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USE OF SOIL SURVEY, FIELD EXPERIMENTS
and
SOIL AND PLANT ANALYSIS
for
DEFINING AREAS OF MICRONUTRIENT DEFICIENCY

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by

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STATEMENT

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of my knowledge and belief, this thesis contains no material previously published or written by any other person, except when due reference is made in the text of the thesis

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I SUMMARY

Land units based on landscape features and geomorphology were defined in two areas, Wharminda and Stokes, totalling 4 600 ha on Eyre Peninsula, South Australia. The soils were mapped and were related to their position within the land units. The soil mapping units were based on principal profile forms, great soil groups and soil properties known to affect micronutrient availability. The topographic relationships of the soils within the land units enabled the soil mapping units to be delineated readily.

Soils deficient in micronutrients were identified by measuring yield responses of wheat to foliar application of Cu, Zn, Mn, Fe, B and Mo in 24 factorial field experiments. The fertilizer applications were made at the 1-2 leaf stage, at tillering and at the boot stage. The plants were harvested at tillering, late stem elongation and maturity for determination of dry matter and grain yields. Plant samples from the control plots were analysed for total Cu, Zn, Mn, Fe, B and Mo. The amounts of Cu, Zn, Mn and Fe extractable from the soils with solutions of EDTA, DTPA and $Ca(NO_3)_2$ were determined.

In addition to the factorial experiments, 18 simple ancillary field experiments were conducted to help relate yield responses to the nature of the soil. The ancillary experiments usually involved application of three micronutrient treatments.

In the factorial experiments, grain yields were increased due to Cu application at 11 of the sites. The increases in yield ranged from 110 to 2 000 kg ha^{-1}, the largest increases usually occurring on those soils which had the largest grain yields without application of Cu. Few increases in grain yield resulted from application of the other

micronutrients. Zn application increased grain yield at one site, Mn at one site, Fe at two sites and Mo at two sites, while no increases due to B occurred. Occasionally fertilizer application decreased grain yield. Interactions between Cu x Zn, Cu x Mn, Zn x Fe and Mn x Mo occurred frequently and sometimes suggested marginal deficiency of particular micronutrients.

The soil survey and field experiments made it possible to identify soils deficient or potentially deficient in micronutrients. Cu deficiency occurred on a wide range of soils, viz. deep siliceous and calcareous sands, solodized solonetz and solodic soils with light brown sand A_1 horizons at Wharminda, lateritic podzolic soils and solodic soils at Stokes. Cu deficiency was not observed on shallow solodized solonetz and solodic soils with brown loamy sand A_1 horizons or on solonized brown soils. Zn and Mn deficiencies were largely confined to soils with high carbonate content in or near the surface horizon. Zn deficiency occurred mainly on solonized brown soils while Mn deficiency occurred mainly on calcareous sands. No relationship between the nature of the soil and the occurrence of Fe, B or Mo deficiency was observed.

The concentrations of EDTA-, DTPA-, and $Ca(NO_3)_2$- extractable Cu in the surface soils of the experiment sites were poorly correlated with grain yield response when all soils were considered. However, grouping of soils with similar properties improved the relationships. Critical values in soils, that indicate a concentration of Cu below which Cu deficiency is likely to occur in wheat, are suggested for these extractants for groups of soils.

Cu concentration in the grain was a better index of Cu deficiency than was Cu extracted from the soil, and the relation between yield and Cu concentration appeared to be independent of the nature of the soil. Grain yield response to Cu was usually associated with <2.5 ppm Cu in the grain. Analysis of the grain or $Ca(NO_3)_2$-extracts of soil may be useful for identifying soils deficient in Mn and Zn. However, it was not possible to obtain critical values for micronutrients other than Cu since there were few yield responses to their application.

II INTRODUCTION

The Eyre Peninsula, South Australia, is an old land surface of archean metasediments largely overlaid to variable depths by a sedimentary mantle of alluvial and aeolian material (Johns 1961). Solodized solonetz and solodic soils, solonized brown soils, red-brown earths, lateritic podzolic soils, terra rossas and calcareous sands are dominant soils (French 1958, Stace *et al* 1968). The area (4 500 000 ha) of Eyre Peninsula developed for agriculture has a typical mediterranean climate with hot dry summers and cool moist winters. The mean annual rainfall varies from 300 mm in the north to 500 mm in the south. Eyre Peninsula is an important cereal and sheep producing district. This is illustrated for 1969, a year of average production throughout the state. Eyre Peninsula in this year carried 13 per cent of South Australia's sheep and produced 32 per cent of the State's wheat and 20 per cent of its barley.

Cu, Zn, Mn and Mo deficiencies in crops and pastures have been reported frequently on the solodized solonetz and solodic soils, lateritic podzolic soils, calcareous sands and terra rossas of Eyre Peninsula (Lee 1951, Tiver 1956, French 1958 and Bicknell 1965). However, the extent of deficiencies, and the spatial relationships between the soils involved, are not known.

This thesis describes an investigation made to delineate soils on which deficiencies of Cu, Zn, Mn, Fe, B and Mo occur in wheat. The soils of two areas were surveyed and field experiments were conducted to measure the response of wheat to foliar application of micronutrients. Soil and plant analyses were used to aid identification of the deficient areas.

III LITERATURE REVIEW

PART 1 SOIL CLASSIFICATION

A Introduction

Prior to Dokuchaev's work in Russia in the late 19th century only rudimentary forms of soil classification existed. These were based on single properties of the soil. Dokuchaev recognized that the environment was involved in soil formation and classified soils using genetic criteria. Soils with similarities in process of formation were grouped together. Similar approaches were used in other European countries, in U.S.A. and Australia.

Soil classification has gradually become based on properties of the soil rather than processes of soil formation. This change has resulted in many more classes of soils being formed and hierarchical keys have been employed to arrange soils in an orderly fashion for easy identification. Problems and usefulness of genetic and morphological classification and the advantages of the use of numerical methods are given.

B Development of soil classification

The development of soil classification can be traced back to Ancient China where soils were classified using colour and structure properties. Linne (1770) in his book "Systema Naturae" gave binominal names to soils, e.g. Arena (sand), ferrea (iron) or A. silica (siliceous sand). Other writers simply named the soil constituents, e.g. calcareous sand, and peat. Later, quantitative expressions were used such as sand, loam and clay and percentage of each, and then specific names based on locality of soils appeared. Geological criteria, physiography and agricultural quality of soils were used to give a qualitative assessment.

Dokuchaev (1883) revolutionized soil classification by recognizing that soils were produced by the interaction of the environmental factors: climate, parent material, vegetation, topography and time. He emphasized the uniqueness of soil bodies developed by the combined action of these widely varying agents, and classified all soils into three divisions -

Normal ~~or Zonal~~ soils: These are characterized by well developed morphologies reflecting the influence of climate and vegetation on their development.

Transitional soils: These have well developed morphologies but reflect parent material and relief rather than climate.

Abnormal soils: This grouping contains soils with poorly developed profiles due to youth or the action of relief or parent material.

The three divisions were then subdivided into 11 soil types, the secondary division being made on the area of occurrence and easily measured or observed properties. Sibirtzev (1914) built on Dokuchaev's work and renamed the divisions normal, transition and abnormal as zonal, intrazonal and azonal respectively. These names were adopted by American pedologists.

The term "great soil group" appears to have been introduced in U.S.A. and is roughly equivalent to Dokuchaev's "soil type". Great soil groups are based on all the properties of the soil profile and derive their names from localities or from one or several properties of the profile. Each great soil group is extremely variable and they merge with one another.

The use of genetic criteria for classifying soils was limited by loosely defined categories and lack of knowledge regarding soil genesis and the use of properties other than those of the soil itself such as climate and parent material (Tavernier 1963, Stephens 1963).

Application of Russian methods in U.S.A.

Coffey (1912) and Marbut (1913) used the genetic approach of Dokuchaev and Sibirtzev to relate soils to parent materials and climate. In 1922 Marbut stated that the object of classification ought to be the natural soil body. In his work published in 1927 he introduced many morphological characteristics but retained some genetic concepts of soils. For example he classified lime free alluvial soils in deserts as Pedocals because he considered lime horizons would eventually form in them.

Baldwin, Kellogg and Thorpe (1938, 1949) tried to avoid the use of genetic criteria and to base classification on measurable properties of the soil. However, they retained as orders in their system Sibirtzev's zonal, intrazonal and azonal divisions defined partly in genetic terms. They divided the orders into nine sub-orders and 39 great soil groups.

Application of Russian methods in Australia

Prescott (1931, 1944) published soil maps introducing the work of Dokuchaev and his associates to Australia. Eighteen soil zones based partly on topographic regions, climatic and vegetation zones were described (Table 1) and delineated.

TABLE 1

Major Soil Zones of Australia (Prescott 1944)

1. Tablelands and ranges
2. Desert sandplains
3. Stony deserts
4. Desert loams
5. Desert sandplain
6. Brown soils of light texture
7. Grey and brown soils of heavy texture
8. Solonized brown soils (mallee soils)
9. Mallee sandhills
10. Solonetz soils
11. Red loams
12. Red-brown earths and terra-rossas
13. Rendzinas and blackearths
14. Podzols
15. Residual podzols and lateritic sandplains
16. Low country subject to periodical flooding
17. Tidal marshes and deltaic formations
18. High moor

Stephens (1953) added to the work of Prescott and described 32 great soil groups, and then in the 3rd edition of "A Manual of Australian Soils" (1962) increased the number to 48.

Stephens (1962) recognized two solum classes, Undifferentiated (alluvial, skeletal soil and calcareous sand) and Differentiated. The latter solum class was divided into Pedalfers and Pedocals using the definitions of Marbut (1951):

a) Pedalfers: Soils with no lime carbonate, and such lime carbonate as may be present in the parent material is lost continually from the soil profile.

These soils were further divided according to pH, peat dominance, sesquioxide and clay illuvial horizons.

b) Pedocals: Lime carbonate has accumulated in the profile as a result of soil forming process.

These are divided further by Stephens using colour, pH, eluvial and illuvial horizons, salt and gypsum presence in the profile.

TABLE 2

Great soil groups in order of degree of profile development and leaching - from Stace et al (1968)

1. No profile differentiation.	1. Solonchaks 2. Alluvial soils 3. Lithosols 4. Calcareous sands 5. Siliceous sands 6. Earthy sands
2. Minimal profile development.	7. Grey, brown and red calcareous soils 8. Desert loams 9. Red and brown hardpan soils 10. Grey, brown and red clays
3. Dark soils	11. Black earths 12. Rendzinas 13. Chernozems 14. Prairie soils 15. Wiesenboden
4. Mildly leached soils	16. Solonetz 17. Solodized solonetz and solodic soils 18. Soloths 19. Solonized brown soils 20. Red-brown earths 21. Non-calcic brown soils 22. Chocolate soils 23. Brown earths
5. Soils with predominantly sesquioxide clay minerals	24. Calcareous red earths 25. Red earths 26. Yellow earths 27. Terra rossa soils 28. Euchrozems 29. Xanthozems 30. Krasnozems
6. Mildly to strongly acid and highly differentiated	31. Grey-brown podzolic soils 32. Red podzolic soils 33. Yellow podzolic soils 34. Brown podzolic soils 35. Lateritic podzolic soils 36. Gleyed podzolic soils 37. Podzols 38. Humus podzols 39. Peaty podzols
7. Dominated by organic matter	40. Alpine humus soils 41. Neutral to alkaline peats 43. Acid peats

Stace et al (1968) reduced the number of great soil groups to 43 by combining and deleting soil groups, then added others and divided all soils into seven profile classes exhibiting progressive increase in degree of profile differentiation (Table 2). These profile classes are not completely satisfactory because some soils in them don't fit the description. For example, there are soils with profile development included in the class described as having "No profile differentiation". In the profile class "Minimal profile development" there are examples of soils that are uniform in texture, others with gradational increase in texture down the profile, and also soils with sharp textural boundaries between A and B horizons.

Each great soil group is defined more carefully by Stace et al (1968) than in the previous systems, and morphological descriptions of great soil groups and representative profiles are given.

Genetic classification has little application in Australia because it requires identification of the soil forming processes and assumes that the soil found is the product of current soil forming processes. Australia consists mainly of old soil surfaces that have been subject to previous climates and are often formed from varied parent materials (Stephens 1962). Australia sharply contrasts with Europe and North America where recent ice ages removed soils, and where the present soils are the products of the interaction of current climate, vegetation and parent materials.

C Three modern systems of soil classification

(1) The Soils of Europe

"The soils of Europe" (Kubiena 1953) brought together many of the synonomous soil names used in Europe, preserving the most commonly used ones and listing others as synonyms. Kubiena established rules for further naming of soils. Kubiena claims that his is a "natural" system of classification, making use of all the properties of a soil that give it its "essential" character. He arranges the soils in a key using a bifurcating system that operates on the presence or absence of certain defined properties.

The zonal, intrazonal and azonal divisions are not used by Kubiena but are replaced by:

1. Subaqueous or underwater soils.
2. Semi-terrestrial or flooding and ground water soils.
3. Terrestrial or land soils.

These divisions are defined on the basis of what the soils are now, and so avoid problems that arise when processes of soil formation are used. Kubiena divides the great soil groups into types or subtypes using one or a few properties and then describes these soil profiles giving variability of the soil and area of occurrence in Europe. Micromorphological details are given of humus forms and some specific horizons.

Kubiena's system appears to have its greatest value when classifying soils in large regions. It does not contain any information at low ~~order~~ categorical level that would allow description of variants normally found in large-scale mapping. Intergrading soils are not given equal ranking with the described modal soils, and the description appears to be of virgin soils only.

(2) Seventh Approximation

The seventh approximation is the most recent attempt to classify the soils of U.S.A. and the authors intend it to provide a permanent classification scheme (Smith 1960). The great soil group names of the previous systems were not used because of their reference to genetic processes and loose definitions, and instead well-defined categories have been constructed for easy incorporation of new information.

The authors claim that the properties used to form classes include many characteristics of the soil, so making it a "natural" system. They aimed to use at the highest level of categorization those soil properties most closely related to a large number of other properties.

Tavernier (1963) considers that the seventh approximation is better defined than existing European systems but believes that it will not be used widely there because of its conflict with traditional genetic approaches.

The categories of Seventh Approximation

Orders: Although the authors did not explicitly use genetic ideas, properties chosen for this category reflect ~~various~~ assumptions concerning soil genetic processes. Climatic grouping occurs as with Aridisol and time is expressed in Entisol and Ultisol (Table 3).

The distinction between the 10 orders is not clear as shown by the following quotation from the Seventh Approximation. "Differentiae used among the orders were developed largely by generalization of common properties of soils that seem to differ little in the kinds and relative strengths of processes tending to develop horizons". Tavernier (1963) considered that two extra orders for hydromorphic and saline soils would have to be included if the seventh approximation was used in Europe.

Suborders: The properties used to form the suborder category are numerous, but are chosen to produce classes with greatest genetic homogeneity. Chemical and physical properties associated with waterlogging, climate and vegetation are commonly used.

Great Groups: Suborders are divided into great groups mainly through presence or absence of diagnostic horizons. Horizons selected are those that show major differences in degree of development and minor differences in kind.

Subgroups: Are defined only with reference to the great group. Subgroups are a system of defining graduation between groups. One subgroup represents the modal great group. Other subgroups have mainly the properties of the great group but some others of neighbouring great groups.

Families: Are differentiated mainly on properties important to growth of plants such as horizon depths, texture, reaction, permeability and consistence.

Series: The soil series is a collection of soil individuals essentially uniform in differentiating characteristics and in arrangement of horizons.

~~Soil Types: Texture alone is used to form the soil type.~~

Soil phase: Subdivision on the basis of some important deviation such as surface texture, erosion, slope etc.

Nomenclature

Roots of words of Latin or Greek origin are put together to produce a systematic way of naming the categories. The names of the orders (Table 3) are coined syllables given the suffix sol (Latin *solum*, soil).

The suborders are named with two syllables. The first is a formative element suggesting a property of the class and the second is the formative element from the name of the order. For example, strongly gleyed soils are a suborder of each order. The formative element aqu (Latin *aqua*, water) is used to convey this meaning. Thus a strongly gleyed Vertisol is named Aquert. Great group and subgroup names are developed by further addition of roots of words and the use of binomial names. Families, series and soil types are given descriptive or place names.

