivariate analyses.

In consequence, rapid advances are being made in the application of statistics to description of the distribution and variation of soil properties. The researcher wishing to use new techniques, such as geostatistics, is thus confronted with the difficulty of choosing from a number of techniques which are embryonic in their application to soil problems, those which show the data set in the most favourable light (Warrick *et al.*, 1986). In this situation, there is a temptation to choose a technique based on whether or not its application to a data set proves a preconceived theory. The following discussion outlines some of the more recently developed statistical techniques applicable to description of soil properties in a field experiment.

3.3.1 Methods assuming spatial independence

Soil variability has long been recognized as an important factor in the design of field experiments. McBratney (1985) claimed that R.A. Fisher's great agronomic achievement in the nineteen twenties was to find a technological solution to the problem of soil variability in field experiments. Through randomization and blocking, Fisher removed, without estimating, the effects of soil and other uncontrolled environmental variables.

Fisher's approach, which has largely stood the test of time, is to use analysis of a uniformity trial to allow the researcher to cope with soil variability by making a choice of plot size and shape, block size and shape, and number of replicates (Nielsen and Biggar, 1985). In a uniformity trial, measurements of plant growth and yield are made at a number of locations in a uniformly treated area; the treatments to be investigated are imposed after analysis of the uniformity trial. Experimental results are typically subjected to analysis of variance (ANOVA) or regression analysis. The results are considered 'positive' if the variance attributed to treatment variables is significantly greater than the variance within each treatment, and 'negative' if this is not the case. A 'negative' result occurs if the treatments do not alter the dependent variable, or if variability of soil and other factors within a treatment is greater than treatment differences.

Application of classical analysis is straightforward where measurements are taken on one factor on one occasion. In studies of soil-plant relations, we are normally interested in soil measurements of a profile to a given depth rather than measurements at a single depth. We are also interested in the shape of the profile of measurements, as well as the integrated, or average value of the measurement for the whole profile. Description of profile variation is a topic within the general field of pattern analysis. Russell and Moore (1976) felt that application of pattern analysis at the soil-plant interface was confronted with formidable problems. Despite these problems, the advantages of summarizing the data for a profile justifies efforts in the application of pattern analysis.

Analysis of soil measurements taken at successive depths is complicated by the dependence between observations at successive depths, and differences between the variances for a range of depths. These features preclude the use of split plot ANOVA in analysis of profile measurements. The observations at each depth are often analysed separately, but, as Roberts and Raison (1983) pointed out, trends through the profile cannot be detected in this way, and interpretation is made difficult by the large number of analyses and tests of significance necessary. The use of multivariate analysis of variance (MANOVA), in which the observations at successive depths are regarded as repeated measures, is applicable as it provides tests of the treatments averaged over depths, and tests of trends with depths.

Roberts and Raison (1983) used a method similar to repeated measures MANOVA to describe variation of a property within a profile using orthogonal polynomials to describe treatment contrasts in measurements obtained from a soil profile. Treatment contrasts (Q) are linear functions which show the magnitude of treatment differences, and are defined (Steel and Torrie, 1980) by:

$$Q = \sum c_i Y_i \quad \text{with} \quad \sum c_i = 0 \qquad 3.3.1$$

where Y is treatment total or treatment mean for i treatments, and c is a coefficient which is normally an integer. Orthogonal polynomials are equations such that each equation is associated with a power of the independent variable, for example X, X^2, X^3, and all equations are pairwise uncorrelated or orthogonal (Steel and Torrie, 1980). Use of orthogonal polynomials permits independent testing of the variance contribution of each term in the regression (Moore *et al.*, 1972), giving criteria for decisions on which coefficients can be dropped to conserve error degrees of freedom in MANOVA tests. The use of treatment contrasts rather than absolute values reduces the order of polynomial needed to describe treatments. Reduced polynomial order simplifies the form of the fitted profile, which reduces the complexity of the polynomial to be interpreted, and conserves error degrees of freedom in the MANOVA.

Changes in profiles of soil attributes over time are often of interest, such as when relating changes in soil properties with stages of crop growth during the growing season. For example, the profile description methods of Roberts and Raison (1983) can be combined with analysis of measurements over time, described by Evans and Roberts (1979), to give a description of changes in soil water profiles over time. This analysis permits description of the size of treatment effects through differences in the overall treatment means, and differences in the profiles of each treatment, as well as changes over time, by the polynomial coefficients. One disadvantage in the description of treatment effects by polynomials, is that one cannot determine from this analysis, either the depths or the times at which treatments are different.

All the techniques described above rely on assumptions that the relationships observed are constant over a field, and that the measurements are spatially independent. If these two assumptions are not met, doubts arise regarding application of results from one experimental site to the entire field (Nielsen and Biggar, 1985). The problem of determining whether a field should be treated or monitored uniformly or nonuniformly is addressed in the following sections.

3.3.2 Geostatistics

Geostatistics has commonly been defined as the application of the 'Theory of Regionalized Variables' to the study of spatially distributed data (Journel, 1986). Although it was developed to improve precision of estimates of ore reserves, geostatistics has a part to play in field experimental design because of its ability to quantitatively describe soil and crop variation and covariation, and to perform block predictions and copredictions (predicting the distribution of one variable from distribution of a second variable and the covariation between the two variables (McBratney, 1985)).

Many recent reports have shown that observations of measurements of soil properties have spatial structure in their variation (Burgess and Webster, 1980; Burgess *et al.*, 1981; Gajem *et al.*, 1981; Lanyon and Hall, 1981; Vieira *et al.*, 1983; Webster and Burgess, 1983; Greminger *et al.*, 1985; Nielsen and Biggar, 1985; Wierenga, 1985; Laslett *et al.*, 1987). Examples where no such spatial structure was observed are much less common (Vauclin *et al.*, 1984; Dane *et al.*, 1986).

Spatial structure of variation limits application of analysis of variance, which assumes that observations are statistically independent (Steel and Torrie, 1980). Variation in observed relationships throughout a field also limits the application of classical statistics. Russo (1984) illustrated this limitation with his study on the relationships between soil electrical conductivity (EC), soil water pressure potential (ψ_p), and yield of trickle-irrigated bell peppers (*Capsicum frutescens* 'Maor'). He found, in areas of the field where the radius of the constant saturated zone was less than 0·05 m, that ψ_p and EC accounted for more than 80% of the variation in crop yield. In areas of the field where the constant saturated zone had a radius greater than 0·08 m, factors other than ψ_p and EC controlled yield. In this situation, results from one part of the experiment are not applicable to the whole experiment as is assumed when using classical statistics.

The techniques most commonly used in determining the spatial structure of soil variation are autocorrelation analysis and variogram analysis. A specialized terminology is associated with these techniques. To clarify discussion, definitions of the more commonly used terms are presented here:

Drift: global mean of the difference between measurements (equals zero if the assumption of constant mean is satisfied).