TABLE 3

Formative Elements in Names of Soil Orders

Names of Orders	Formative Element	Meaning	Mnemonicon
Entisol	ent	nonsense syllable	recent
Vertisol	ert	turn	invert
Inceptisol	ept	beginning	inception
Aridisol	id	dry	arid
Mollisol	oll	soft	mollify
Spodosol	od	wood ash	odd
Alfisol	alf	nonsense syllable	pedalfer
Ultisol	ult	last	ultimate
Oxisol	ox	oxide	oxide
Histosol	ist	tissue	histology

(3) Factual Key

Even with the refinements that have been made to great soil groups by Prescott, Stephens and Stace and his associates, Northcote (1960) considered it necessary to develop a system of classification based solely on well-defined soil properties. A Factual Key (Northcote 1960, 1965, 1971) was developed after the examination of 500 soil profiles throughout Australia. Four primary divisions of soils are made using changes in texture in the soil profile. This characteristic was chosen because many other properties of the soil are related to the change.

Table 4 shows the four divisions and subdivisions of the factual key. The subdivisions were divided into sections, subsections, classes, subclasses and principal profile forms are represented by a combination of letters and numerals in the key.

TABLE 4

Divisions and Subdivisions of the Factual Key

Divisions		Subdivisions	
Organic	-O	no further categories defined	
Uniform	-U	Coarse textured	-Uc
		Medium textured	-Um
		Fine textured, not cracking	-Uf
		Fine textured, cracking	-Ug
All soils			
Gradational	-G	Calcareous throughout	-Gc
		Not calcareous throughout	-Gn
Duplex	-D	Red clay B horizons	-Dr
		Brown clay B horizons	-Db
		Yellow-grey clay B horizons	-Dy
		Dark clay B horizons	-Dd
		Grey clay B horizons	-Dg

Table 5 shows the division of Uc soils into principal profile forms. The other subdivisions of the key are divided into principal profile forms in a similar manner. Table 6 presents the soil properties used to divide the subdivisions into sections. Where possible, Northcote has used the same properties to form sections from each subdivision but it has not always been possible; for example, Uc1, Um1, Uf1 and Ug1 vary only in texture represented by c m f and g but Uc6, Um6, Uf6 and Ug6 vary in many ways, and 6 represents different properties in each case. Within Division D sections Dr1, DbO, Dy1 vary only in clay colour; the 1, 0 and 1 being the same property. Dr2, Db1, Dy2, Dd1, Dg1 vary only in clay colour, the 1 and 2 referring to the same property. This anomaly developed as new categories were being added to the key.

TABLE 5

Principal Profile Forms of Subdivision Uc, Section Uc1

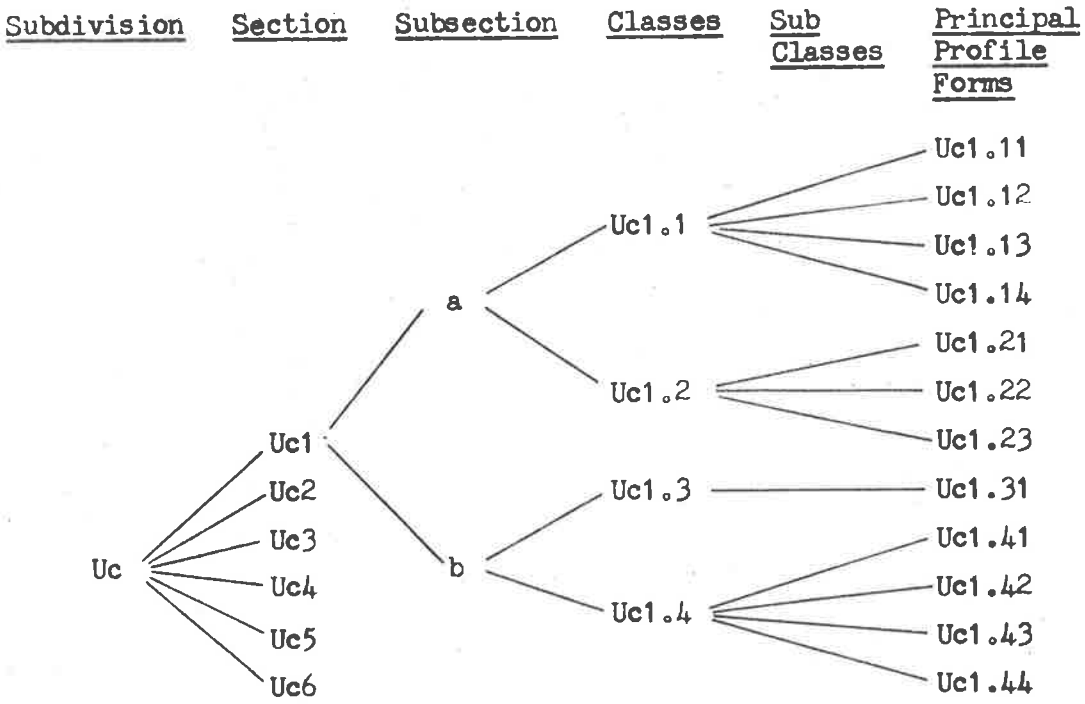


TABLE 6

Soil Properties used to divide Subdivisions into Sections

Division	Properties used in all Subdivisions	Additional properties used to divide Subdivisions
U	General pedologic organization, A_2 horizon presence or absence and colour	Um: peds, A1 horizon colour; Uf: plasticity; Ug: peds
G	Pedality of B horizons	Gn: Fabric of B horizon
D	A_1 horizon hard setting or not B horizon colour and mottling	Dr, Db, Dy: surface crust

D Specific purpose classifications

Where land is being used for specific purposes such as building sites, roadways, aerodromes and reservoirs, soil classification systems have been devised that classify particular properties of the soil related to the use of the land.

Casagrande (1947) classified soils using texture, horizon depth and compression tests ~~in~~ to classify soil as an aid to road construction, and of ability to support runways of aerodromes. The Federal Housing Administration of U.S.A. (1961) published the unified soil classification system placing soils in 15 textural groups and created other categories for various plasticity of clays and behaviour of soil after working and after long term stress. In another scheme (1963) geological, hydrological and topographical features of the soil, and soil site, were used to classify the capacity of soils to absorb effluent from septic systems.

E Use of numerical methods in soil classification

Mulcahy and Humphries (1967) emphasized the need for statistical investigation of variation in soil properties. They pointed out that appropriate breaks could be made in properties that vary continuously only when large numbers of examples were studied. The same principle applies to the concept of modal profiles and these can be approximated only after description and analysis of a large number of profiles.

Rayner (1966), Arkley (1968) and Cipra et al (1969) used numerical methods to form a hierarchy of soil properties by choosing first those properties most highly correlated with other soil properties. Arkley (1968) found that soil pH had the greatest effect on other soil properties and should be used first. ~~in constructing a hierarchy.~~

Texture of the soil and then colour were next in order of numbers of associated variables. When he examined the orders of the Seventh Approximation he found that the soil properties used to separate them were distributed at various levels in his hierarchy, suggesting that greater homogeneity of orders could be obtained by using different properties to define them. On the other hand, Rayner (1966) and Cipra *et al* (1969) found that the sequence of soil properties, given by choosing the most highly correlated ones first, was similar to the sequence of the properties used to differentiate among the various orders of the Seventh Approximation.

Numerical methods have been used to choose properties that best describe the soil. Sakar *et al* (1966) used co-variance analysis to reduce the number of parameters required to adequately describe a soil. They chose 26 soils and measured 61 properties and showed that the number of properties used to describe the soil could be reduced to 22 without appreciably affecting the precision of the description. Arkley (1968) retained highly correlated variables during analysis by a technique called cluster analysis which determines the natural groups of soils in the population.

Tavernier and Marechal (1958) used co-ordinate methods to classify soils of Belgium. They defined soil series in terms of soil texture, ~~and~~ organic matter, drainage and profile development and the information was stored in three dimensional graphs for computer retrieval.

Numerical methods are useful tools for examining and improving existing hierarchical keys and for systematic study of soil properties. However these methods do not overcome the problems of existing classification systems, are difficult to operate and concepts such as multi-dimensional space are difficult to visualize.

F Problems of soil classification

Unit of soil The object classified, the spatial unit of soil, is not well defined and varies between soil classification systems. Northcote conceptualized the solum which is that portion of the soil profile influenced by current soil processes and each profile examined has to be related to this. An example of the difficulty that can occur is illustrated in solodized solonetz soils. These can be Dy5.43 if the solum is the sand and clay horizons, or the soil could be Uc2.2 if the solum is the sand horizons, these being aeolian and of more recent origin than the clay.

The Seventh Approximation classifies pedons (an area of $1m^2$ to $10m^2$). This may suffice for most soils, but there are some such as gilgai soils and those with discontinuous horizons that require larger pedons to include all the horizons.

Continuum Chemical and physical properties of the soil show almost continuous variation in the field and the sampling of the soil and measurement or analysis of it add further variation. Soil horizons vary vertically and horizontally, ending abruptly or gradually merging into another on their upper, lower and lateral boundaries. The use of rigid class boundaries to form categories from continuously varying properties is an arbitrary way of dealing with variation, and may result in separation of soils which are essentially similar, because a property in the key happens to be divided in such a way that two similar soils are on either side of the division. It may result in grouping of unlike soils which happens when important properties are not used in the key, or when soils are at opposite ends of a category having a wide range of values (Fitzpatric 1971). Often soils that do not fit easily into preset categories are regarded as intergrades rather than soils in their own right (Leeper 1952, 1954).

Webster (1968) suggests two ways of reducing the problems created by forming categories. Boundaries around soils or soil properties could be defined in a particular region, and could be allowed to vary from one region to another. He suggested that flexible boundaries with broadly defined limits of variation would allow surveyors to fit soils into homogenous groups more easily.

Importance of soil properties Selection of diagnostic properties is required for grouping soils into various classes for the purpose of forming hierarchical classifications. Hierarchies are necessary to handle the masses of data. However, the properties have to be ranked in order of importance, and those with highest covariance with other properties used first in the hierarchy. This choice often cannot be made correctly due to insufficient information about the soil properties, and the error has the same effect as arbitrarily dividing continuously varying properties into categories, and again separates similar soils and groups unlike soils (Stephens 1963, Fitzpatric 1971).

Co-ordinate representation of soils in multidimensional space overcomes the need for a hierarchy based on an order of importance of properties because all soil properties used have equal importance.

PART 2 SOIL SURVEY AND MAPPING

The purpose and scale of operation of any survey largely determines the techniques employed and the amount of information conveyed in any map produced. Procedures involved in soil survey and mapping are described and their cost and utility are discussed in the following pages. Examples of soil survey and land mapping at small and large scale are presented.

A Types of mapping

(1) Soil mapping

The U.S.D.A. Soil Survey Manual (1951) presents four types of soil maps based on the degree of field work involved and the scale of operation.

Detailed soil maps are of soil types and phases, and are mapped in enough detail and with enough accuracy to plan agricultural activity in the field.

Reconnaissance soil maps approach the accuracy of detailed maps at large scales but are mainly of soil associations. They are usually intended for exploratory purposes and are less precisely defined, contain fewer units and have smaller mapping scales than the detailed maps.

Generalised soil maps are produced by orderly abstraction from more detailed ~~original~~ soil surveys. The large numbers of detailed soil maps produced has increased the need for generalised soil maps depicting soil associations of broad regions.

Schematic soil mapping resembles generalised soil mapping but is at smaller mapping scale such as 1 : 1 000 000 and does not necessarily include field survey. These maps are drawn by orderly abstraction from all available information and topographic maps in particular. This type of mapping is generally used in large sparsely developed regions, and is the first step in planning more detailed study of previously undescribed areas.

(2) Land mapping

Christian and Stewart (1953) argued that large relatively unused regions of land for which no inventory of resources is available should be initially mapped to show the essential characteristics of the region, placing equal emphasis on the various environmental features relevant to possible land use. This would allow expression of one character of the land in one part, and another in a different part of the region. As an example of this principle Christian (1958) considers climatic effects on land use and draws attention to rainfall which may limit land use in one area, and frost which may be more important in another area.

In Australia the Division of Land Research, C.S.I.R.O., developed a system of land mapping based on the recognition of land zones, systems, units and components (Christian 1958, Taylor 1970). The regional surveys of Australia conducted by this division describe land systems in terms of geology, vegetation, soils, topography and existing land use. Comment is made on potential land use and technical problems of development are outlined. This approach can be applied at any scale of mapping, and the mapping categories maintain their relative systematic relationship. For example, land units in large, sparsely used areas become land systems in moderately intensive areas, and components become units.

Speight (1968) used a numerical technique to classify the topography of a previously mapped region. He defined land elements as topographical components of a land system. Land elements were described in terms of slope, rate of change of slope, contour curvature. Land systems were described in terms of ridge density, ridge reticulation and magnitude and direction of ridge vectors. The diagram so produced resembled closely the land systems mapped by the conventional method. Speight believed that definition and reproducibility of land systems could be improved by this method.

(3) Land-use mapping

Land can be mapped into classes based on particular public requirements. Agricultural and urban planners have created classes associated with particular uses in order to promote orderly development of an area.

Land capability mapping relative to agriculture is demonstrated by the work of Klingebiel (1958) in the U.S.A. and Obeng (1968) in Ghana. Each of these authors divided the land into eight classes based on risk of deterioration and agricultural use. Their class I contained the most productive land with the least risk involved, and class VIII was steep, rocky or saline with little agricultural use. Classes II-IV were based on steepness of slope and land in these classes required control of erosion when developed for agriculture.

B Survey and mapping procedure

(1) Collation of relevant information

The U.S.D.A. Soil Survey Manual (1951) p. 43 outlines a program for soil survey and mapping. The principles apply to other forms of mapping as well. The preliminary steps are:

Establish the exact reasons for the survey together with special uses to be made of it, and delineate the boundaries of the area to be surveyed.

Describe the physical features of the area and examine all previous surveys of soil, relief, geology and vegetation.

Decide on field and publication scales of maps, and bring together base maps, national grid systems and other controls of the area.

Plan the preparation and publication of the report in terms of time, labour and finance.

Arrange items such as soil analysis and field equipment.

(2) Interpretation of aerial photographs and use of remote sensors

Aerial photography has been used extensively in soil and land mapping. Analysis of pedological elements in photographs is often possible where they are clearly visible and measurable. Buringh (1954) estimated that preliminary examination of photographs can reduce the usual field work by 75 per cent. Furthermore, extrapolation from a mapped and photographed area to an unmapped but photographed area can reduce field work to 15 per cent of that required without aerial photography.

Wavelengths other than the visible light spectrum have also been successfully used. Infra-red and radar sensors have been used for mapping natural plant communities, determining hydrologic features and soil water content, discriminating among forms of land use, crop type and various factors affecting growth, and delineating soil and geomorphic units (Simonett 1968, Colwell 1968, Romanova 1968).

(3) Survey procedures

Beckett (1968) divided soil survey procedures into three groups which differ mainly in the relative use of profile examination and extrinsic properties. The different procedures may be used singly or in combination.

Grid survey

By this procedure soil profiles are examined at predetermined points along a traverse or set of traverses. This procedure has its greatest use in large scale mapping and can be used to estimate the proportion of particular soils in an area. Beckett and Burrough (1971) suggested that the proportion of a particular soil series in a region is better estimated from grid than from free survey, especially where there is no obvious surface expression of soil boundaries. Burrough et al (1971) showed that precision of soil series mapped by grid survey is related linearly to the logarithms of cost and scale.

Free survey

This is the most commonly used method in Europe, U.S.A. and Australia and refers to mapping of soils by locating their boundaries. The surveyor makes a preliminary examination of the soils in the area and determines the mean or modal properties of the units to be mapped. He then locates the boundary of the soil, and follows it until the boundary is closed. This method overlooks inliers more than does grid survey. ~~techniques~~.

In free survey the soil differences must show at the surface or have other external expression in the landscape, and the surveyor only uses the soil auger to confirm that the boundary lies where predicted. As the mapping scale becomes larger, the proportion of soils with external expression becomes progressively less and grid surveying becomes necessary.

Beckett and Burrough (1971) showed that the density of soil observations required to map soil series by free survey at the same map scale in different terrain was approximately proportional to the length of mapped boundary per km^2, or to the number of separately mapped soil occurrences per km^2. The density of soil observations is least where soil boundaries have clearest external expressions. Survey effort was increased by observation density, the need for cross-country access, and the work necessary to identify the soil at each site.

Physiographic survey

Physiographic survey maps are drawn with little or no ground check on boundaries, and are similar to the schematic soil maps of the U.S.D.A. Soil Survey Manual (1951). Boundaries are drawn around areas of tone or pattern difference visible on aerial photographs, and field checks are then used to identify but not to map the soil in each mapped area.

At small map scales, physiographic mapping is equal or superior to free mapping and is likely to require fewer observations to achieve this, but at larger map scales the precision of the physiographic survey does not increase while that of free or grid survey is proportional to effort.

Use of single property maps

Beckett and Burrough (1971) compared special purpose maps of one soil property only, with general purpose maps and concluded that there is little advantage in mapping one property ~~only,~~ rather than several simply determined field properties, such as would be required in soil series mapping. Burrough et al (1971) showed that the cost of producing isoline maps of a single chemical property is twice as much as that for a series map by grid survey.