Intrinsic assumption: a random function is intrinsic when the mean exists and does not depend on the position of the observation; the variance of the differences depends on the separation distance between two points, but not their location (McBratney and Webster, 1986).

Lag: separation distance between a pair of observations.

Nugget: the limiting value of semivariance as the lag approaches zero.

Range: for variables which are distributed with a transitive semivariogram (Table 3.1), the lag at which measurements become spatially independent.

Second order stationarity: a random function is stationary of order 2 when:

(i) the mean exists, and does not depend on the position of the observation.

(ii) for each pair of random variables, the covariance function exists, and depends on the lag (Vieira et *al.*, 1983).

Semivariance: the expectation of the variance per site when the sites are considered in pairs.

Semivariogram: graph of semivariance against separation distance.

Sill: for variables which are distributed with a transitive semivariogram, a constant value of the semivariance for lags greater than or equal to the range.

Stationarity: a variable is stationary if the statistics on the random variable are constant throughout the population. According to the number k of statistical moments that are constant, the variable is called stationary of order k (Vieira *et al.*, 1983). The assumption of stationarity is common to all statistics (Srivastava, 1986).

Transitive model: semivariance increases with increasing lag to some maximum (Sill), at which it remains with further increase in lag.

Unbounded model: semivariance increases with lag without limit.

Application of autocorrelation analysis is limited as there are analytic difficulties in two dimensions, and second order stationarity in a moderately strong form is required (Gajem *et al.*, 1981) It will not be considered further in this discussion. Variogram analysis relaxes the stationarity conditions, is computationally simpler than autocorrelation analysis, and is thus more widely used.

Variogram analysis

If the intrinsic assumption (the mean of a soil observation is constant for all locations, and the variance between observations depends only on their separation distance) is satisfied, there is no underlying mathematical relation between the soil and its position on the ground (Webster and Burgess, 1983). Instead, relationships are expressed in terms of separation (*h*) regardless of absolute position. Using this assumption, the semivariance ($\gamma(h)$) is defined for a set of values $Z(x_1), Z(x_2),..., Z(x_i)$ by:

$$\gamma(h) = {}^1\!/\!_2 E\{[Z(x) - Z(x + h)]^2\} \qquad 3.3.2$$

which is estimated by:

$$\gamma^*(h) = {}^1\!/\!_2\, N(h) \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad 3.3.3$$

The semivariogram is the most important single tool in the application of geostatistics to soil science. Despite this importance, there is no efficient way of calculating confidence intervals for semivariance (Burgess and Webster, 1980; McBratney and Webster, 1986). Dane *et al.* (1986) have postulated that the bootstrap technique, described by Efron and Gong (1983), although computationally inefficient, could be used to estimate confidence intervals for the semivariogram. In the absence of estimates of the precision of the semivariogram, Burgess and Webster (1980) recommended performing spatial analysis on long runs of data, or numerous short runs, so that errors in estimating the semivariogram are minimized, particularly for short lags.

The mathematical form of the fitted semivariogram must be such that it is conditional, negative, semidefinite (CNSD) (McBratney and Webster, 1986). The term CNSD refers to properties of the covariance matrix of points of the fitted semivariogram, with the result that a CNSD function can never predict negative semivariance. The most commonly used models which satisfy this criterion are shown in Table 3.1, and some are also illustrated in Figure 3.3. McBratney and Webster (1986) outlined procedures for selecting the appropriate semivariogram, including corrections to allow for anisotropy in the semivariogram.

Table 3.1 Examples of simple authorized functions used to describe semivariograms where h is lag, a is range, r is spatial scale analagous to range, c_0 is nugget variance and $c_0 + c$ is sill variance (from McBratney and Webster, 1986).

Model	Lag values	Semivariogram function
Transitive with sill		
Linear with sill	0	$\gamma(h) = 0$
	$0 < h < a$	$\gamma(h) = c_0 + c(h / a)$
	$a < h$	$\gamma(h) = c_0 + c$
Circular	0	$\gamma(h) = 0$
	$0 < h < a$	$\gamma(h) = c_0 + c\{1 - (2/\pi)\mathrm{Cos}^{-1}(h / a) + (2h / \pi a)(1 - h^2 / a^2)^{0.5}\}$
	$a < h$	$\gamma(h) = c_0 + c$
Spherical	0	$\gamma(h) = 0$
	$0 < h < a$	$\gamma(h) = c_0 + c\{3h / 2a - (1/2)(h / a)^3\}$
	$a < h$	$\gamma(h) = c_0 + c$
Exponential	0	$\gamma(h) = 0$
	$0 < h$	$\gamma(h) = c_0 + c\{1 - \exp(-h / r)\}$
Unbounded		
Fractional	0	$\gamma(h) = 0$
Brownian	$0 < h$	$\gamma(h) = c_0 + (1/2)h^{\theta}$

Variables which follow a transitive semivariogram (Table 3.1) satisfy the criterion of second order stationarity within the lags covered by the semivariogram. The range of the transitive semivariogram marks the minimum lag for which the stationarity assumptions of classical statistics hold. Conversely, if the semivariogram is unbounded, the stationarity and independence assumptions of classical statistics are never satisfied.

A large number of samples is required to accurately ascertain the form of the semivariogram. McBratney and Webster (1986) questioned whether accurate semivariogram estimates are obtainable from sample sizes less than 100. When determining sample size, the most important parts of the

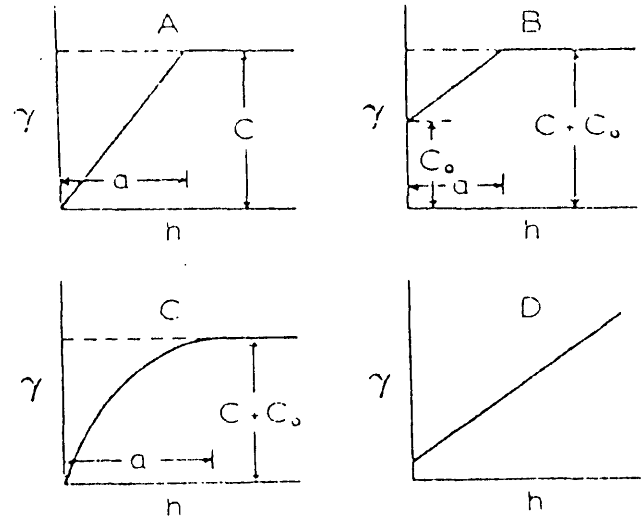

Figure 3.3 Idealized semivariograms; A is a linear model with range a and sill c, B is a linear model with range a, nugget c and sill c+c0; C is a spherical model with range a; and D is a linear model without a sill (unbounded) (from Warrick *et al.*, 1986).

semivariogram are estimation of the form of the semivariogram for lags less than the range, and estimation of the value of the sill.