Single property maps, using other than soil properties, have been used to assist in mapping micronutrient deficient areas. Two examples follow:

(i) In landscapes with large numbers of streams the geochemical stream sediment technique can be employed. Analyses are made of sediments to detect differences in micronutrient concentrations over a large area. By relating the concentrations of micronutrients in the sediment to that in paddocks, successes in delineating deficient areas have been achieved (Webb et al 1968).

(ii) In New Zealand regional micronutrient deficiencies for livestock are surveyed by measuring directly the response to micronutrients fed to animals. Andrews (1968 and 1970) delineated Se and Co responsive areas by this method.

(4) Naturally occurring groups of soils

When properties of soils change abruptly in the field, boundaries may be drawn readily, but when properties vary continuously so that one soil merges with another, arbitrary boundaries are interpolated after soil examination at a set of sampling points.

Where continuous variation occurs, grouping of soils has frequently been based on repeating sequences. Milne (1935) and Middleton (1954) observed the regular repetition of sequences of soil profiles in association with recurring topographic patterns. Milne suggested the catena as a generic term describing repeating sequences of soils formed by differences in drainage associated with topography. Middleton used the term toposequence to describe the sequence of soils in the topography. Ruhe (1960) recognized four elements associated with slope from upland areas to adjacent plains, and related the soil profile at any one place to erosion and gravitational creep of the soil. Butler (1959) recognized that erosion and deposition were principal soil forming processes in Australia. Buried profiles are common indicating periods of inactivity and activity of erosion and deposition. Butler proposed the terms "K cycles" for a period in which a new soil was formed at one locality. He recognized 5 "K cycles" in south-east Australia. Calton (1954) showed

that in East African soil catenas were developed
partly from lateral movement of decomposition products of soils. The catena has proved to be a useful mapping unit especially in small scale maps where the amount of information has to be restricted.

The soil series and association are two common groupings used in mapping. In these groups soils bear no fixed relation to one another, and the definition of each group is influenced by the conceptual scheme employed by the surveyor (U.S.D.A. Soil Survey Manual 1951).

C Examples of soil and land surveys

Two soil surveys and two land surveys are described to illustrate and to contrast approaches to mapping at various scales of operation.

(1) Soil survey

Atlas of Australian Soils

The Atlas of Australian Soils (Northcote et al 1960-1968) aimed to introduce uniform morphological description of soils throughout Australia, and to equate local names, great soil group names and other soil names with the code names of the "Factual key for the recognition of Australian soils" (Northcote 1971).

To prepare the Atlas, Northcote and his associates derived soil boundaries and principal profile forms mainly from previous surveys. Where previous surveys were not available, the authors used aerial photographs of the land to divide it into geomorphological areas. These were examined in the field along traverses and the principal profile forms were determined at regular sampling points.

The mapping units of the Atlas are soil associations that contain dominant soils and modifiers. The dominant soils either cover most of the area of the mapping unit or have properties that are common in the mapping unit, so that the mapping unit can be characterized by that soil. Modifiers are soils or groups of soils that are extensive in the mapping unit and which indicate soil variability in the unit.

The continent of Australia was divided into 10 regions. Maps of each region were drawn at 1:2 000 000 scale and booklets were prepared for each map listing local names of soils and giving basic geological data. Principal profile forms of the dominant soils of each mapping unit are listed together with one or two main features such as pans, B horizon structure or the occurrence of laterite. Principal profile forms were related to the topography in each mapping unit by dividing the land in the unit into landscape components, and listing the soils occurring on these.

Topography affects the incidence of rainfall over short
~~The topography of the Australian continent alters the incidence~~
distances in the wetter areas of the Australian continent. Rapid changes
~~of rainfall in short distances in the wetter areas of the continent~~.
in soil also occur in these regions and this, together with the
~~This results in rapid changes in soil over short distances, and, tog-~~
greater amount of information from previous surveys, has resulted in
~~ether with the greater amounts of information from previous surveys~~,
a greater number of mapping units per unit area.
~~increases the number of mapping units per unit area in these regions~~.

Soils and land use in part of Goulburn Valley, Victoria

This survey was conducted on an area of 228 000 ha in the irrigation areas of the Goulburn Valley by Skene and Poutsma (1962). Half of the area is used for irrigated fruit growing, dairying, fat lamb production and market gardening. The remainder is used for dryland sheep and wheat ~~industries.~~ production.

The object of this survey was to map accurately the soil types of the area, and to indicate the suitability of these soils for irrigated crops. Particular attention was given to the permeability of the surface and subsoil, because the soils are susceptible to waterlogging and much damage had occurred to horticultural crops in the area, particularly in wet autumns and winters.

Skene and Poutsma identified six land use categories based on drainage characteristics and recommended crops for each category. They recognized and described 26 main soil types, divided the area into 40 parts and presented maps of the soil types for each part at 1:30 000 scale. Potential land use, based on the permeability characteristics of the soil horizons was described for each soil type. Chemical and physical properties of each soil type were determined and the morphologies of representative profiles were described in detail.

To aid in locating the soil types in the field toposequences were presented with the position of each soil type marked on diagrams. A general view of the soils was given by mapping them at 1:120 000 scale in 10 soil associations in which individual soil types were classed as dominant or subdominant.

(2) Land survey

A study of the land in south-western Victoria

In this survey Gibbons and Downes (1964) applied principles and methods for the study of land developed in Victoria since 1953. They mapped the land at various scales making use of environmental features, and considering erosion risk and potential productivity to form categories for classification. The area of 1 200 000 ha was classified into 9 land zones, 21 land systems and 100 land units and the land systems were mapped at 1:250 000.

The land component is the smallest, discrete unit described by Gibbons and Downes. It is regarded as an area where climate, parent material, topography, soil and vegetation vary within limits that bound particular forms of land use. Land components are grouped to form land units which are usually derived from one parent material. Land units that are related to one another by similar geomorphology or climatic conditions are grouped together to form land systems. Land systems having broadly similar climate, parent material, topography and vegetation are grouped together as land zones.

The text and the legend attached to the map describe each land system, in terms of landscape and extent of the land surface. Parent materials of soils, topography, native vegetation, crop types and potential productivity and susceptibility to erosion are detailed for each land system. The land units were not mapped, but were described; the great soil groups, soil series and types, using the survey of Blackburn and Leslie (1949), being given for each unit.

The approach of Gibbons and Downes relies on boundaries of land components, units, systems and zones being identifiable in aerial photographs or by field reconnaissance.

Murray Newtown site selection

The aim of Chittleborough and Wright (1973 a,b) in this survey was to present to urban planners an integrated study of 35 000 ha of land near Murray Bridge, South Australia, together with an evaluation of the area for urban land use.

The authors compiled information from geological and soil surveys, contour plans and aerial photographs. They then divided the area into 10 landform units based on topographical differences and described each unit. Within each unit landform and geology were detailed and the soils were described giving the relation of them to topographic features such as crests and slopes of dunes, flats and calcrete ridges. Morphological descriptions of the soils and principal profile forms were given.

The authors envisaged two broad categories of land use: namely, engineering (roads, buildings, drains) and agricultural (parks, market gardens). Two problem areas were detailed in the survey:

(i) Saline soils with plastic clays that would give poor support to foundations of buildings were found in the south-west of the area.

(ii) Sand dunes that are unstable and liable to wind erosion if disturbed, were found in the north-west of the area.

PART 3 SOIL CHEMISTRY OF MICRONUTRIENTS

A Distribution of micronutrients in soils

Occurrence in parent materials

Micronutrients tend to concentrate in certain minerals contained in igneous rocks depending on the ionic radius and charge of the ion and the interatomic spaces of the mineral (Goldschmidt 1954). Also, Cu, Zn, Mn and Fe are more abundant in basalt and Mo and B more abundant in acid rock such as granite (Krauskopf 1972).

Cu and Mo are associated with sulphides (Goldschmidt 1954) and Hodgson (1963) concludes in his review that Zn is frequently found in silicates and sulphides, Fe in silicate, sulphides and oxides, Mn in silicates and B frequently in tourmaline.

Soil weathering processes release elements at varying rates depending on the type of mineral containing them. Cu, Zn and Mn often occur in more readily weathered minerals (Mitchell 1964).

During the formation of sedimentary rock the micronutrients are unevenly distributed with some rocks containing more than others (Krauskopf 1972). Mn is concentrated in limestone while the other micronutrients are more abundant in shales. Boron is particularly high in shales due to incorporation of dissolved borates from sea water during sedimentation.

The geographical distribution of micronutrients in soils is closely related to the composition of the parent material (Hodgson 1963), although the effect of the parent material is less in old soils (Mitchell 1964).

Distribution in the soil profile

As rock weathers into soil, the micronutrients are subject to leaching, reaction with soil constituents and use by micro-organisms and plants. The principal effects of these processes on the distribution of micronutrients in the profile are given by Mitchell (1964):

(i) Surface enrichment from organic debris.

(ii) Leaching of soluble micronutrient constituents into zones of accumulation or out of the profile.

(iii) Translocation of the nutrients during soil formation in clays, sesquioxides and organic matter, resulting in their being concentrated in lower soil layers; erosion and soil creep move micronutrients laterally.

(iv) Weathering of soil minerals as a result of gleying increasing soluble forms of micronutrients lower in the profile.

Wright et al (1955) analysed a modal podzolic profile and showed that surface enrichment of Cu, Zn and B occurred. Depletion of Cu, Zn, Mn, B and Mo was found in a bleached horizon just below the surface and accumulation of Cu, Zn, Mn and Mo in the illuvial clay horizon. Mitchell (1964) analysed sandy soils from Scotland and found that the sand fraction contained a large proportion of the total soil micronutrients but the clay contained higher concentrations. Swaine and Mitchell (1960) and Follett and Lindsay (1970) found no evidence of depletion or accumulation of total micronutrients in different horizons in the soils of Scotland and Colorado respectively. However, in the latter study the concentration of DTPA (diethylene triamine penta-acetic acid) extractable Zn, Mn, Fe and Cu decreased with depth.

Subsurface zones of accumulation of micronutrients usually result from conditions favouring impedence of leaching. Swaine and Mitchell (1960) showed that in poorly drained Scottish soils gleying increased the mobilisation of micronutrients.

McKenzie (1957, 1959) examined South Australian soils and found that in red-brown earths total Cu and Mo content was highest in the clay horizons and Mn was distributed evenly in all horizons. In shallow terra rossa and rendzina soils there was no variation in the distribution of micronutrients with depth.

B Chemical forms and reactions of micronutrients in soil

(1) Concept of chemical pools

Each micronutrient exists in the soil in different amounts and in a variety of chemical forms which have varying reactivity. Viets' (1962) concept of chemical pools (a - e) illustrates the relationship of different chemical forms of micronutrients:

(a) Contains water soluble micronutrients that are readily available to plants.

(b) Readily exchangeable ions e.g. cations that are readily displaced by NH_4^+.

(c) Adsorbed, chelated and complexed ions exchangeable by ions or chelates with high affinities for the exchange site or ion. Not readily displaced by NH_4^+.

(d) Micronutrients in lattices of secondary clay minerals, insoluble oxides or carbonates.

(e) Ions held in lattices of primary minerals.

Pools (a), (b) and (c) are in equilibrium with one another and contain the available micronutrient fraction. Pool (c) is usually much larger than (a) or (b). Pools (d) and (e) are generally not in equilibrium with pools (a) - (c) but the minerals of pools (d) and (e) may fix micronutrients from pools (a) - (c) by isomorphous substitution for Al and Si in clay lattice structures or they may contribute to these pools by weathering.

Except in arid regions and in young soils pool (d) is usually much larger than (e).

(2) Adsorption reactions and occlusion

It is evident from the review of Hodgson (1963) that the availability of the micronutrients Cu, Zn, Mn, Mo and B is regulated in the soil by adsorption reactions or combination on mineral and organic surfaces. Greenland (1971) demonstrated mechanisms involving the attachment of humic materials to clay minerals in the soil and showed that cations can be involved in forming bridges between the humic and clay substances.

The species of metal ion adsorbed has a large influence on the amount adsorbed. Bingham et al (1964) observed that the apparent cation exchange capacity of the soil increased when Cu or Zn compared to Ca were adsorbed. Similar effects have been reported for Co (Hodgson 1963). An explanation for this lies in hydrolysis of Cu, Zn or Co (M) before adsorption followed by reaction with and displacement of H^+ from the crystal lattice by the monovalent MOH^+ ion. Hodgson Tiller and Fellows (1964) tested two postulated reactions, one involving hydrolysis and the other direct reaction of the divalent ion with clay. The reactions tested were:

$$M^{2+} + H_2O \rightleftharpoons MOH^+ + H^+$$

$$MOH^+ + X^- \rightleftharpoons XMOH$$

and

$$M^{2+} + HX \rightleftharpoons M^+X + H^+$$

where M^{2+} is the divalent metal ion and X the adsorbing surface. Their evidence suggested that a step involving hydrolysis of the cation occurred. Above pH 7.0 $ZnOH^+$ and $CuOH^+$ are important forms of Zn and

Cu in the soil solution (Ellis & Zenek 1972).

Hatcher <u>et al</u> (1967) showed that B can be adsorbed on Fe and Al oxides and hydroxides, micaceous clays and Mg hydroxy compounds, while Jones and Smith (1972) demonstrated that Mo is commonly adsorbed by Fe and Al hydroxides and oxides.

Where micronutrients are involved in entry into crystal lattices or co-precipitation with other soil materials, occlusion occurs. Evidence for these reactions is presented by Elgabaly and Jenny (1943), Hodgson (1963) and others.

Data from Hodgson (1960) shows that a small proportion of Cu and Zn added to soil could not be removed by neutral salts or acids and this fraction was regarded by the authors to have been incorporated into the octahedral layer of the crystal lattice, possibly by solid state diffusion.

Soil Mn and Fe exist principally as oxide and hydroxide precipitates (Geering and Hodgson 1969, Lindsay 1972). The transfer of these metals to pools (a) and (c) depends largely on reduction - oxidation processes.

Experiments conducted at Rothamstead experimental station reported by Mitchell (1964) show that the amorphous Fe_2O_3 fraction of the soil often contains large portions of the soil micronutrient metals. For example, a soil consisting of 5 per cent Fe_2O_3 contained 60 per cent of the soil Fe, 50 per cent of the Cu, and 80 per cent of the soil Mn in the Fe_2O_3. The work of Jones and Smith (1972) indicates that Mo is adsorbed by Fe and Al oxides and may also be occluded during precipitation reactions.

Boron is frequently present in the soil in tourmaline. Few reactions remove B from solution and added B remains water soluble for long periods (Wear 1965).

(3) Organic matter reactions

a) Total soil organic matter and micronutrient deficiency

Micronutrient deficiency has frequently been demonstrated in soils with high organic matter content. For example, peat soils of Europe and U.S.A. have been reported to be severely deficient in Cu by Van Alphen (1956) and Kubota and Allaway (1972) respectively. Conversely, high organic matter content may sometimes be associated with increased availability of micronutrients. Berger and Truog (1945) reported that B deficiency occurs on certain Wisconsin soils when the organic matter of the A_1 horizon is less than two per cent of the soil material. Miljkovic et al (1965) showed that B accumulates in organic layers of the soil.

Jensen and Lamm (1961) calculated a correlation coefficient of 0.81 between Zn content and organic matter content of soils in Scandinavia. Hodgson (1963) refers to work showing that both Cu and Mo concentrations in the soil are frequently increased in soils with high organic matter content. These relationships can be explained by strong affinities for organic matter. Highly organic soils have many sites where these micronutrients can be bound, in some cases preventing uptake by plants and causing deficiency, in others the micronutrients are still able to be absorbed by plants.

b) The chemical forms and reactions of organic matter complexes

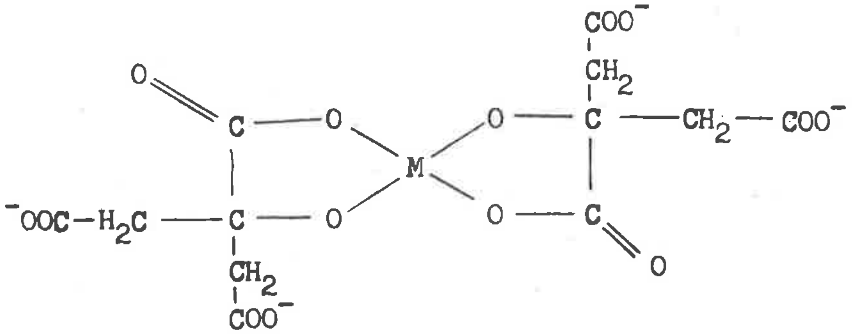
A wide range of micronutrient-organic matter complexes exist in the soil. Most of these compounds are insoluble in water, but the small percentage that are water soluble are extremely important in movement of micronutrients in soils. For example, uncomplexed Fe content in soil solution is much less than that required by plants. At pH 7-8 inorganic Fe in solution is 10^{-11}M or 10^5 times lower than that required by plants. Organic complexes of Fe supply the plants' requirements (Lindsay 1972).