The theoretical restriction that the maximum distance between points used in estimation of the semivariogram should be one quarter of the total extent of the transect (Clark, 1980), means that an *a priori* estimate of the range should be used when designing the transect. A first approximation to a semivariogram can be obtained from components of variance in a nested experimental analysis (Oliver, 1987). Alternatively, an estimate of the range could be obtained from published semivariograms. For properties such as soil texture, and horizon thickness, estimates of the range vary from 8 m (Greminger *et al.*, 1985), to 100 m or more (Burgess *et al.*, 1981). For water relations, Wierenga (1985), when summarizing the results of a number of experiments, reported variation in the range for soil water potential in flood irrigated fields of 1·2 to 27 m. For a different data set, the range for soil water content varied from 8 to 22 m, but Greminger *et al.* (1985) reported a range as small as 1 m for water content.

Factors affecting the range for soil water measurements include sampling depth, soil water status, and method of water application. It is disturbing to note that separation distance between samples also strongly influences the range (Gajem *et al.*, 1981), with the range increasing as the sample separation distance increases. Because of this correlation, the researcher can influence the range obtained from geostatistical analysis by selecting an appropriate sample separation distance. A further complication in determination of the semivariogram is that the time over which the samples are collected, and the method of physically analyzing the samples may affect the form of the semivariogram.

Variogram analysis can tolerate a small drift (variation in the mean) across the sampling site. Cressie (1986) has developed a technique to be applied in the presence of drift known as median polish kriging, in which simple geostatistical techniques are applied to residuals from a Tukey (1977) median polish. The median polish is an additive model which, when fitted to a two way table, has the form (Emerson and Hoaglin, 1983):

$$Y_{ij} = G + R_i + C_j + E_{ij} \quad 3.3.4$$

where Y is a measured value, G is a grand effect, R and C are row and column effects respectively, and E is error or residual from the fitted value. Performing the median polish is an iterative process in which the row and column median are in turn subtracted from each observation until the median of each row and column is zero (Emerson and Hoaglin, 1983). The median rather than mean is used as the median is influenced less by the presence of outliers. In median polish kriging (Cressie, 1986), a semivariogram is fitted to residuals from the median polish.

In conclusion, geostatistics provide a description of soil variability which accommodates the three spatial dimensions, and is valid under less stringent assumptions than classical statistics. Despite advances in computational techniques, difficulties in estimating the precision of the semivariogram remain a limitation to the adoption of geostatistics. Geostatistics, and similar methods taking account of spatial variability, provide a suitable framework to describe heterogeneous regions, and to explain the cause or existence of heterogeneity (Nielsen and Biggar, 1985). Classical statistics remain, however, the preferred method for observing the response of an assumed initially homogeneous region to different levels of treatments.

3.3.3 Estimation of sample size

The optimal sample size is the minimum sample size which achieves a desired level of precision. The optimal sample size will depend on measurement variability as well as spatial variability, and is different for differing soil properties. Warrick and Nielsen (1980), using data from a number of sources, quoted a range of typical coefficients of variation ((standard deviation / mean) * 100%) of 7% for bulk density to 250% for electrical conductivity. The following discussion considers the effect of variability on sample size.

The estimated optimal sample size for a given precision of measurement has a large bearing on the cost of sampling. Estimates of required sample size predicted by statistical techniques are frequently beyond the resources of a research project. However, electronic measurement devices referred to in Section 3.3 have substantially reduced the costs to the extent that it is becoming realistic to obtain estimates with the required intensity and frequency.

An alternative method of reducing total sampling cost where analysis of samples accounts for a large proportion of the total cost is bulking. The use of bulking is limited to properties which are additive, and can be determined on disturbed samples (Webster and Burgess, 1984). Using classical statistics, or if all measured variance is nugget variance, the variance of the bulked sample (σ^2_B) from randomly positioned subsamples is given by:

$$\sigma^2_B = \sigma^2 / n \quad 3.3.5$$

where σ^2 is the population variance, and n is the number of samples bulked. Where the property exhibits spatial dependence, σ^2 is similar to the kriging variance of samples taken from an identical grid (Webster and Burgess, 1984).

Using classical statistics, the approach used to estimate the required sample size is to randomly choose a number of sites, measure the property of interest at each site, and compute the sample variance (s^2) as an estimate of the population variance (σ^2). The required sample size is then estimated by Stein's two stage sample (Steel and Torrie, 1980) where the number of samples (n) is given by:

$$n = t^2_{\alpha}\, s^2 / (X - \mu)^2 \qquad 3.3.6$$

where $(X-\mu)$ is the half width of the desired confidence interval, and t_α is Student's t value at the chosen level of probability (α) and degrees of freedom equal to the number of samples used to estimate s^2.

The use of geostatistics to estimate the sample size required for a given precision may result in a much smaller sample size than that required by classical statistics (McBratney and Webster, 1983). However, the substantial cost of sampling to determine the form of the semivariogram for a given locality must be weighed against the potential savings in subsequent sampling (Webster and Burgess, 1984). As the number of data sets for which the semivariogram has been determined increase, the researcher will have information on which to base *a priori* estimates of the expected sample size (Wilding, 1985). This will reduce the number of samples needed to estimate the nature of spatial variation for a given locality to that needed to check the accuracy of an *a priori* estimate.

If a soil property exhibits spatial dependency, application of the theory of geostatistics leads to the conclusion that the sampling scheme which gives the most efficient estimate of the soil property of interest is an equilateral triangular grid (Webster, 1985). In most field situations the square grid is preferred to the triangular grid for reasons of convenience in indexing, computer management, site location and logistics, despite its slightly lower efficiency.

3.3.4 Conclusions

A coherent framework has been developed from modern statistics to describe soil variability and the relationship between soil variability and plant response. In situations where the soil variability is constant and the samples independent, orthogonal polynomials and MANOVA can be used to describe soil profiles and their changes over time, allowing trends to be extracted from large data sets.

Geostatistics allows mathematical description of the form of long range variability of physical properties in soils. Of particular relevance to this study is that description of this long range variability will assist formulation of the optimum sampling plan for soil physical properties in vertisols.

Similar estimates of the required sample size for a given precision are obtained from using both classical and geostatistical techniques if the property being studied shows no spatial dependence. Substantial reductions in estimates of required sample size can be achieved if spatial dependence is observed. However, the extra sampling needed to determine the semivariogram may outweigh the savings in subsequent sampling.

The application of the above techniques to description of soil properties is in its infancy. The time involved in performing analyses in the absence of computer software written specifically for these analyses, and the lack of familiarity of researchers with the techniques will limit their application for some time ahead.

CHAPTER 4

GENERAL DESCRIPTION OF EXPERIMENTS

4.1 INTRODUCTION

The problems and previous research leading to the establishment of the project described in this thesis, and the aims of the experiment, were presented in Chapter 1. The central part of the project is a replicated field experiment, located 8 km north of the village of Nevertire (31°52'S, 147°47'E), covering 47 ha of Field 30 of the Warren farm of Auscott Ltd. (Figures 1.1 and 4.1). Crop growth and soil properties at the site were monitored from January, 1985 until April, 1987. Crops on the site were grown using commercial management practices, although minor modifications were made to ensure that the site was treated as evenly as possible.