Hodgson et al (1967) and Elgawhary et al (1970) demonstrated that chelating agents increased the rate of diffusion of Zn in agar gel and soil respectively by 100 times and 17 times that of uncomplexed Zn.

Hodgson et al (1966) found Cu concentrations in soil solution of 11 x 10^{-3} ppm and that 99 per cent was in chelated form. The other 1 per cent probably consisted of Cu carbonates, hydroxides and phosphates. In contrast to Cu only 60-75 per cent of the Zn occurred as chelate in a soil Zn solution concentration of 2 x 10^{-3} ppm. Zn carbonates and hydroxides were suggested as the main forms of non-chelated Zn. Geering and Hodgson (1969) showed that 84-99 per cent of Mn in soil solution was chelated.

Aliphatic and amino acids form important complexes with micronutrient metals. Dolar and Keeney (1971) and Hodgson et al (1965) showed that Cu and Zn were attached to soil organic chelates of these acids. Aliphatic acids are more important when the pH is less than 7.0 and amino acids, when pH is greater than 7.0 (Geering and Hodgson 1969).

Organic acids such as acetic, oxalic, acrylic and succinic abound in soils and form many types of water soluble chelates (Hodgson et al 1965). The most effective acids are di and tricarboxyllic types. Stevenson and Ardakani (1972) show the complex structure with citrate as



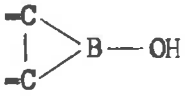
Amino acids are almost as important as other organic acids as solubilizers of metal ions according to Bremner (1967) and Ivarson *et al* (1970). Stevenson and Ardakani (1972) report that free amino acids in soils are increased by fallowing and Rovira (1965) found that amino acids increase in concentration in the vicinity of roots and in higher fertility conditions.

Sugar, aromatic and phenolic acids occur frequently in soils and might possibly be important in chelation of metals, but Stevenson and Ardakani (1972) report that many of these chelates are not stable.

Soluble chelates formed by reaction of metals with carboxyl groups of fulvic acids are responsible for movement of metal ions in the soil during pedogenesis (Geering and Hodgson 1969). They are frequently found in natural waters indicating their movement out of the soil profile.

Insoluble metal complexes are formed through binding of metal ions with both humic acids and clays. Four types of site of attachment of Cu to humic acids were demonstrated but not identified by Broadbent (1957) by eluting Cu from humic acids with various concentrations of hydrochloric acid. Dawson and Nair (1950) found evidence for complexes of Cu with SH and COOH groupings in peat soils.

Hodgson (1963) thought that B might be immobilized through metabolic pathways, and Parks and White (1952) demonstrated that B can form diols such as



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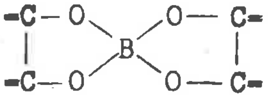


with polysaccharides or cyclic compounds.

Davies (1956) showed that naturally occurring Mo chelates can be found in the soil, and Smith and Leeper (1969) found evidence for retention of added Mo by soil organic matter. The chemical nature of the Mo chelates in soil is still unknown.

c) Synthetic chelates

Micronutrient deficiency in soils has been overcome by application of chelates of the deficient element, and this method is particularly important in high pH and calcareous soils. Various studies have shown that Cu and Zn uptake can be increased by applying chelates rather than inorganic salts. However, the salts are usually used because they are moderately effective in overcoming deficiencies and are much cheaper than the chelates. The latter are mostly used in gardens and orchards.

The behaviour of chelates in soils has been predicted successfully by Lindsay et al (1967), Lindsay and Norvell (1969), Halvorson and Lindsay (1971), Lindsay (1971), Norvell (1972) and others from chelate stability diagrams. For example, Norvell (1972) calculated the stability of metal chelates for defined relationships of H^+, OH^-, Ca^{2+}, Mg^{2+}, Al^{3+} and Fe^{3+}. He showed that Fe was almost completely chelated by EDTA (ethylene diamine tetra-acetic acid), DTPA (diethylene triamine penta-acetic acid) and EDDHA (ethylene diamine di (O-hydroxy-penta-acetic acid))at pH values less than 6. Above pH6 precipitation of $Fe(OH)_3$ becomes important and Fe tends to be replaced in the chelates although EDDHA continues to complex Fe strongly to pH 10.

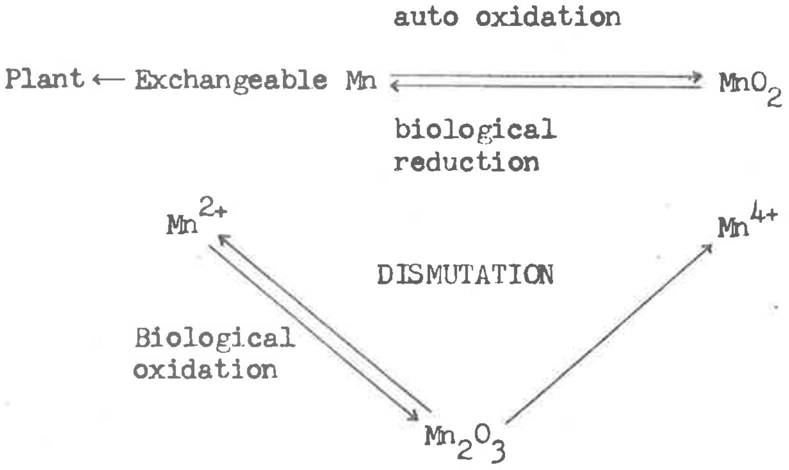
Lindsay et al (1967) tested the stability of Fe chelates in a greenhouse experiment with sorghum on an Fe deficient calcareous soil. For the first crop Fe-EDTA, and Fe-DTPA gave equal responses but did not entirely overcome the deficiency. In the second crop Fe-EDTA gave no advantage but Fe-DTPA continued to give a slight response while Fe-EDDHA was highly available to both crops. Murphy and Walsh (1972) report that Fe chelates of EDTA, HEDTA*, EDDHA have been used in the U.S.A. to overcome Fe chlorosis.

Fe is most strongly complexed by the ligands followed in order by Cu, Zn and Mn. Norvell (1972) showed that Mn chelates would not contribute significantly to available Mn in the soil.

(4) Reduction and oxidation reactions

Mn and Fe are subject to reduction and oxidation reactions in the soil. Olumu et al (1973) showed that valence state changes in Fe and Mn can be caused by chemical and by biological means.

Most evidence shows that biological oxidation of Mn is more important than chemical, even in alkaline soils where the rate of chemical oxidation increases with pH (Rivenbark 1961, Uren 1969). Dion and Mann (1946) proposed the following scheme for Mn transformations in soils.



The essential features of the scheme are:

(i) Watersoluble and exchangeable divalent Mn is available to plants.

(ii) Mn oxidizes spontaneously from +2 to +4 when the pH is greater than 8.

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* hydroxy-ethyl-ethylene-diamine-triacetic acid.

(iii) Biological oxidation of Mn from +2 to +3 occurs when the pH is less than 8.

(iv) Mn^{3+} dismutates to Mn^{2+} and M_2^{4+}.

(v) Micro-organisms may reduce Mn^{4+} to Mn^{2+}.

This scheme over-simplifies the soil reactions. The oxides of Mn include four forms of MnO_2 that have different crystal structures and solubility, and over 20 forms of other insoluble oxides are known e.g. hausmanite (Mn_3O_4) manganite (MnOOH) and cryptomelene (KMn_8O_{16}).

Although micro-organisms reduce and oxidize soil Mn, Leeper (1970) reasons that the processes may also be catalysed by non-microbial organic materials released, for example, by waterlogging resulting in the formation of strong reducing compounds without changes in pH. Drying of the soil reduces the production of MnO_2 by biological oxidation due to the inactivity of the micro-organisms, while the reduction of MnO_2 to Mn^{2+} may proceed through the action of volatile organic compounds such as hydroxybenzaldehyde (Leeper 1970) moving freely in the soil. The net result is increased availability of Mn in the soil.

Fe^{2+} does not exist in significant amounts in soils except under acid or anaerobic conditions where reducing compounds may be formed (Lindsay 1972).

Fe^{3+} is extremely insoluble in water. The reaction $Fe(OH)_3 \rightleftharpoons Fe^{3+} + 3OH^-$ has a solubility product of 10^{-38}. Altering the pH by one unit alters the solubility of Fe^{3+} 1 000-fold. The pH has to be lowered to 4 before Fe^{3+} concentration becomes micromolar (Leeper 1970).

C Plant factors affecting micronutrient availability

(1) Genotypic variations

Differences between species and varieties in susceptibility to micronutrient deficiency are common. For example, wheat, oats and barley are more susceptible to Mn deficiency than vetch and beans (Nambiar and Cottenie 1971). Loneragan, J.S., Gladstones, J.S. and Simmons, W.J. (1970) cited by Brown et al (1972) found that rye and oats took up more Mn, and both were better adapted to low Mn soils than barley and wheat. Reith (1968) reported that oats and barley are more likely to be deficient than grass-clover pasture. Piper (1942) and Smilde and Henkens (1967) found that wheat was more susceptible to Mn deficiency than oats and rye. In particular climatic zones only a narrow range of genotypes of each cereal species is grown and differences between species may be apparent but over a wider range of climate differences between cultivars assume greater importance.

Gallager and Walsh (1943) indicated that different cultivars of each cereal could be found such that some were susceptible to and others tolerant of low concentrations of available micronutrients in the soil. They deduced from this that it is not valid to make comparisons between species of cereals until the cultivars have been examined against one another. Greaves and Anderson (1936) showed that resistance in wheat to Cu deficiency may be partly due to higher uptake in resistant cultivars. They showed that resistant cultivars of wheat contained higher concentrations of Cu in the grain than susceptible varieties on deficient soils.

Various mechanisms through which differential uptake of nutrients may occur between species and cultivars are reviewed by Vose (1963). The distribution of roots in the various soil horizons may have a large bearing on the amount of micronutrient that can be absorbed. In section A (p. 34) it was shown that micronutrients are frequently more available in the topsoil than within other horizons. ~~and~~ Hence plants with high proportions of roots in the topsoil might be expected to absorb more micronutrients than deep rooting plants.

Brown _et al_ (1961) showed that Fe utilisation by soy-beans was enhanced by fluorescent reducing compounds. These were exuded by the roots of healthy soy-beans but were absent from the roots of deficient plants. The effect was shown to be related to a single gene difference between the two strains.

Differential tolerance of species to toxicity occurs also. Brown _et al_ (1972) illustrated this by comparing potatoes and barley grown in rotation on acid soils containing high available Al concentrations. The potatoes grew normally while the barley showed severe toxicity symptoms. These authors report variable concentrations of Mn that can be tolerated in the tops of plants. Rice can contain 2 500 ppm, beans 1 000 ppm and peas only 500 ppm before toxicity symptoms appear.

Brown _et al_ (1972) also discuss the mechanisms of tolerance to high concentrations of micronutrients. For example, Cu is precipitated as CuS or removed from solution as protein complex. Zinc tolerance in bentgrass is due to reaction of zinc with pectins in cell walls of roots and by formation of stable anionic structures in the tops of resistant cultivars.

(2) Rhizosphere effects

The micronutrient requirement of plants is usually very small and any change in the supply of available forms in the soil may determine whether plants are deficient or not. Changes in rhizosphere conditions are also important because most of the micronutrient absorbed by roots comes from the rhizosphere volume, due to the relative immobility of micronutrients with the exception of boron.

Several effects that influence micronutrient availability take place near the root. During the process of water absorption ions are transported towards the root surface. Differential ion uptake may occur. Cations and anions are absorbed by the root and H^+ or HCO_3^- released into the soil to maintain electrolytic neutrality. If more cations than anions are absorbed the soil pH is lowered while excess anion absorption increases pH. The evolution of CO_2 by the root during respiration may also decrease pH. Wilkinson (1972) argued that ions such as Ca^{++} moved to the plant root by convection and excluded from entry into the root could change the precipitation and adsorption reactions of other ions in the region.

Exudates from the plant roots may directly affect soil pH or form chelates with micronutrients sometimes increasing their mobility and even bringing insoluble forms into solution. Exudates also stimulate growth of micro-organisms which may compete with plants for micronutrients. Rovira (1965) showed that the micro-organism content of the rhizosphere is 10-50 times higher than in the soil beyond. The micro-organisms themselves accelerate release of nutrients from insoluble sources (Ivarson et al 1970, Wilkinson 1972). On the other hand, Mn oxidizing bacteria in the rhizosphere of susceptible oat varieties have been demonstrated by Timonin (1946) who inferred from this that the deficiency was caused by oxidation of Mn by the bacteria. Other effects of micro-organisms and exudates are described by Rovira (1965), Foy et al (1967), Riley and Barber (1969) and Wilkinson (1972).

D Micronutrient soil tests

Micronutrient soil tests are designed to provide a diagnostic method to separate soils on which micronutrient deficiency occurs from those not deficient. Relatively few attempts have been made to grade responses to applied micronutrients because the micronutrient requirements of most crops is small and soils are often classified as responsive or unresponsive. The following methods are used:

(1) Biological tests

Fried and Dean (1952) developed the glasshouse 'A' test to determine whether an extractant removes available forms of the nutrient being studied, as judged by comparison with plant uptake. Other workers have added micronutrients to soil collected from the field and measured growth responses to applied nutrients. The Mitscherlich equation can generally be used to describe the growth response; all other nutrients being in ample supply.

$$\frac{dy}{dx} = (A - y)c \quad \text{where}$$

y is the yield when the amount of nutrient (x) is applied. A is the maximum yield and c is a constant.

Microbiological techniques have been used to detect available levels of micronutrients in the soil. Nicholas (1960) specifies eight requirements of micro-organisms to be used in bioassay procedure, and concludes that *Aspergillus niger* fills these prerequisites. Besides *A. niger* other fungi, bacteria, yeast and blue green algae have been used to detect available micronutrients (Donald *et al* 1952).

Donald *et al* (1952), Tucker *et al* (1953) and Pinkerton (1967) used *A. niger* to detect available forms of Cu, Zn, Mn, Co, Fe and Mo. Donald *et al* (1952) collected samples of several great soil groups from various parts of Australia known to be deficient in Cu, Zn, Mn, Fe or Mo as a result of field experiments with various crops. They found that deficiency in *A. niger* on these soils corresponded with deficiency of Cu, Zn and Mo but not Mn or Fe. Roschach (1961) found that the concentration of soil Mo extracted with ammonium oxalate was correlated ($r=0.8$) to the concentration of Mo extracted from the soil by *A. niger*. The main limitation to biological techniques of soil testing is the length of time and labour required to do the test.

(2) Chemical tests

Bray (1948) proposed that ideally, extractants used for soil tests should extract all or a proportionate part of the available form of the nutrient in the soil. The nutrient should be accurately and quickly measurable, and the amount extracted should be correlated with the growth response of each crop to that nutrient.

Quantity-intensity relationships of the extracted ion are important with micronutrients because only a small proportion of the total element is removed. Successive extractions may remove similar amounts of micronutrient or a sharp decline may occur. Tiller et al (1972) showed in a range of South Australian soils, that the amount of Zn extracted with EDTA solution decreased with successive extractions and then reached a constant value. This was interpreted as removal of Zn by dissolution rather than desorption. Tiller et al (1972) also emphasized the need for careful consideration of pH, soil-solution ratio, and amount of time for shaking.

Water soluble fraction

Water has been used as an extractant to remove soluble or weakly adsorbed forms of Cu, Mn, Mo and B. Although the quantity of element extracted is sometimes very low and difficult to measure, it is often closely related to uptake by crops. Berger and Truog (1940) and Wear (1965) used hot water as an extractant for B, because nearly all added B could be recovered from the soil by this method. Barshad (1951) showed that Mo extracted with hot water was closely related to uptake by plants.

Neutral salts

Solutions of NH_4Cl, NH_4NO_3, $NH_4C_2H_3O_2$, $CaCl_2$, $Ca(NO_3)_2$, $MgCl_2$

and $NaNO_3$ have been used to remove micronutrient cations weakly adsorbed by colloidal sized particles (Cox and Kamprath 1972). Exchangeable Mo has been displaced from the soil by solutions of oxalate, acetate, citrate and resins (Grigg 1953, Bhella and Dawson (1972).