Safflower was grown two seasons prior to establishment of the experiment, then the field was ripped, disced, and landplaned in the eight month period between harvesting of the safflower and planting of a cotton crop (Table 4.1). These operations were carried out when the soil was dry and there was no evidence that they caused compaction or smearing. This was considered an optimum soil treatment, commonly used when preparing land for cotton after a winter crop (D. Anthony, personal communication). Tillage treatments were imposed after this cotton crop, thus permanent beds had been in place one season before the field experiment began.

The experiment was maintained at the same site for the 2 $^1/_2$ year duration of the project. This was done for two reasons. First, the question most asked by local cotton growers about permanent beds was 'How long can I leave the beds undisturbed before yields decline?' The practice of keeping beds in the one place for two consecutive seasons was not new (Beale, 1982), but leaving beds in one place for three or more seasons was rare prior to the establishment of this experiment. Consequently it was important to monitor a site at which permanent beds were maintained for as long as possible. Second, part of the data collected during the first season (1984/85) was used to characterize the spatial variability of soil moisture (Section 6.3.1). This information was then used in the design of the sampling scheme for the second cotton season studied (1986/87).

In this chapter a description is given of the design of the field experiment, the rationale for cultural practices, and the climatic and soil conditions of the experimental area.

4.2 EXPERIMENTAL DESIGN

In order to study the effects of the depth of soil disturbance on plant growth and soil physical properties, the main treatments imposed were three depths of soil disturbance prior to seedbed preparation for cotton crops. The three treatments of rip, chisel, and direct list were imposed in a randomized complete block design with three blocks (replicates) under the supervision of Mr. D. Anthony (farm manager Auscott Ltd., Warren) in May, 1984, and reimposed in April, 1986. Each plot was 90 m wide by 580 m long (5·2 ha).

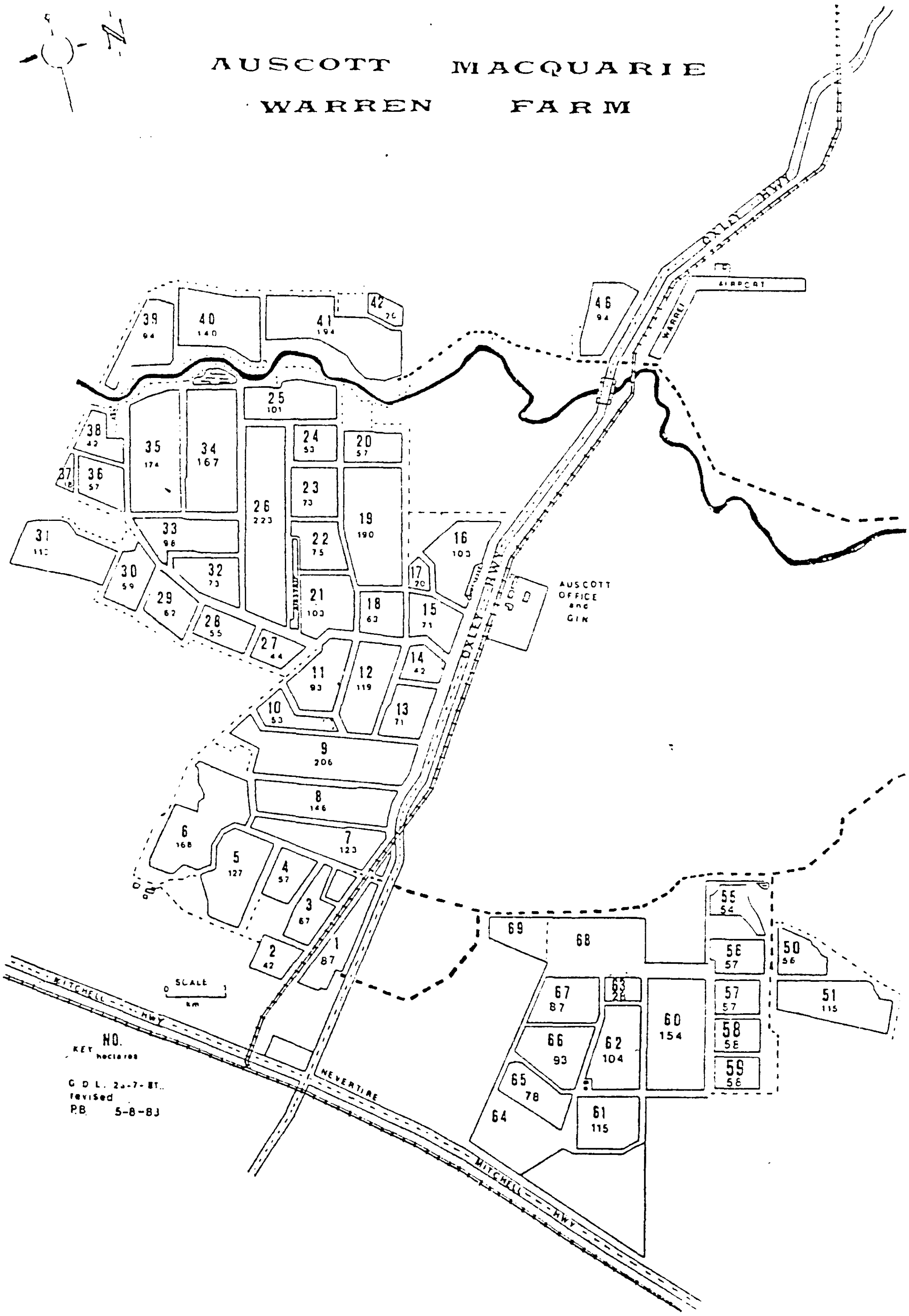

Figure 4.1 Field locations and sizes, Auscott Ltd. Warren farm (from Auscott Ltd., unpublished).

Table 4.1 Cropping, fertilizer, and seedbed preparation histories of experimental site, Field 30, Auscott, Warren.

Crop	Month planted	Fertilizer	Seedbed preparation
Safflower	July 1982	15 kg N ha^{-1} as NH_4NO_3	Planted into cotton trash
Cotton	October 1983	90 kg N ha^{-1} as NH_3	Ripped, disced, landplaned twice
Cotton	October 1984	124 kg N ha^{-1} as NH_3 8 kg N ha^{-1} as $CO(NH_2)_2$	Tillage treatments imposed
Wheat	May 1985	7 kg N ha^{-1} 14 kg P ha^{-1} as $NH_4H_2PO_4$	Planted into cotton trash
Maize	January 1986	nil	Planted into hills built with go-devils
Cotton	October 1986	80 kg N ha^{-1} as NH_3	Tillage treatments reimposed

Ripping was carried out to 0·45 m depth using tines at 1 m spacings, mounted directly to a crawler tractor by a parallelogram linkage (Plate 4.1). Chiselling depth was 0·25 m using tines at 0·3 m spacings on a trailing plough (Plate 4.2). Both deep tillage operations were carried out with the crawler driving parallel to the direction of the cotton hills. After both ripping and chiselling, the soil was ploughed to 0·15 m with heavy offset discs (discs 0·78 m diameter and 0·3 m apart) as shown in Plate 4.3. Hills and furrows were then formed using a lister. The least disruptive soil treatment was permanent beds formed by direct listing, which involved one pass with a lister to reform the hills (Plate 4.4). The most recent deep tillage in these plots was deep ripping in 1983 (Table 4.1). Figure 4.2 shows the extent of soil disruption in each treatment. Due to unavoidable inaccuracy in the listing operation, the cotton hills formed after ripping and chiselling (but not direct listing) were not on exactly the same site before and after deep tillage. This leads to variation in the location of the ripper tine with respect to the reformed cotton hills as shown in Figure 4.2. Subsequent tillage and cultural practices were identical for all treatments, and are outlined in Section 4.3.

Plate 4.1 Side view of ripper tine (left); ripping operation at experimental site (above).

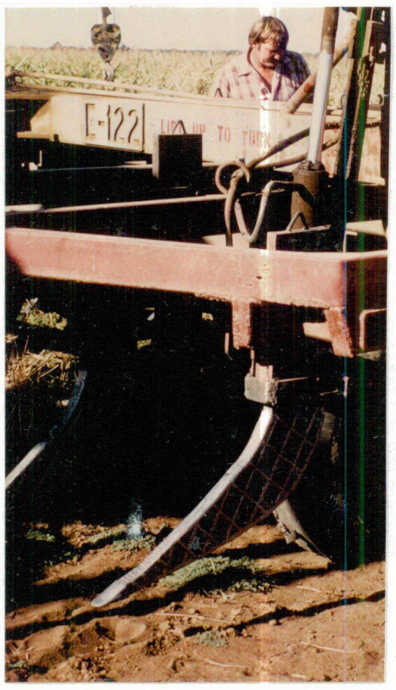

Plate 4.2 Chisel plough tine (left) and chisel plough (above) used to impose experimental treatment.

Plate 4.3 Disc plough used after experimental deep tillage

Plate 4.4 Lister forming hill and furrow configuration after deep tillage and disc ploughing.

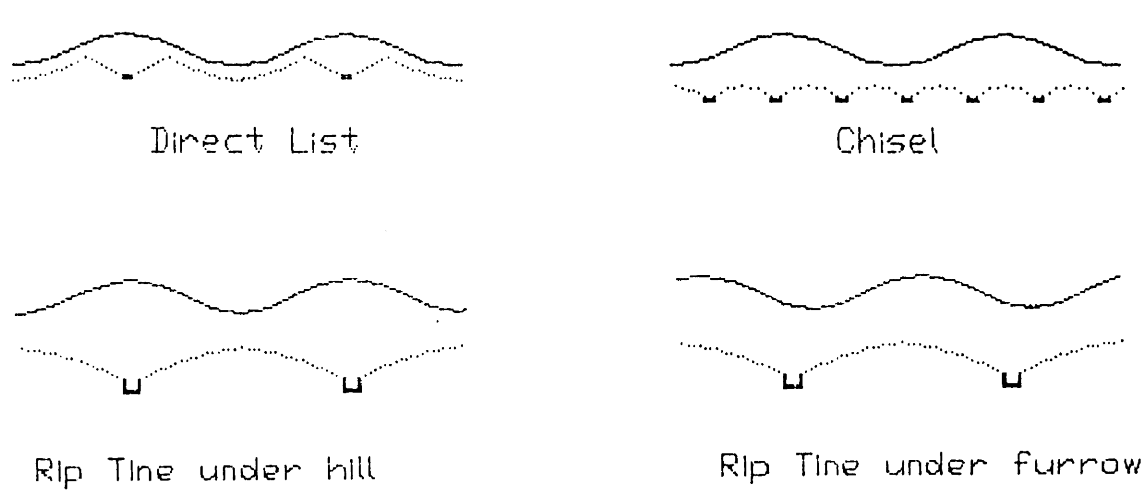

Figure 4.2 Extent of disturbance for three primary tillage treatments. Dotted lines indicate extent of soil disturbance by each tillage operation, and thick lines indicate areas of soil shearing by tines. (Scale 30:1)

Vehicle traffic and cultivation can cause structural degradation (Section 2.2), thus differences in traffic between treatments could override soil structural differences created by the tillage treatments. Each cotton season, all traffic after listing was common to all tillage treatments. The only traffic which differed between treatments was during primary tillage, which was carried out when the soil was dry. The effect of this traffic was considered to be small, and differences between soil physical conditions of the treatments thus considered to arise from the tillage treatments imposed.

Sampling sites were distributed evenly over the 582 m length of each plot for the 1984/85 cotton crop, and the 1985 wheat crop. However, two factors emerged during that time leading to a decision to concentrate subsequent sampling in a 50 m long subsection of each plot. First, the slope of the experimental field was much more variable than at first thought. The range of the average downfield slope was from 0·08% (1:1250) in the southern-most plots in the experiment to 0·165% (1:606) in the northern-most plot (Figure 4.3). For a given duration of irrigation, Hodgson (1986) recorded a trend of shorter duration of waterlogging as the downfield slope decreased. As waterlogging is an important yield limiting factor of irrigated cotton grown on vertisols (Section 2.3.2), it was felt that sampling should be limited to areas of the field with similar slope and equidistant from the head ditch. This conclusion was supported by a survey of soils used for growing irrigated wheat within a 20 km radius of the experimental site, in which Abbott and Higginson (unpublished data) observed for grey clays that yields from steeper slopes were higher than those from the same soil on gentler slopes. A trend of lower soil moisture near the tail drain was recorded during geostatistical analyses in 1985, which showed that this area was atypical of the whole field.

The minimum size of the sampling area was determined after the geostatistical analysis of the 1984/85 soil moisture data, which showed that sampling sites separated by 26 m were statistically independent of each other. This finding meant that statistical efficiency was independent of access tube location, as long as sampling sites were at least 26 m apart. For the above reasons a sampling area, 50 m long, starting 100 m from the head ditch was used in the 1986/87 cotton season (Figure 4.3).