Dilute acids

Acids have been used extensively to remove water soluble, exchangeable and soluble combined forms of Cu, Zn, Mo and B from the soil. Dilute HNO_3 was used to extract Cu from low moor and fen peat soils of Europe (Knabe 1967) and the concentration of Cu in the extract was closely related to yield response and plant uptake. Wear and Evans (1968) showed that the concentration of Zn extracted with dilute HCl and H_2SO_4 from 12 coarse textured soils from southern U.S.A. was highly correlated ($r=0.89$) with Zn uptake by corn.

Cox and Kamprath (1972) report that Mo and B extracted by dilute acids from a range of soils in Europe and U.S.A. were not closely correlated with yield increase or uptake, and that extraction by water gave better correlations.

Acids have disadvantages as extractants because they radically alter the pH of the soil, and this may itself change the availability of micronutrients (Hodgson 1963). Soils with high carbonate concentrations may release occluded elements, as well as neutralizing the acid extractant.

Chelating agents

Strongly bound or adsorbed forms of Cu, Zn, Fe, Mn and Mo have been extracted from the soil by solutions of EDTA, EDDHA and DTPA. Mn and Mo are not readily complexed by soil organic matter, and there is less scope for the use of chelates.

The amounts of micronutrient extracted from the soil by the chelating agent are often closely correlated with plant response, are high enough to be measured easily by atomic absorption methods, and consequently are used widely in soil testing laboratories (Viro 1955, Fiskell 1964, Johnson and Young 1968, Norvell and Lindsay 1969, Lindsay and Norvell 1969 a and b).

Reducing agents

Easily reducible Mn can be extracted by adding solutions of quinone (Jones and Leeper 1950) or hydroquinone (Johansson 1962). $NH_4C_2H_3O_2$ has been used with quinol but breakdown of higher oxides that are not considered to be available to plants occurs. These methods have not been used extensively due to low correlations frequently obtained between extracted amounts of Mn and plant uptake.

(3) Calibration and interpretation

The usefulness of soil tests depends on the effort put into calibration, and in defining the conditions to which the results apply. Factors that influence the interpretation of a soil test include the ability of the soil to replenish removed nutrients, and the effect of pH, lime and clay on the amount extracted. The managerial skills of the farmer, yield potential of the land, type of crop being grown and social and economic aims also affect interpretation.

Standards for interpretation of soil tests need to be defined. Some authors, for example Trierweiler and Lindsay (1969) simply separate soils into two groups - deficient and non-deficient. Cate and Nelson (1965) plotted lines parallel to the X (soil concentration) and Y (% yield response) axes so that most of the points were contained

TABLE 7

Soil Test Methods, soil factors influencing their interpretation and typical ranges in critical values

Element	Interacting factors	Extractant	Range in critical values ppm soil
B	Texture pH Lime	Hot water	0.1-0.7
Cu	Organic matter Fe	$NH_4C_2H_3O_2$ (pH 4.8)	0.2
		0.5 m EDTA	0.75
		0.43 N HNO_3	3-4
		Biological assay	2-3
Fe	pH Lime	$NH_4C_2H_3O_2$ (pH 4.8)	2.0
		DTPA + $CaCl_2$ + TEA (pH 7.3)	2.5-4.5
Mn	pH Organic matter	0.05 N HCl + 0.025 N H_2SO_4	5-9
		0.1N H_3PO_4 + 3N $NH_4H_2PO_4$	15-20
		hydroquinone + $NH_4C_2H_3O_2$	25-65
		H_2O	2
Mo	pH, Fe P, S.	$(NH_4)_2C_2O_4$ (pH 3.3)	0.04-0.2
Zn	pH, lime, P	0.1N HCl	1.0-7.5
		Dithizone + $NH_4C_2H_3O_2$	0.3-2.3
		EDTA + $(NH_4)_2CO_3$	1.4-3.0
		DTPA + $CaCl_2$ (pH 7.3)	0.5-1.0

in the lower left hand and upper right hand quadrats. The intersection with the X axis was defined as the critical value. Table 7, adapted from Cox and Kamprath (1972), gives the main extractants used to detect available micronutrients in the soil, and presents likely interacting factors that cause wide ranges in critical values obtained.

E <u>Occurrence of micronutrient deficiencies</u>

The nature of the parent material of the soil, its organic matter, carbonate and clay content and pH frequently determine whether enough micronutrient is available for normal plant growth.

<u>General</u>

Copper deficiency frequently occurs on organic soils and peats in Europe and U.S.A. (Van Alphen 1956, Kubota and Allaway 1972). Other soils on which Cu deficiency occurs include sandy soils with low Cu content in parent material in Scotland (Reith 1968) and Australia (Stephens and Donald 1958), and the lateritic podzolic soils of Australia (Tiver 1956, Gilbey <u>et</u> <u>al</u> 1970).

Zinc deficiency most commonly occurs on neutral to alkaline soils where the Zn is unavailable to plants (Viets 1966). The calcareous grey brown soils of heavy texture, gilgae soils and calcareous lake bed soils of the Riverina in Australia (Kleinig <u>et</u> <u>al</u> 1962), clayey calcareous soils in the Wimmera of Victoria (Jessop and Tuohey 1973), and black earth soils of the Darling Downs of Queensland (Duncan 1967) are Zn deficient. Acid leached sands and podzolic soils of Australia are deficient in Zn due to low concentrations in the soil (Stephens and Donald 1958, Ozanne <u>et</u> <u>al</u> 1965 and Anderson 1970). In the U.S.A. responses have been obtained on various textured soils from sands to clays (Viets 1967). Cass Smith (1948) similarly reports a wide range of texture for responsive soils in Western Australia.

Availability of Mn to plants is closely related to soil pH and carbonate content. Australian soils reported to be deficient include calcareous sands, terra rossas, rendzinas and shallow calcareous soils (Stephens and Donald 1958, Leeper 1970). Kubota and Allaway (1972) report examples of Mn deficiency in reclaimed highly organic soils of U.S.A. and Tiver (1956) found deficiency on lateritic podzolic soils in Australia.

Boron deficiency is often associated with humid areas and soils with low organic matter content (Berger and Truog 1945, Berger 1962). Cooling and Jones (1970) and McComb et al (1970) found B deficiency on plateau soils of Zambia and basaltic soils in Nigeria respectively. In contrast to the studies mentioned, Burdine and Guzman (1969) showed responses on organic soils in Florida. B deficiency has been proved on silty soils in France (Dutil 1970) and granitic soils of New South Wales by the Biology Branch of the Department of Agriculture.

Deficiency of Mo occurs extensively in Australia and New Zealand on lateritic soils, deep siliceous sands and many others (McLachlan 1955, Davies 1956, Stephens and Donald 1958 and Leeper 1970). Deficiency has been reported in the U.S.A. by Berger (1962) and in Holland (Henkens 1972) on sandy soils and acid organic soils with high iron content.

Kubota and Allaway (1972) report that Fe deficiency may occur on a wide range of soils but the most frequent occurrence is on arid calcareous soils, with high pH.

Occurrence in South Australia

The histories of South Australian agriculture, horticulture, forestry and pastoral industries are dependent on discoveries of

Cu, Zn, Mn, Mo and Fe deficiencies while B deficiency is rare. An occurrence of B deficiency was reported in the Adelaide Hills by Walkley and Kemp (1939) and Piper (1936) indicated that B deficiency was unlikely in South Australia. Summaries of plant and animal responses to micronutrients on various soils of South Australia are given by Riceman (1943), Tiver (1956), Stephens and Donald (1958) and Pearson (1962).

The calcareous sands and rendzina soils of South Australia have been shown to be deficient in Cu, Zn, Mn and Fe by Samuel and Piper (1928), Blackburn (1959), Winn (1965), Seeliger (1971), Reuter and Alston (1972) and Egan (1972).

Deep siliceous sands and solodized solonetz soils of the upper South East were shown to be deficient in Cu, Zn, Mn and Mo by Riceman (1943-1949), Riceman and Powrie (1948). Later, responses to these elements on these soils were also reported by Tiver (1956), French (1958), Blackburn (1959), Pearson (1962) and Bicknell (1965).

Responses to Cu, Zn, Mn, Mo and Se have been reported on the lateritic podzolic soils of South Australia by Anderson (1942), Tiver (1956), French (1958), ~~and~~ Carter and Wigg (1963) and Godwin et al (1970).

Red-brown earths and mallee soils are relatively free of micronutrient disorders with marginal deficiencies of Zn being reported by Seeliger (1968).

The application of lime to solodized solonetz and lateritic podzolic soils has induced Fe and Zn deficiency and overcome Mo deficiency (Stephens and Donald 1958, Carter and Wigg 1963).

IV LAND AND SOIL CLASSIFICATION AND MAP

Two areas shown in Figs. 1 and 2 were chosen to represent the soils in the solodized solonetz and leached sandhill, and podzol and solodized solonetz mapping units of French (1958). The area in the former unit is referred to as Wharminda and the latter, Stokes. The areas were delineated so that the climate was similar in each but large differences occurred between them.

Mapping system

Land components and land units (Gibbons and Downes 1964) were identified in each area and marked onto 1: 16,000 aerial photographs. The land component is an area where climate, parent material, topography, soil and vegetation are uniform within the limits significant for a given form of land use. The land components are seldom distributed at random but occur in subrandom patterns. This makes it possible to describe larger areas in terms of basic sequences of components termed land units. Idealised block diagrams are presented for each land unit showing the relative proportion of the land components.

FIGURE 1

Wharminda - showing land units

Land Units

I Dune and swale system

II Irregular dunes and flats

III Rock strewn calcrete hills

IV Rounded hills, broad flats

V Stream valley

WHARMINDA

PARTS OF HUNDREDS OF VERRAN AND BUTLER

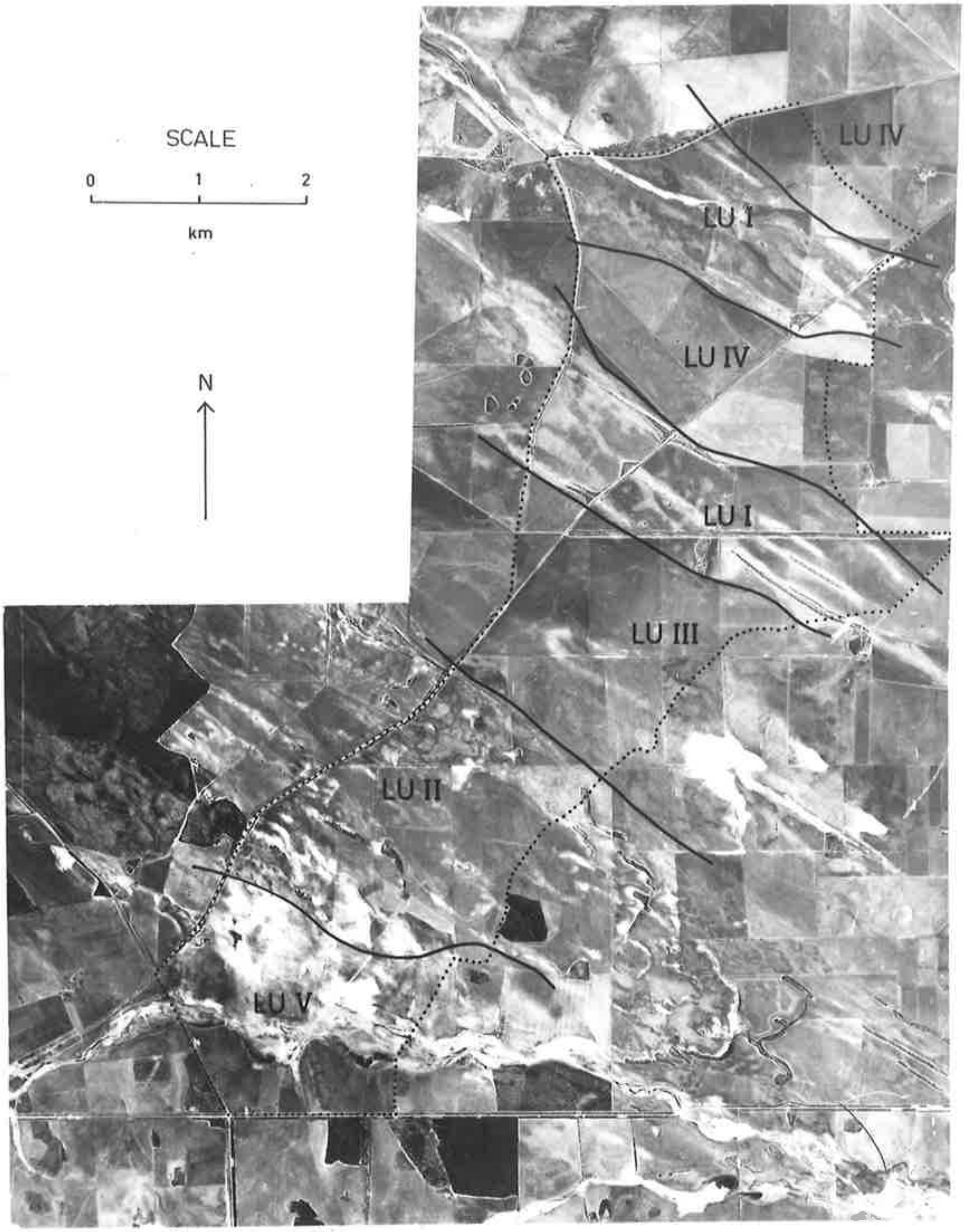


FIGURE 2

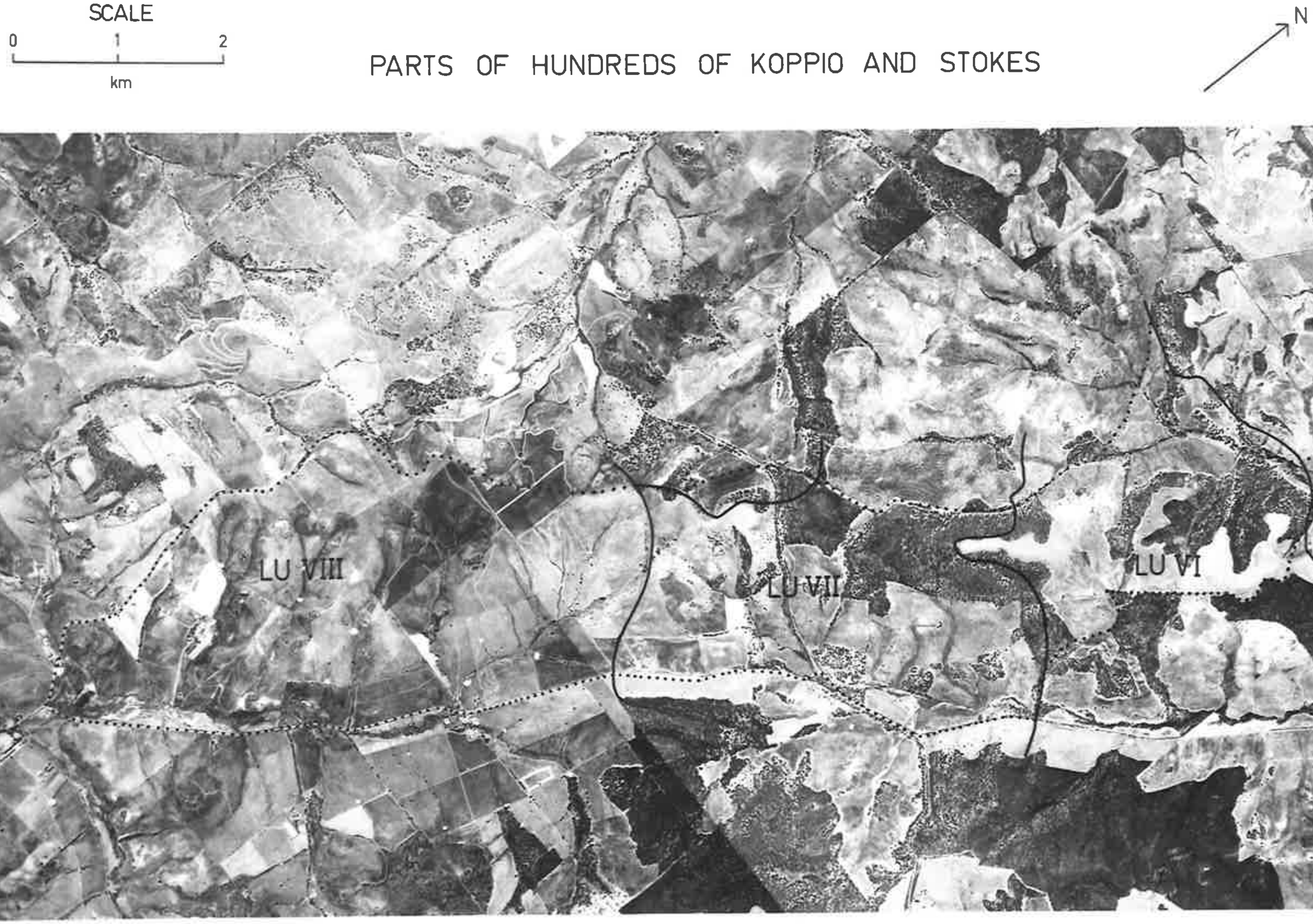
Stokes - showing land units

Land Units

VI	Lateritic peneplain, steep scarp
VII	Low rounded hills
VIII	Lateritic peneplain, dentrital ridges and gullies

STOKES

PARTS OF HUNDREDS OF KOPPIO AND STOKES



Soils of the land components were mapped by free survey as outlined by Beckett (1968). Single land components were usually comprised of one or two soil mapping units.