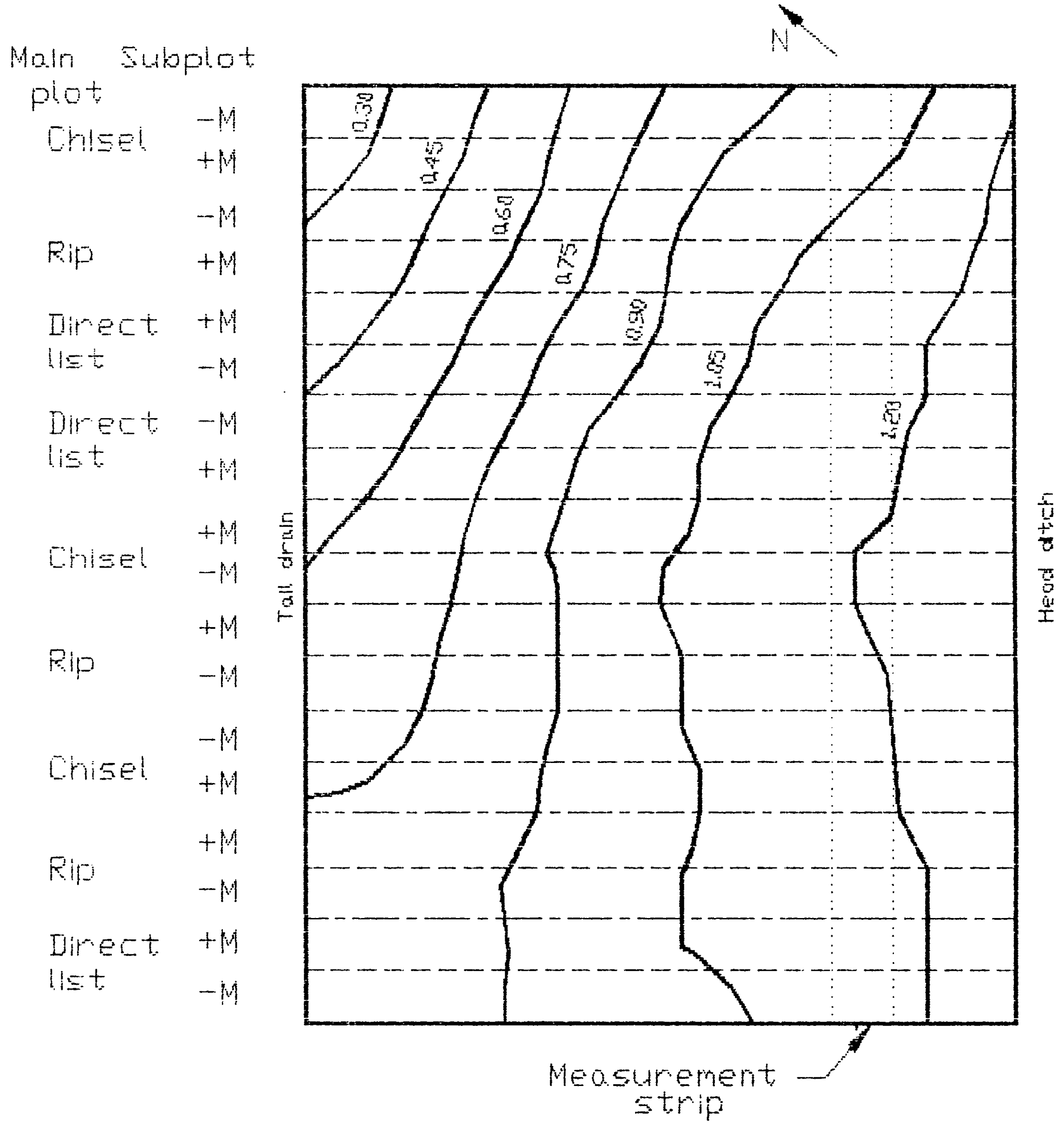

Figure 4.3 Contour map of Field 30, Auscott, Warren, onto which layout of tillage experiment has been superimposed (Scale 1:5800, elevations are in m from arbitrary datum, dashed lines are plot boundaries, M is maize).

A second important design change for the 1986/87 season was the imposition of a split design on the field trial when maize was planted on half of each plot in January, 1986. The maize was planted to dry the soil when rain prior to and soon after the wheat harvest in November, 1986 left the soil too wet ($\theta_g > 0{\cdot}25$ kg kg^{-1} 0·3 and 0·4 m below the centre of hills) to carry crawler tractors performing tillage operations. By planting maize, it was intended to obtain different moisture regimes during reimposition of the tillage treatments in the plots. The final design is shown in Figure 4.3.

4.3 CULTURAL PRACTICES

Cultural practices on the experimental site were similar to those used on surrounding fields, part of a corporate farm growing 3000 ha of cotton in most seasons. Crops were managed to attain maximum economic rather than maximum biological yields in a cotton cotton safflower, cotton cotton wheat rotation. As the gross margin for wheat was 10% of the gross margin of cotton per unit area (O'Sullivan, 1987), levels of fertilizer and water inputs for the wheat crop were low (Table 4.1). Similarly, the maize crop received no fertilizer. In contrast, inputs to the cotton crops were applied at optimum rates and times within the timetabling constraints imposed by the large area farmed. In the remainder of this section, cotton management is discussed in general terms, with details for each season given in Chapters 6 and 8.

Cotton and maize were grown on hills 1 m apart and 0·15 m high. Until slashing of the maize in April, 1986, all tillage operations were carried out in six row sets with wheel traffic being confined to two furrows in each set (Figure 4.4). Eight row sets were used in the 1986/87 season when operation of the whole farm changed from six to eight row machinery. To maintain comparability, soil measurements during that season were confined to hills adjacent to furrows wheeled in the 1983/84, 1984/85, and 1986/87 cotton seasons (Figure 4.4).

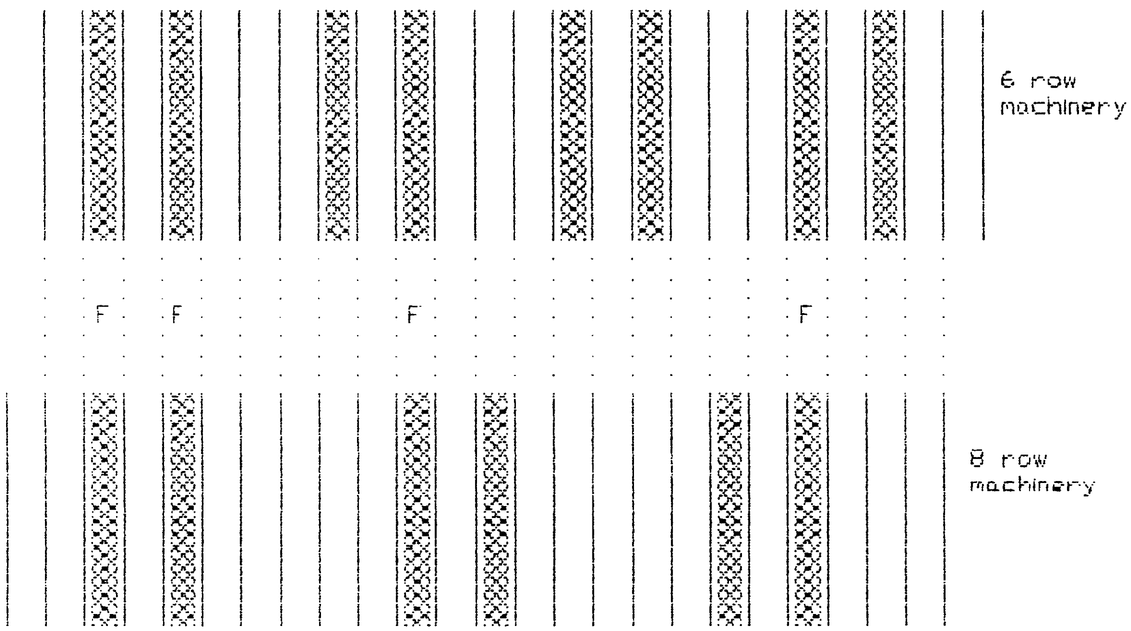

Figure 4.4 Wheeling pattern (hatched areas) for 6 row machinery (used prior to 1986/87) and 8 row machinery (used in 1986/87). Vertical lines indicate rows of cotton; furrows designated by F were wheeled by both tillage systems. Measurements in the 1986/87 season were taken adjacent to these furrows.