Colour of the surface soil, surface rock, and plant species were useful for fixing soil boundaries and could often be distinguished on the photographs. Geological data of Johns (1961) was used in Stokes but little geological information was available for Wharminda. The mean density of profile pits was 0.25 per ha.

The soil was classified into great soil groups (Stace et al 1968) and then keyed to principal profile form (Northcote 1971). Further subdivisions were made using differences in texture, depth and colour of A horizons, depth of solum, presence of and form of laterite. Grouping of several principal profile forms into one soil mapping unit was made where soils had small structural or colour differences in the A or B horizons or where cultivation, or wind and water action had mixed or removed shallow A horizons, locally producing several principal profile forms. Areas where wind or water erosion had removed large amounts of soil were mapped as one unit. No attempt was made to identify the soils in such areas. Small areas (2-4 ha) of red-brown earth and solodic soil were mapped together, because they were too small to warrant separation.

The following procedures were adopted in the subsequent description:

(i) Occurrence: Each soil is located in the land units (abbreviated LU), which are referred to by Roman numeral, and in land components referred to by a letter.

(ii) Profile description: Physical and chemical description of the soil profiles at the sites of the factorial experiments are given in Appendix 1.

(iii) Definitions of soil terms used in the text were taken from Northcote (1971). Soil Mapping Unit is abbreviated to SMU.

(iv) Names for the original plant community and botanical names of species were taken from Black (1943-1957) Boomsma (1971) and Specht (1972). Botanical names are used in the text when a species is mentioned for the first time. Subsequently common names are used for the better known species. Both common and botanical names are given in Appendix 2.

Soil maps of Wharminda and Stokes are included at the back of the thesis. These maps indicate the great soil groups and principal profile forms of the soil in the mapping units.

WHARMINDA

Sections 4 Verran, 19,20 Butler

This area extends from the township of Wharminda in a south westerly direction for about 10 km. It is 2 km wide and 2,350 ha in area.

Archean basement rock is overlain by Quarternary limestone and recent aeolian deposits (Johns 1961). The area tilts gently downwards towards the east and sand dunes are orientated in a N.W. - S.E. direction across it. At least two movements of sand occurred as siliceous and calcareous dunes exist and frequently can be found superimposed, the former overlying the latter. Ephemeral stream beds trend parallel to the dunes.

Mean annual rainfall at Wharminda is 330 mm, 65 per cent occurring between May 1 and October 31 (Appendix 3). Rainstorms can occur in all seasons. Winter temperatures are mild, the mean maximum July temperature at Cleve is 15°C. The summers are hot, the mean maximum January temperature being 28°C. Mean annual temperature for each month at Cleve is given in Appendix 3. The drought frequency at Cleve is 41% and at Arno Bay is 52% (Trumble 1948). For comparison in the Wharminda area the drought frequency is 50±%

Small areas of original vegetation remain on skeletal soils, along roadsides, and on high dunes where clearing is restricted by law. A number of types of mallee (Eucalyptus gracilis F.v.M., E. incrassata Labill, E. leptophylla F.v.M., E. oleosa F.v.M.) are dominant on these uncleared areas.

The land is used for sheep and cereal production with cattle becoming more important in recent years. Wheat is grown on the more fertile areas and barley and cereal rye on the less fertile sandy soils. The pastures consist chiefly of annual grasses - Wimmera ryegrass (Lolium rigidum Gaud.), rigid brome (Bromus rigidus Roth.), barley grass (Hordeum leporinum Link) and wild oat (Avena barbata Brotero.), together with lesser amounts of annual medics. Areas of lucerne (Medicago sativa L.), perennial veldt grass (Ehrharta calycina Sm.), evening primrose (Oenothera spp) and blue lupin (Lupinus pilosus L.) occur on deep sands.

Since clearing of the land in the 1920's wind erosion has been a continuous problem. At first the problem was extremely serious due to low soil fertility and insufficient management experience. At present the problem is less severe but it still affects crops which are easily damaged by moving sand.

References to erosion in the Soil Mapping Units sections refer to wind action because this occurs nearly every year. Water erosion occurs on rare occasions and is associated with storms. In 1966, storms that produced 330 mm of rain in five days led to gullying and sheet erosion, which together removed much surface soil from certain land components.

The following categories are used to describe wind erosion:

(i) Extremely high erosion risk describes conditions where light winds move sand. Generally the sand is deep and plant growth is very poor, as on dune crests.

(ii) Severe erosion occurs on dune slopes where some protection from wind occurs. However, extensive damage to crops may occur particularly when wind direction is along the slopes of the dunes.

(iii) Moderate erosion occurs on sandy areas where higher fertility results in more rapid growth of pasture and crop and residues protect the soil surface from wind. Here erosion occurs only in dry windy years.

Loamy sands covered with crop residue or pasture have a low likelihood of erosion. Calcareous loamy surfaces resist drift and there is no risk of erosion.

LAND UNITS

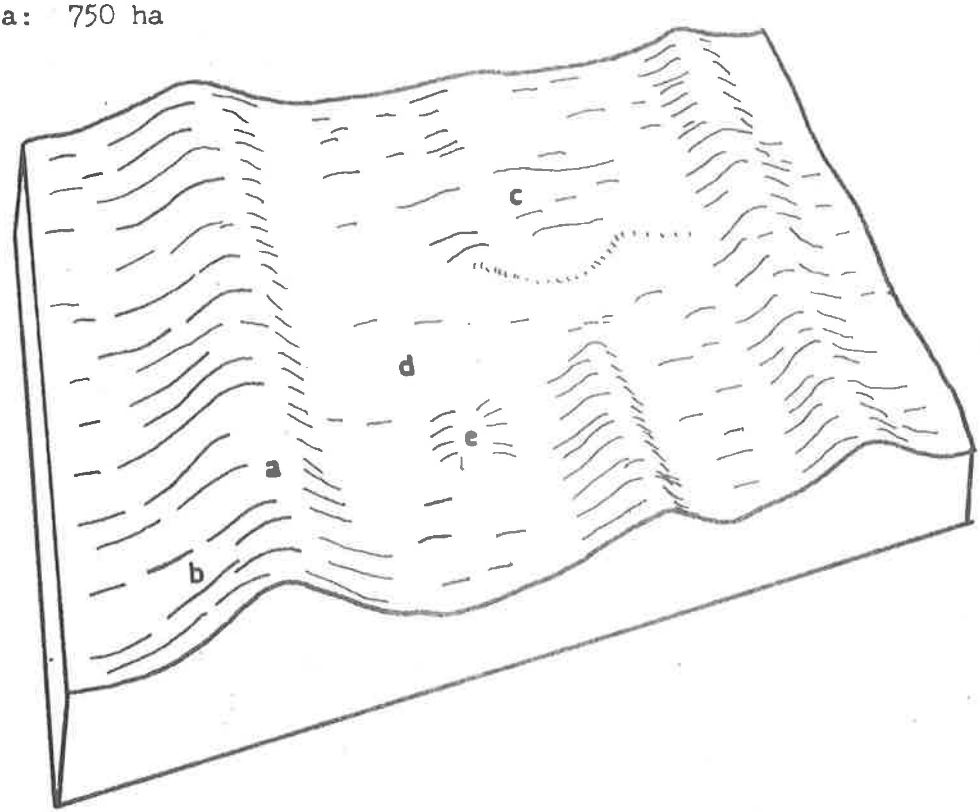
Five land units were identified as shown in Figs. 3-7.

FIGURE 3

LU I Dune and swale system

Parallel siliceous sand dunes originating from the western part of Eyre Peninsula cross Wharminda in two distinct areas.

Area: 750 ha



a Tops and upper slopes of dunes

b Middle and lower slopes of dunes

c Sandy rises in flats

d Flats between dunes

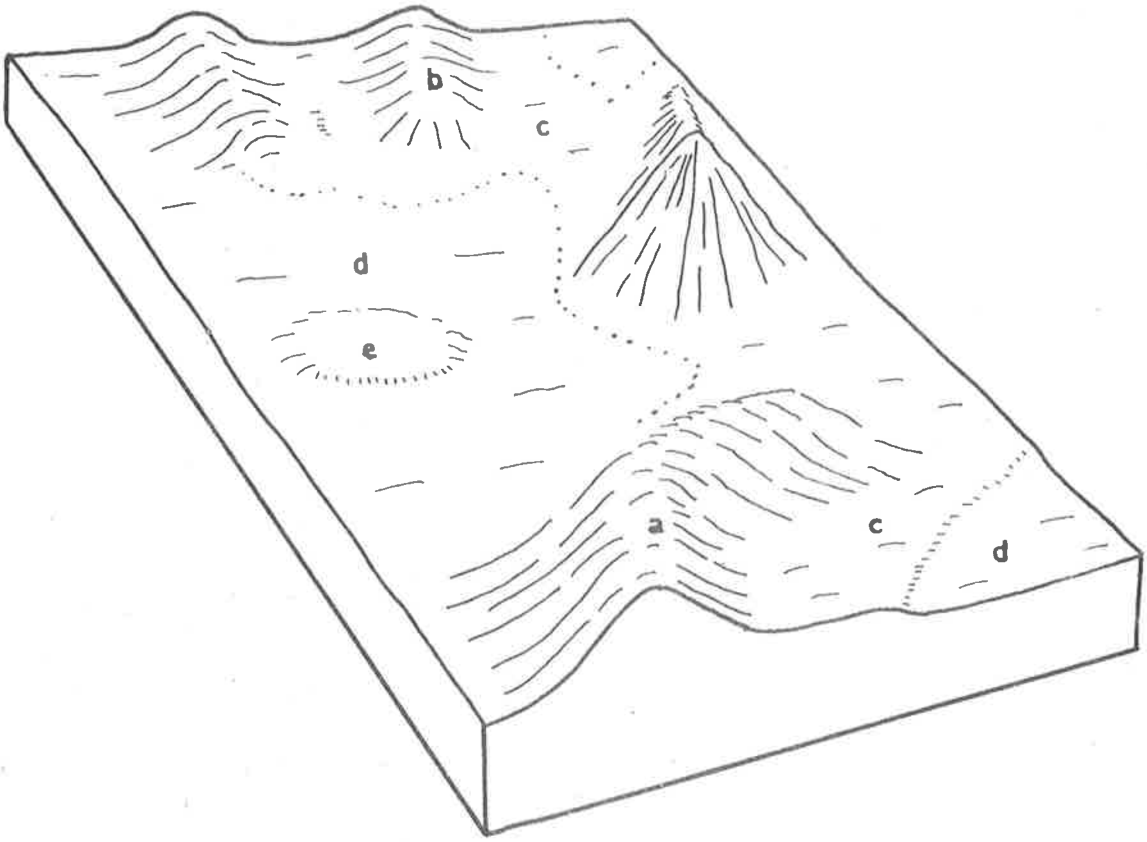
e Calcrete rises in flats

FIGURE 4

LU II Irregular dunes and flats

The calcareous sands of the Tooligie-Nicholls area (French 1958) form a long, thin spur in the south-east which crosses Wharminda, forming this land unit.

Area: 470 ha



a Crests of high dunes

b Lower slopes of high dunes, low dunes

c Slightly raised, undulating area between dunes

d Broad flats

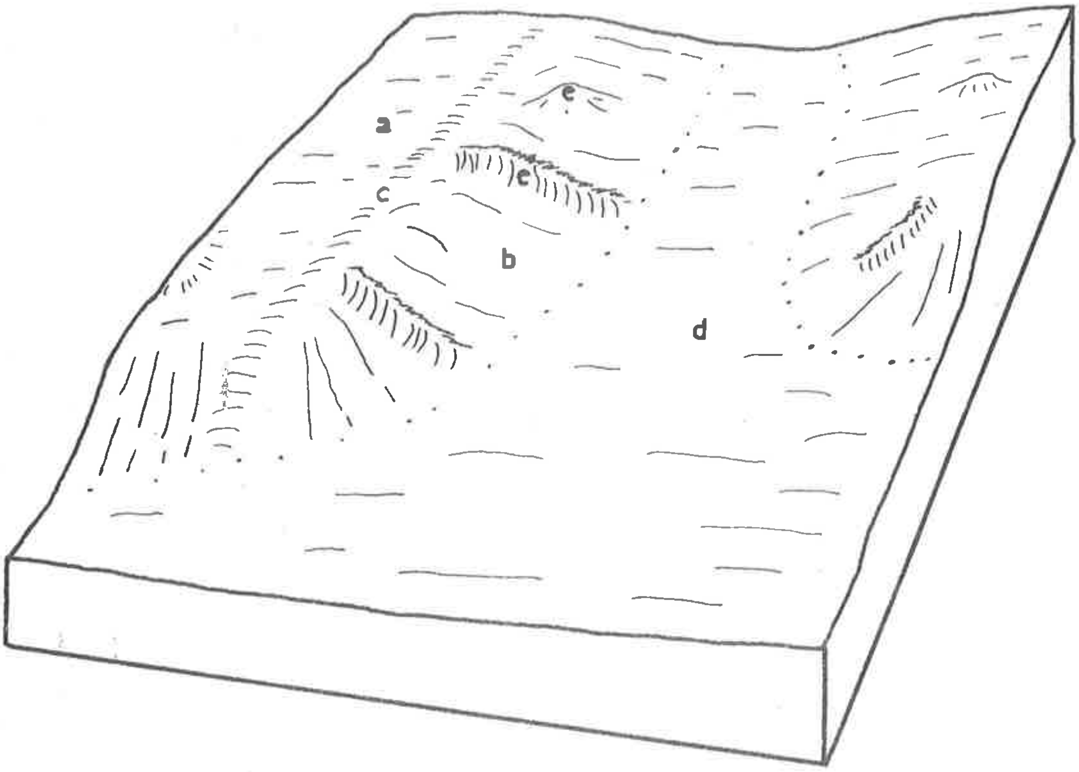
e Calcrete rises on flats

FIGURE 5

LU III Rock strewn, calcrete hills

Surface calcrete is a feature of the unit. Soils are shallow and include recent deposits of sand.

Area: 410 ha



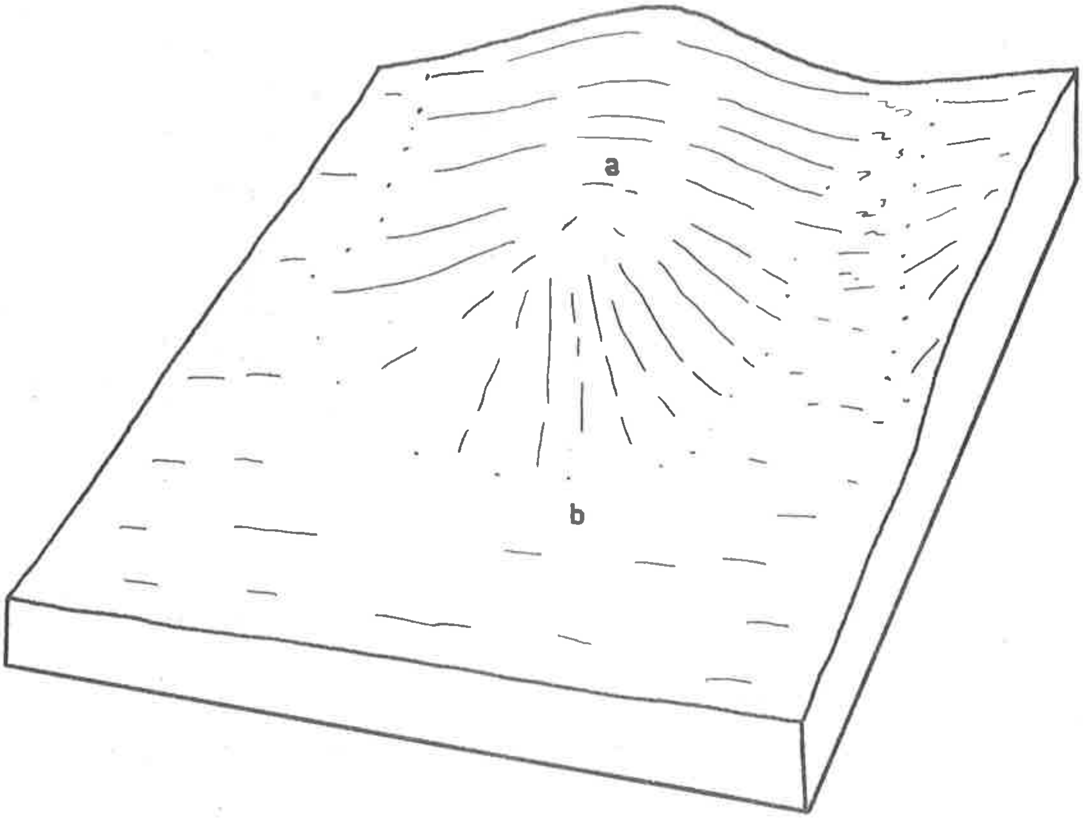
- **a** Flat tops and upper slopes of hills
- **b** Lower slopes of hills
- **c** Raised areas of sand
- **d** Flats between hills
- **e** Sharp calcrete ridges

FIGURE 6

LU IV Rounded hills, broad flats

Gently undulating area with broad flats. Almost devoid of surface calcrete.

Area: 390 ha



a Low rounded hill

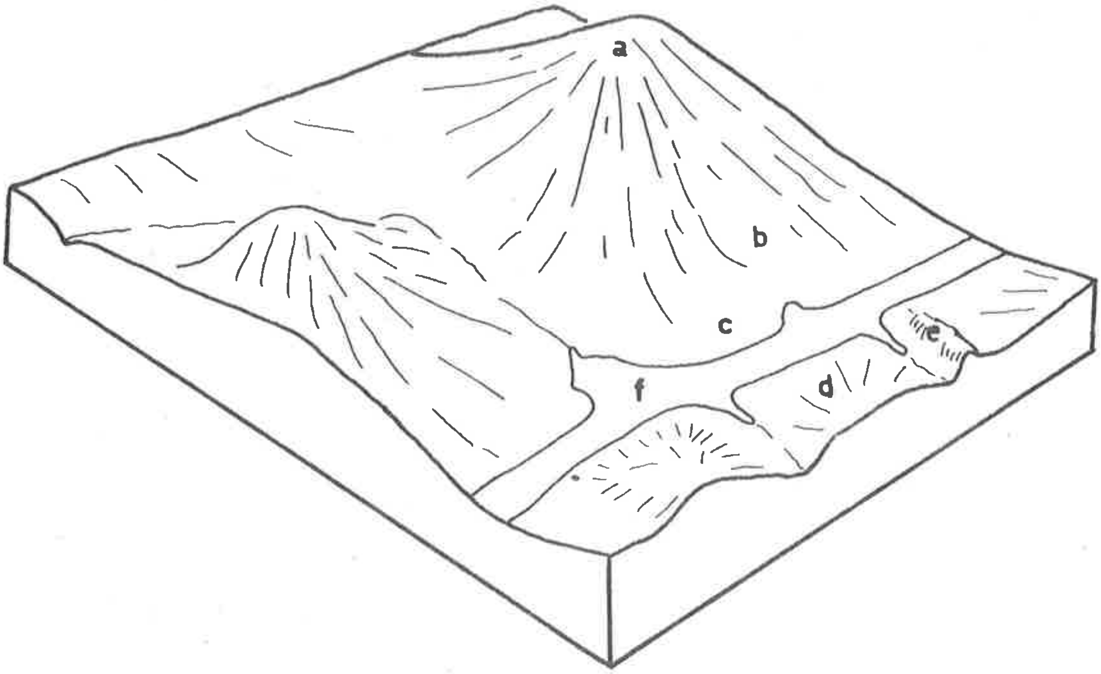
b Broad flat

FIGURE 7

LU V Stream valley

The southern end of Wharminda is crossed by the Dutton river which is an ephemeral, saline stream in a mature valley.

Area: 400 ha



a Upper slopes and tops of hills

b Lower slopes of hills

c Dutton river flats

d South bank slopes with abrupt boundary to watercourse

e Sharp calcrete ridges

f Water course

SOIL MAPPING UNITS

SILICEOUS SANDS

1. Deep sand

Principal Profile Form : Uc2.21

Morphology : Deep sand, greater than 75 cm and often 5 m deep. Three horizons exist. An organic A_1 usually very light-brown (dry) overlying a white (dry) A_2 grading to brownish yellow as the A_3 merges into the B horizon. This is underlain by sandy clay, limestone or calcareous sand.

Occurrence : Land Units I a, II c, V a b

Profile description : 1, 2, 3

Original vegetation : Low woodland. Dominant trees : *Eucalyptus incrassata*, *Eucalyptus gracilis*, *Casuarina stricta* Ait. Common herbs : *Themeda* spp., *Danthonia* spp.

Land use : Grazing and intermittent cropping. Common pasture species are perennial veldt grass, evening primrose, blue lupin. Crops grown are cereal rye, barley and wheat. Erosion risk is extremely high. Crown law prohibits clearing of this soil where it occurs in high dunes. Vermin are a serious problem where this soil carries natural vegetation.

2. Shallow sand

Principal Profile Forms : Uc1.41, Uc5.22, Uc5.11, Uc2.11

Morphology : Solum is shallow (usually less than 15 cm) and low in carbonate although underlain by calcrete. The A2 is bleached or coloured, B horizons may or may not be present.

Occurrence : Land Units III a, V a

Original vegetation : Low woodland. Dominant trees : Eucalyptus incrassata. Common shrubs : Melaleuca uncinata R.Br., Leptospermum spp.

Land use : Grazing and cropping, shelter belts. Pasture consists of silver grass (Vulpia myuros (L.) Gmel.) rigid brome, barley grass, Wimmera ryegrass and cluster clover (Trifolium glomeratum L.). Wheat and barley are grown. Erosion risk is severe. Much of this soil is left under scrub because calcrete prevents cultivation.

CALCAREOUS SANDS

3. A_1 Horizon low in carbonate

Principal Profile Form : Uc5.12

Morphology : A_1 horizon, low in carbonate and darker in colour than underlying material. Soft carbonate concretions occur at 70 cm.

Occurrence : Land Unit II b

Original vegetation : Low woodland : Eucalyptus spp.

Land use : Grazing and cropping. Pasture consists of barrel medic (Medicago truncatula Gaertn.) cv. Hannaford and woolly burr (Medicago minima (L.) Grufb.) medic with silver grass, rigid brome, Wimmera ryegrass, wild turnip (Brassica tornefortii Govan.), Lincoln weed (Diplotaxis tenuifolia (L.) DC.) and capeweed (Arctotheca calendula (L.) Levyns). Wheat and barley are cropped. Erosion risk is moderate.

4. Calcareous throughout

Principal Profile Form : Uc1.11

Morphology : A_1 horizon, slightly darker in colour than underlying material. Soft concretions of carbonate occur at varying depths below the surface

Occurrence : Land Unit II a

Profile description : 4

Original vegetation : Low woodland. Dominant trees : *Eucalyptus incrassata*, *Eucalyptus gracilis*. Common shrubs : *Melaleuca uncinata*. Common herbs : *Triodia irritans* R.Br., *Themeda* spp.

Land use : Grazing, intermittent cropping, shelter belts, Pasture consists of barrel medic, Lincoln weed, wild turnip, capeweed, silvergrass, rigid brome and Wimmera ryegrass. Wheat and barley are cropped. Erosion risk is moderate and restriction of clearing has been imposed on some areas.

SOLODIZED SOLONETZ AND SOLODIC SOILS

These are the most extensive soils of Wharminda. The solum of these soils varies in depth from less than 15 cm to one metre. There is no clear demarcation between deeper phases of the solodized solonetz and solodic soils and the deep siliceous sands.

Six subdivisions of the solodized solonetz and solodic soils based on colour and texture of the A_1 horizons, depth of the two A horizons and solum depth were recognized (Table 8) and mapped.

The subdivisions are associated in the field with differences in vigour of plant growth, botanical composition and management practice.

TABLE 8

Subdivisions of solodized solonetz and solodic soils

SMU	Principal Profile Forms	Subdivision	Occurrence Land Units	Profile description
a. A_1 horizon very light brown (dry) sand				
		A horizon depth		
5	Dy5.83	> 45 cm	I b c, II c, V b	5,6
6	Dy5.83	30-45 cm	I b c, II c, V b	7
7	Dy5.83 Dy5.43	15-30 cm	I b c, II c, III c, V b c	8,9
8	Dy5.43	< 15 cm	I b c d, II c d, III c, IV b, V b c	10
b. A_1 horizon brown (dry) loamy sand A horizons <15 cm deep				
		Solum depth		
9	Dy5.43 Dy5.83 Dy5.13 Dy5.53 Dr5.43 Dr5.83	> 15 cm usually 50-100 cm	I d, II d, III d, IV b	11,12
10	Dy5.83 3	< 15 cm	I e, II e, IIIa b e V a b	13

Morphology :

a Soils with very light brown (dry) sand A_1 horizons :

The A horizons consist of an A_1 slightly darkened by organic matter and a bleached A_2. The deeper soils show yellowing at the base of the A_2. B horizons are yellow mottled sandy clay with soft carbonate concretions or calcrete lower in the horizon. Soils in SMU 7 and 8 show pronounced doming at the surface of the B horizon.

b Soils with brown (dry) loamy sand - sandy loam A_1 horizons : The A horizons consist of a dark coloured A_1. An A_2 horizon of white (dry) sand is sometimes present but cultivation often mixes it with the A_1. B horizons are red or yellow, mottled, blocky or apedal underlain at varying depth by calcrete.

Fig. 8 shows the horizons of the dune-swale system. The depth of sand has a large effect on the horizons that develop. In the deepest sand areas a yellowish brown B horizon develops that intensifies in colour as depth increases. It appears that depth of sand affects the nature of Fe compounds that occur.

The clay layer of the solodized solonetz and solodic soils is finest in texture and shows the greatest amount of doming when the depth of sand above it is less than 30 cm.

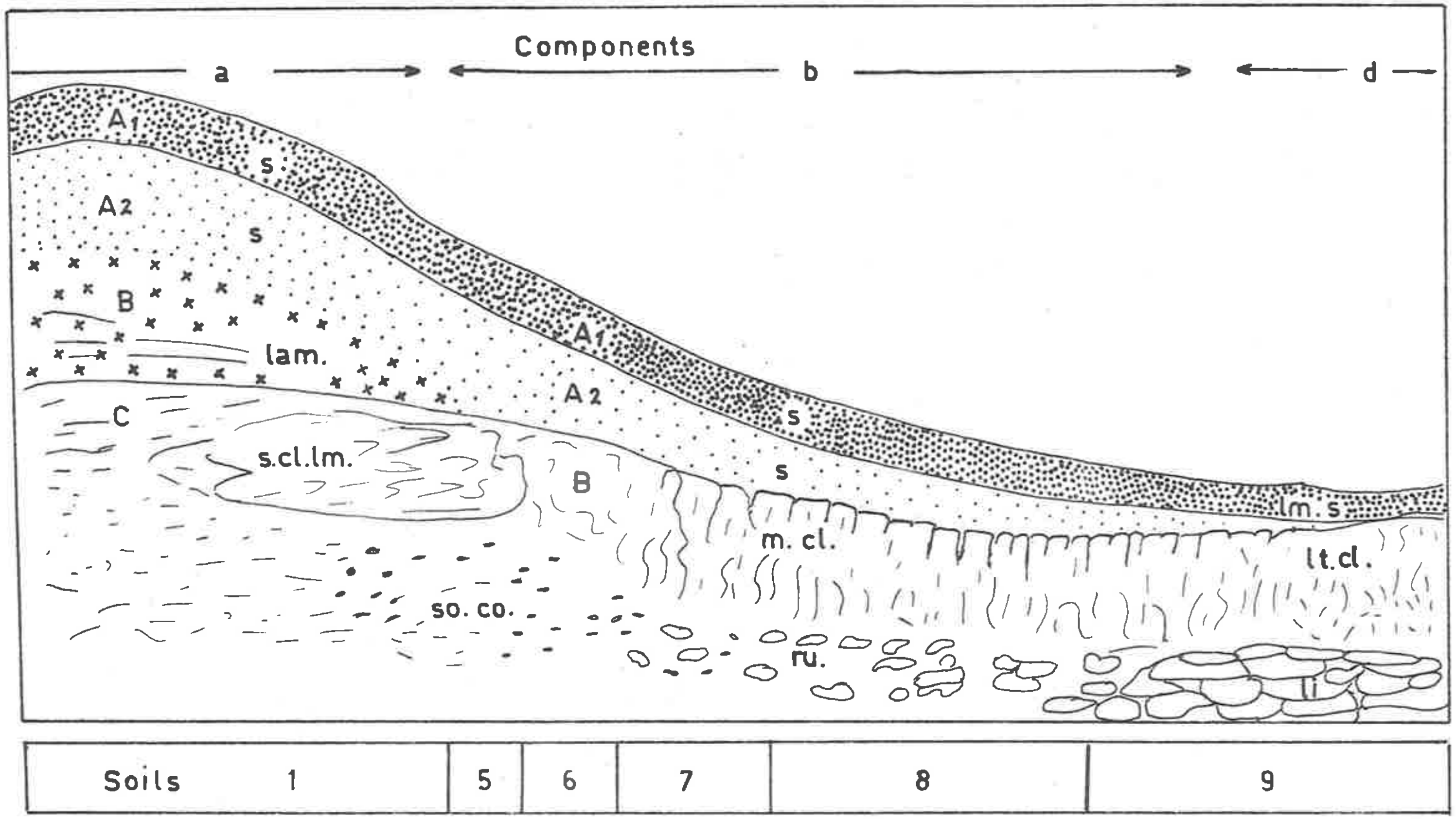
Soils with brown loamy sand A_1 horizons appear to have developed from underlying materials rather than from the aeolian materials of the dune soils(Firman, J.B. S.A. Dept. Mines, personal communication).

Original vegetation : Low woodland. Dominant trees : Eucalyptus incrassata and Eucalyptus gracilis Common herbs : Triodia spp., Themeda spp. Danthonia spp.

Land use : Grazing and cropping. Pasture species occurring on SMU 5, 6 and 7 are evening primrose, lucerne, blue lupin, perennial veldt grass but capeweed, rigid brome and wild turnip frequently dominate over these. SMU 8, 9 and 10 contain soils that are among the most fertile in Wharminda. Hannaford and strand medic (Medicago littoralis Rhode) cv. Harbinger make up the bulk of the pasture. Burr medic

FIGURE 8

Horizons and soils in dune and swale land unit



Textures: s - sand; lm. s. - loamy sand; s.cl.lm. - sandy clay loam
lt.cl. - light clay; m.cl. - medium clay; lam. - lamellae

Carbonate layer: so.co. - soft concretions; ru. - calcrete rubble
li. - calcrete sheet, rock or rubble

Horizons: A_1, A_2, B, C.

(*Medicago denticulata* Willd.) grows in some seasons. Barley grass, rigid brome, silver grass, Wimmera ryegrass, capeweed and wild turnip grow prolifically. Wheat, barley and oats are grown on all soils and cereal rye on SMU 5 and 6 only.

Productivity is low on SMU 5, 6 and 7 and these soils are cropped less frequently than those of SMU 8, 9 and 10. Erosion risk is severe on soils of SMU 5 and 6, moderate on 7 and 8, low on 10 and almost nil on the soils of 9.

SOLONIZED BROWN SOILS

11. A_1 horizons low in carbonate

Principal Profile Forms : Gn1.83, Gn1.63

Morphology : A_1 brown (dry) loamy sand, single grained. B horizon highly calcareous, light coloured, ~~increasing in texture to~~ clay loam, apedal. Underlain by calcrete rubble.

Occurrence : Land Units III a, IV a

Profile description : 14

Original vegetation : Low woodland. Dominant trees : *Eucalyptus* spp.

Land use : Intensive grazing and cropping. Pasture is mainly barrel medic with rigid brome, Wimmera ryegrass, barley grass, wild turnip, capeweed and Lincoln weed. Wheat, barley and oat crops are grown. Erosion risk is almost nil.

12. A_1 horizons high in carbonate

Principal Profile Forms : Gc1.12, Gc1.22

Morphology : Solum dominated by fine carbonate. A_1 dark reddish brown (dry) loam, weak crumb. B horizon pale brown, increasing to clay loam, apedal, underlain by calcrete rubble or sheet stone.

Occurrence : Land Units II d, III a, V d

Original vegetation : Low woodland. Dominant trees : *Eucalyptus* spp. Common shrubs : Leptospermum spp.

Land Use : Grazing and cropping. Pasture species mainly woolly burr and barrel medics with barley grass, Wimmera ryegrass and Lincoln weed. Wheat and barley are the main crops. The erosion risk is nil.