The direct list treatment has been termed minimum tillage (McKenzie and Hulme, 1986); however this term can only be used loosely. Six or more passes with shallow (< 0·1 m) cultivating rowcrop tools were made after the hills were formed each cotton season. There were at least two tillage operations, involving a selection of cultivator, go devils, and lillistons (see Appendix 2) between the formation of the hills and planting in early October to break down clods in the seedbed and incorporate herbicides. Two tillage operations were conducted around planting: the planting operation, and rolling with a rubber-tyred roller. Two or more interrow cultivations to kill weeds and increase the height of the hills then occurred between emergence and early January, when the plants become too tall to be cultivated without suffering mechanical damage from the tractor or cultivator. As care was taken to ensure that these tillage operations were carried out when the soil was drier than the lower plastic limit, they caused little structural degradation.

Herbicides were applied to assist mechanical weed control. Pre-emergent herbicides were applied with preplanting cultivations to kill broadleaf weeds such as *Datura* spp. and burrs (*Xanthium* spp.) as well as grass weeds, such as barnyard grass (*Echinochloa* spp.) and wheat. A second application of broadleaf herbicide was made on a 0·3 m wide band centred on the hill at planting. A post-emergent herbicide was used to kill perennial weeds, mainly nutgrass (*Cyperus* sp.), during the 1984/85 season.

A large number of insecticide applications were also made through the growing season, primarily to kill *Heliothis* spp. larvae, mites (*Tetranychus* spp.), and aphids (mainly *Aphis gossypii*). Decisions regarding insecticide application were based on observed insect and egg numbers in the field, guided by the Siratac computer based expert management system. Siratac is a commercial system which recommends type of insecticide, application rate and timing of application, based on insect counts, climatic data and observed stage of crop development.

Nitrogen fertilizer rates (Table 4.1) were determined using results from test strips laid down in previous seasons (D. Anthony, personal communication). Most of the fertilizer nitrogen was applied as anhydrous ammonia (NH_3) 0·2 m below the centre of the hill three to five months before planting of the cotton. The tine which placed the NH_3 disturbed the soil in a manner similar to under-the-row subsoiling (Section 2.4.2). No phosphatic fertilizers were applied to the cotton, as no response to their application had been found in previous years.

Cotton seed was planted as early in the season as possible to obtain a long growing season and maximize yield potential. Planting started after the soil temperature at 0·1 m at 9 am exceeded 15^{o}C for 3 consecutive days. Rowcrop planters with hoe openers (Appendix 2) were used to plant 15 to 16 kg of acid delinted seed per hectare 0·03 m deep.

An irrigation was applied one day after planting to initiate crop emergence in the 1986/87 season, but not in the 1984/85 season when rain fell soon after planting. The first irrigation after crop emergence was applied at about the time when the first flowers opened, one week before Christmas. During the remainder of the season, irrigations were scheduled when neutron moisture meter readings indicated that soil moisture had declined to a refill point (Cull, 1986). The refill point was determined by correlating visual symptoms of plant moisture stress and leaf water potential as measured by a Scholander pressure bomb (Scholander *et al.*, 1965) with cumulative profile water determined by the neutron moisture meter. The final irrigation of the season was scheduled to ensure that the majority of bolls on the plant would mature, subject to the limitation that bolls formed from flowers opening after the first week in February would probably be killed by frost before maturity. Irrigation dates are given with description of experiments for each season.

A conditioner was applied to encourage defoliation of the crop when the topmost bolls on the cotton bush were judged to be mature. Sodium chlorate ($NaClO_3$) was applied later as a defoliant.

Seed cotton (lint and seed) was picked by spindle pickers and dumped into presses in which it was compacted before being transported to a cotton gin.

4.4 CLIMATE

The closest source of reliable long term weather data to the experimental site is at Trangie, 35 km to the south-west (Figure 1.1). Although a weak trend of increasing temperature and decreasing rainfall occurs in a north-westerly direction from Trangie toward the field site, only small differences exist between the two locations. Thus average annual rainfall at Warren, 10 km from the field site and 40 km from Trangie, is only 6 mm less than rainfall at Trangie (Anon, 1975). Temperature gradients are even smaller, with a difference in mean temperature of 1°C between Trangie and Nyngan, 60 km to the north-west (Downes and Sleeman, 1955). Consequently, climatic data from Trangie should be a reliable approximation of the field site, and are used in this description.

The local climate was described by Downes and Sleeman (1955) as one of mild winter and hot summer temperatures. Mean summer rainfall is greater than winter, but it is more variable, as a large proportion of the summer rainfall is from thunderstorms. The median monthly rainfall is less variable than mean monthly rainfall (Figure 4.5). Despite the lower mean winter rainfall, there are slightly more rain days (falls > 2 mm) in winter than summer (Table 4.2). Mean evaporation exceeds mean rainfall throughout the year, with a fivefold difference in the summer, hence summer growing crops need to be irrigated.

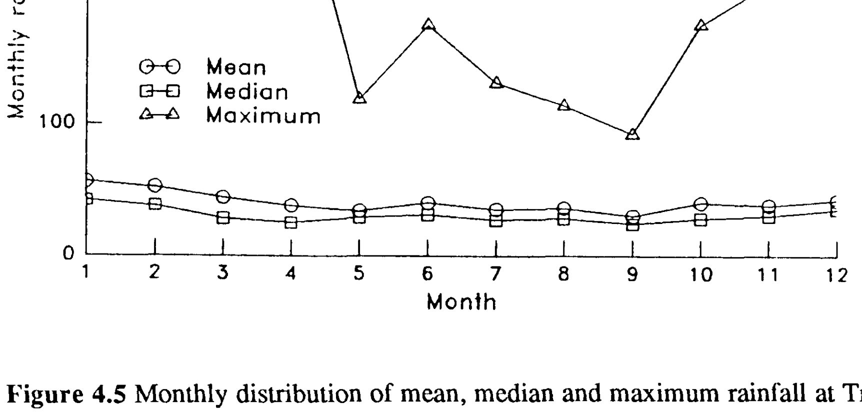

Figure 4.5 Monthly distribution of mean, median and maximum rainfall at Trangie for the period 1886 to 1975 (From Anon, 1975).

Table 4.2 Climatic means for Trangie, 1948 to 1985. Evaporation and rain are monthly totals (mm), rdays is the number of days with more than 2 mm rain in month, soil temperature is measured at 0·1 m, and frosts is the number of frosts in month (from Cooper and Harris ,1985).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evap	281	222	191	127	77	50	54	79	113	177	230	297
Rain	52	48	44	36	40	39	35	34	31	42	40	37
Rdays	6·5	6·2	6·2	6·2	7·0	7·5	8·1	8·0	6·5	8·3	6·1	5·6
Temperatures (^{o}C)												
Min	18·0	18·1	15·4	10·9	6·9	4·3	2·8	4·0	6·2	10·1	13·0	16·1
Max	32·9	31·8	29·3	24·9	19·2	16·0	15·1	16·8	20·0	24·7	28·7	32·2
Soil	24·5	24·8	22·7	18·7	14·4	10·4	8·9	10·2	13·0	17·5	20·5	23·5
frost	0	0	0·1	2·1	8·1	13·7	19·4	17·8	10·7	2·9	0·7	0

Temperature is more important than rainfall in limiting cotton yields under irrigated agriculture. Cotton will not germinate or grow unless the soil temperature is above 15^{o}C (Thompson, 1979) This normally occurs at Trangie after early October (Table 4.2). Subsequent cotton lint yield is determined by heat accumulated from planting until growth is halted by frosts (Thomson, 1979). On average, the first frost occurs on 25th April (Cooper and Harris, 1985), giving an average growing period of 207 days.

4.5 SOIL DESCRIPTION

The soil at the study site may be described as a grey, moderately self mulching, seasonally cracking, uniformly textured clay (N.J. McKenzie, personal communication). It is classified as a grey clay (Stace *et al.* 1968), Ug 5.24 (Northcote, 1979), entic chromostert (U.S.D.A., 1975), and chromic vertisol (FAO, 1974). A profile description is given in Appendix 3. Aggregate size in the described profile increased from 10 to 20 mm near the surface to 50 to 100 mm at 0·95 m. The grade of structure increased with depth being moderate near the surface and strong at 0·28 to 0·95 m (Appendix 3).

The analytical data from this site may be compared with soils used for related experiments on cotton growth on grey clays. Soil physical and chemical properties of the profile described above, determined according to the methods of Loveday (1974) were similar to those obtained by McKenzie (1987) for soils in an adjacent land system (Table 4.3). The clay mineralogy of vertisols at Auscott, Warren was found by Greenwood (1984) to be dominated by montmorillonite, with inter-layer material present in smaller quantities, and only traces of illite and kaolinite. The pH profile and particle size analysis results (Table 4.3) are similar to those of farmed and unfarmed sites near Field 24, Auscott Warren (McKenzie *et al.*, 1984b). Organic carbon content of this soil is similar to the unfarmed site of

McKenzie *et al.* (1984b), which is much higher than their unfarmed site. Electrical conductivity of this soil at 0·1 and 0·3 m is five times that in both farmed and unfarmed sites of McKenzie *et al.* (1984b), and twice their values at 0·7 and 1·3 m. The higher organic carbon content and EC of the soil described here than of the farmed site of McKenzie *et al.* (1984b) should impart a more stable structure to the soil at the site of this experiment.

Table 4.3 Laboratory analyses of soil collected from pit near south-western corner of Field 30, Auscott, Warren (Ign. is ignition, Org. Car. is organic carbon, CS is coarse sand, FS is fine sand, Si is silt, C is clay, E.C. is electrical conductivity).

Depth (m)	pH 1:5	Air-Dry Water $kg\ kg^{-1}$	Ign. Loss	Org. Car.	Particle size CS	FS	Si	C	E.C. $mS\ cm^{-1}$	15 bar water retention $m^3\ m^{-3}$
			Per cent Oven Dry Weight							
0·1	8·4	0·034	5·1	0·39	6	33	13	44	1·3	0·208
0·3	8·7	0·034	5·0	0·40	12	23	13	49	1·7	0·201
0·7	9·4	0·031	4·3	0·31	13	25	13	46	3·0	0·199
1·3	9·3	0·031	4·2	0·31	11	27	9	51	7·8	0·166

Cation relationships for the surface 0·3 m were determined according to the method of Tucker (1974) on one sample, bulked from 15 subsamples collected at equal intervals from the head ditch to the tail drain in each of the 18 plots, were uniform across the site and are shown in Table 4.4. The soils have a Ca:Mg ratio greater than 2:1 which is favourable for soil structural stability. The exchangeable sodium percentage (ESP) at 7·6% is greater than the commonly accepted critical ESP of 6%. These cation relationships are less favourable than nearby farmed and unfarmed sites of McKenzie *et al.* (1984b), where the ESP at 0·1 and 0·3 m averaged 5%, and the Ca:Mg ratio averaged 2·5. Despite these unfavourable cation ratios, the soil has an Emerson (1967) structural stability class of 3, which indicates that its saturated hydraulic conductivity (K_{sat}) is sufficient for irrigated crop production (Loveday and Pyle, 1973). Using the criteria of Loveday (1980), the surface 0·3 m would be moderately responsive to gypsum application.

Table 4.4 Exchangeable cation concentrations (mmol (p^+) kg^{-1}) determined on 18 samples each bulked from 15 subsamples from 0 to 0·3 m. Field 30, Auscott, Warren. (TEB is total exchangeable bases).

Ca	(s.d)	Mg	(s.d.)	Na	(s.d)	K	(s.d.)	TEB	(s.d.)
183	5	80	5	22	3	9	1	294	18

Swelling properties of the soil centred on 0·2 and 0·3 m depths are described in Section 5.2. The shrinkage limit at both depths is 0·09 kg kg^{-1}, and the swelling limit at both depths is 0·22 kg kg^{-1}. Shrinkage between these water contents is nearly normal, so the specific volume of aggregates can decrease by 0·13 m^3 Mg^{-1}, 20% of the fully swollen volume, during air drying of the soil from a saturated state. The lower plastic limit (LPL) of soil from the surface to 0·2 m, determined according to the method of Sowers (1965) on samples from the profile described above, is 0·23 kg kg^{-1}. This value is slightly higher than the LPL of 0·19 to 0·22 kg kg^{-1} determined.by Greenwood (1984) for vertisols at Auscott, Warren.

In summary, the soil at the experimental site has no properties which preclude its use for irrigated crop production, but is susceptible to degradation because of its low organic carbon content, and high ESP. The high ESP is conducive to the dispersion of the clay fraction by tillage of wet soil, while the low organic carbon content predisposes the soil to slaking. Domination of the clay fraction by montmorillonite allows regeneration of structure by shrinkage when drying, as indicated by the swelling properties of the soil.