RED-BROWN EARTH and SOLODIC SOIL

13. A_1 horizon pale red (dry)

Principal Profile Forms : Dr4.63, Dr2.63, Dy5.63

Morphology : A_1 horizon pale brown to red (dry), sand to loam, apedal. A_2 pale red (dry) sand to loamy sand. B red or yellow, mottled or whole coloured, medium clay, apedal. Underlain by calcrete rubble.

Occurrence : Land Units V b c

Original vegetation : Low woodland. Dominant trees : *Eucalyptus* spp.

Land Use : Grazing and cropping.

TERRA ROSSA

14. Solum varies in depth (a) 15-45 cm (b) less than 15 cm

Principal Profile Forms : (a) Gn2.13, Gn2.63 (b) Um4.31, Um5.11

Morphology : A_1 horizons red (dry) loamy sand - sandy loam. B horizons present or absent, loam or clay loam, red, apedal, underlain by calcrete sheets or boulders.

Occurrence : Land Unit V d

Land Use : Light grazing

ALLUVIAL SOIL and SOLONCHAK

15. Saline swamp

Principal Profile Forms : Uc1, Dy1.83, Dr1.63

Morphology : Areas of solonchak soils with flaking surface, A_1 horizon, sand to sandy loam and B horizons of clay are interspersed with alluvial sand and gravel and exposed surfaces of truncated profiles.

Occurrence : Land Unit V f

Original vegetation : Samphire swamp. Common herbs : *Arthrocnemum* spp.

Land Use : Light grazing of salt water barley grass (*Hordeum murinum* L.)

UNCLASSIFIED SOILS

16. Severely eroded areas

The original profiles are unrecognizable, the land is devoid of vegetation and not used. Wind eroded areas are unstable and drift continuously. Water eroded areas have bare hard clay horizons exposed.

Occurrence : Land Units I a d, V a b c.

STOKES

Sections 3,4,12-16,29,30,33-35,56-59 Stokes. 79A,81,140 Koppio

This area is located at the northern end of the Lincoln uplands. It extends in a north-easterly direction from Yallunda Flat for 13 km, and is 2 km wide and 2 270 ha in area.

The area is hilly with one ridge and adjacent valleys extending throughout its length. Three geological formations are described by Johns (1961). These are archean metasediments named the Flinders series which outcrop in the area as two forms of granitic gneiss, one dominantly pink in colour and the other white (Appendix 4). Overlying the Flinders series are tertiary laterites which are remnants of a peneplain. These are found on top of the ridge. Areas of recent alluvium cover the archean basement in low lying areas.

Both fossil and cyclic salts have been leached from the soils and parent materials, due to changing water relationships in the area resulting from clearing the original vegetation (J.B. Firman, S. Aust. Mines Dept. personal communication, Bettenay et al 1964). The salt has moved into low lying areas causing the rapid spread of salinized flats.

The mean annual rainfall is 500 mm, 72 per cent occurring between May 1 and October 31. Winter temperatures are mild. The mean maximum July temperature at Pt. Lincoln is 16°C. The summers are hot, the mean maximum January temperature at Pt. Lincoln being 25°C. The drought frequency at Koppio is 15 per cent (Trumble 1948) and is 2 or 3 per cent higher in the area of study.

Large areas of original vegetation consisting mainly of eucalypts, broombush and bottlebrush exist on steep slopes, in gully lines and along roadsides. Dense stands of eucalypts deter clearing in some areas because of high costs.

Intensive grazing of predominantly subterraneum clover (*Trifolium subterraneum L.*) and Wimmera ryegrass pasture, with some perennial grass pasture, is the main land use. Wheat, barley and oats are grown but the area that can be sown is limited by waterlogging of the soil. This restricts the use of machinery in cultivation and weed control.

Water erosion has been severe in the area, particularly in wet winters. The shallow soils do not hold large amounts of water. Contour banking of the area has progressed steadily since 1948 and most of the sloping crop land has been banked.

LAND UNITS

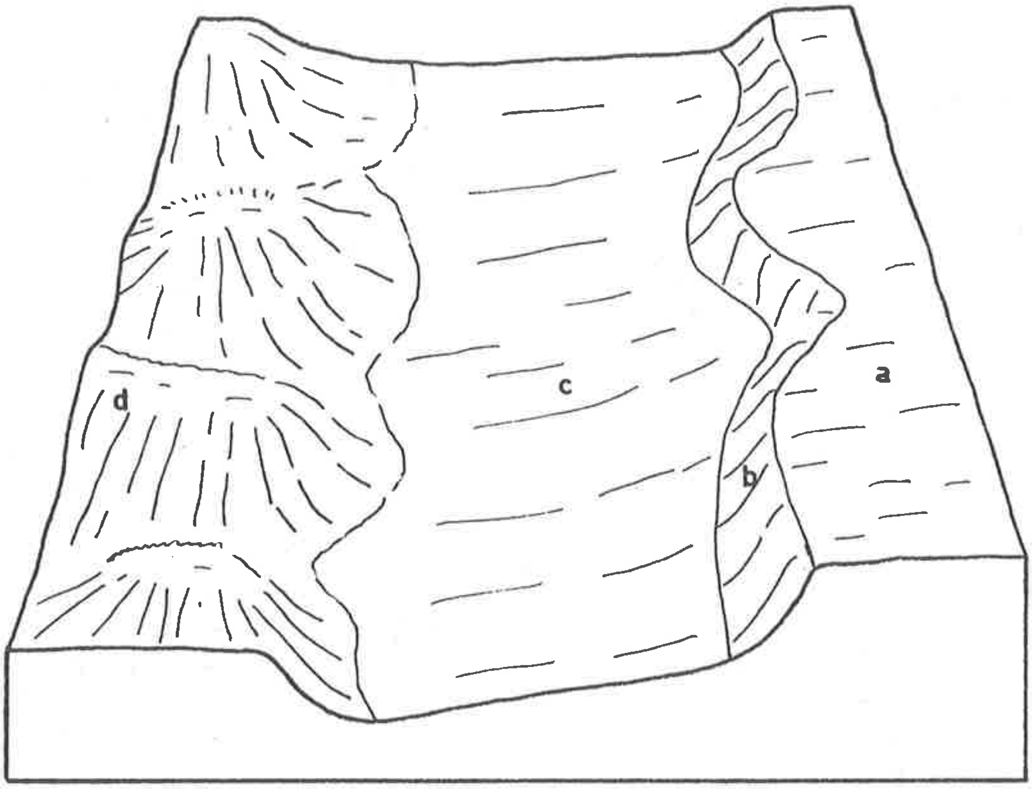
Three land units were identified as shown in Figs. 9-11.

FIGURE 9

LU VI Lateritic peneplain, steep scarp

Component a is formed from tertiary lateritic materials, b from white granitic gneiss and c and d from pink granitic gneiss.

Area: 440 ha



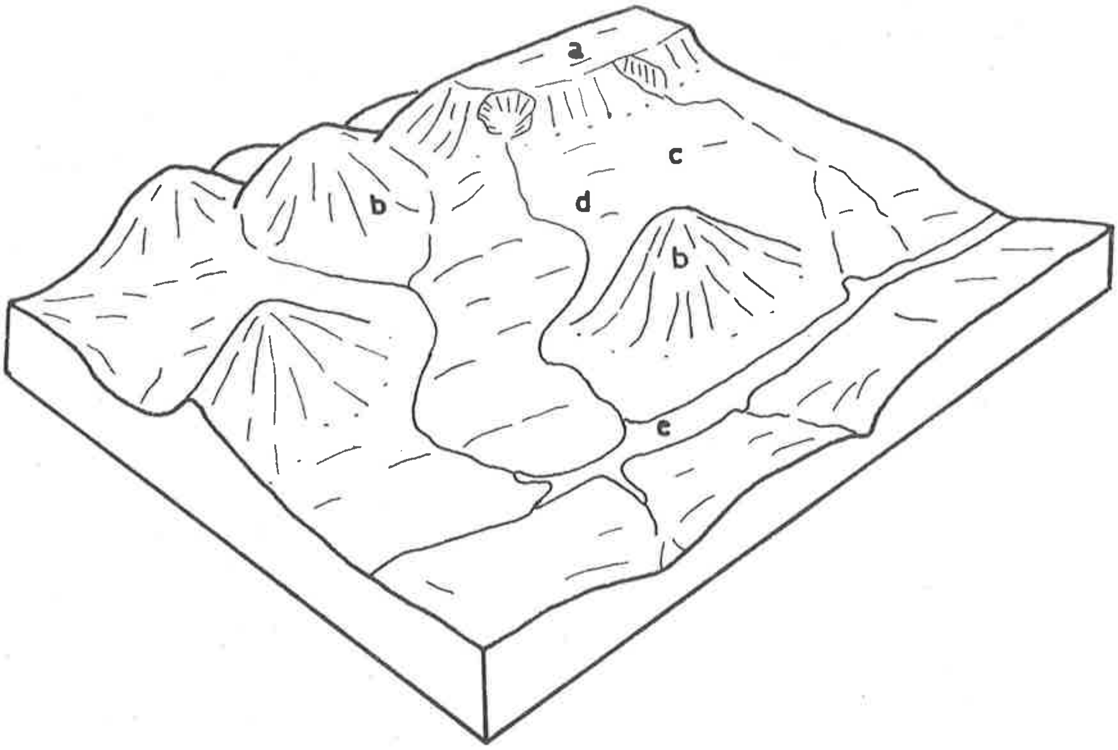
- **a** Lateritic peneplain
- **b** Steep scarp
- **c** Gentle slope
- **d** Rocky granite hills

FIGURE 1C

LU VII Low rounded hills

Component a is formed from tertiary lateritic material, b, c and d are mainly formed on white granitic gneiss with pink granitic gneiss on the lower slopes of c. Areas of alluvium occur.

Area: 690 ha



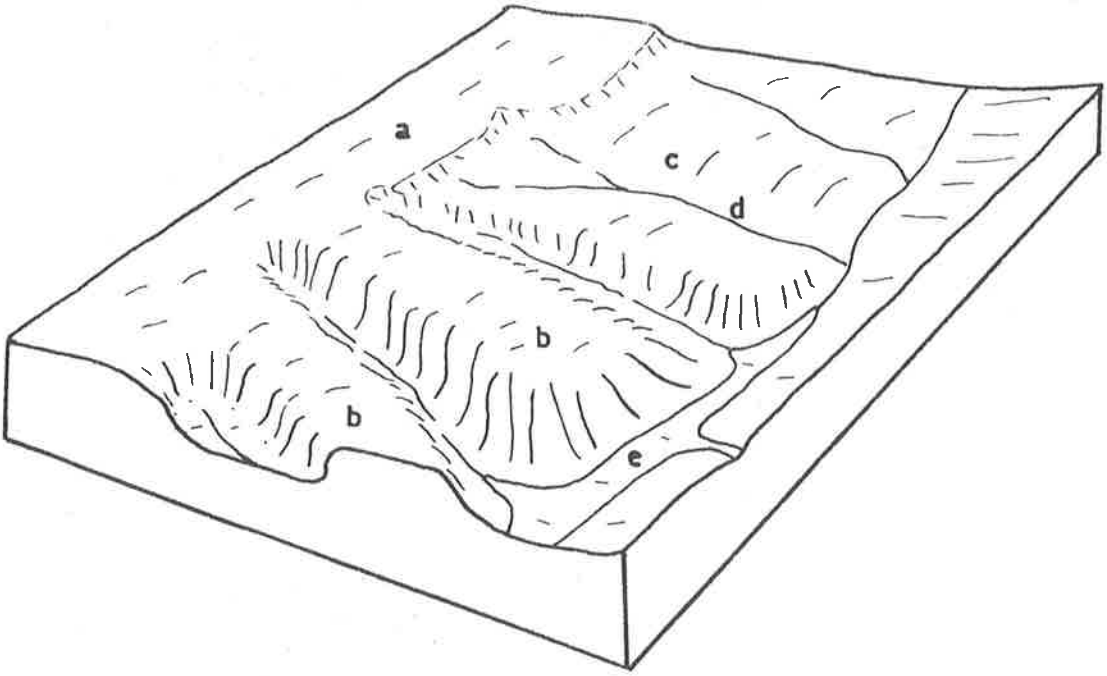
- **a** Lateritic peneplain
- **b** Rounded hills and deeply dissected peneplain
- **c** Irregular slopes
- **d** Tributary gullies
- **e** Uranno creek water course

FIGURE 11

LU VIII Lateritic peneplain, dendritic ridges and gullies

Long lateritic ridges and gullies extend from the peneplain to the main valley floor. As the main stream descends so the dendritic ridges become more pronounced. Small areas of granite and alluvium occur.

Area: 1070 ha



a Lateritic peneplain

b Dendritic ridges

c Subdued ridges in higher watercourse area

d Tributary gullies

e Tod river watercourse

SOIL MAPPING UNITS

LATERITIC PODZOLIC SOILS

Three forms of lateritic soils occur differing mainly in A horizon characteristics (Table 9). All are developed on tertiary lateritic sandstone and their development is related to minor changes in topography and drainage.

TABLE 9

Subdivisions of lateritic podzolic soils

SMU	Principal Profile Forms	A horizon conditions	Occurrence Land Units	Profile description
17	Dy3.82 Dy3.62	Dominated by massive and concreted pisolitic laterite	VI a VIII a b	15,16
18	Dr2.22 Dr2.62 Dr3.62 Dy3.62	Red-brown (dry) pisolitic laterite only, coloured A_2	VI a VII a VIII a b c	19
19	Dy3.82 Dy3.62	Grey to grey brown with pisolitic laterite, bleached A_2	VIII a b c	17,18

SMU 17 occurs on small abrupt rises, 19 occurs in areas prone to waterlogging and 18 on the areas in between.

Morphology : A_1 horizons are loamy sand to sandy loam, apedal. A2 horizons are loamy sand to clay loam, apedal. B horizons red, whole coloured or yellow and red mottled, medium clay, usually apedal. Soils of SMU 18 occasionally are structured in the top 15 cm.

Original vegetation : SMU 17 Closed scrub. Pure stands of Melaleuca uncinata occur. SMU 18 and 19 Low woodland. Dominant trees : Eucalyptus cladocalyx F.v.M. Common shrubs : Melaleuca uncinata and Calistemon spp.

Land use : Grazing and cropping. Pastures consist of subterraneum clover with barley grass, Wimmera ryegrass, wild oat, geranium (Erodium botrys Cav. Bertol) and capeweed. Wheat, barley and oat crops are grown. SMU 18 is more productive than SMU 17 or SMU 19.

SOLODIC SOILS

20. A_1 horizon grey (dry) with white quartz gravel

Principal Profile Forms : Dr2.42, Dr.3.42, Dr2.12, Dy3.42, Dy3.82

Morphology : A_1 grey (dry) loamy sand - sandy loam , apedal, much quartz gravel, surface often littered with scree lateritic material. A_2 sometimes non-existent; bleached (dry) sand to sandy clay, apedal. B red or yellow, mottled or whole coloured, medium to heavy clay, blocky or rarely apedal. Solum usually underlain by weathering rock at 75 cm or less.

Geology : White granitic gneiss occurs on outcrops and often can be recognized in and under the solum. Some of these soils may arise from the deeper weathered horizons of lateritic profiles.

Occurrence : Land Units VI b, VII b c, VIII b

Profile description : 22, 23

Original vegetation : Woodland formation. Dominant tree : Eucalyptus cladocalyx occurring in pure stands.

Land Use : Intensive grazing and cropping, shelterbelts. Subterraneum clover is the main pasture plant with Wimmera ryegrass, barley grass, wild oat, geranium and capeweed also common. Wheat and oats are grown on less steep, cleared areas.

21. A_1 horizons brown (dry), with pink, coarse sand grains

Principal Profile Forms : Db2.22, Db2.62

Morphology : A horizons brown (dry) with characteristic pink sand that colours the surface, sandy loam - loam, apedal or weak crumb. Separation into an A_1 and A_2 is gradual. Gravel and rock frequently occur at the interface of A and B horizons. B horizon mottled, brown medium to heavy clay, blocky or apedal. The lower portion contains weathering granitic materials and occasional carbonate.

Geology: Pink granite gneiss occurs as outcrops where the soils of this SMU occur. Fragments of this rock can be found in the soil profile.

Occurrence : Land Units VI c d, VII b c, VIII d.

Profile description : 20, 21

Original vegetation : Woodland formation. Dominant tree : Eucalyptus odorata Behr et Schlechtd occurs as pure stands.

Land Use : Intensive grazing and cropping. Pasture consists of subterraneum clover, phalaris (Phalaris tuberosa L.) and Wimmera ryegrass with geranium, capeweed, wild oat, barley grass, silver grass and cluster clover as subordinate species. Wheat, barley and oats are prolific producers on these soils.

22. A horizons sand

Principal Profile Form : Dy5.82

Morphology : A_1 light-brown (dry) sand, single grained. A_2 bleached (dry) sand. B yellow, mottled, medium clay, apedal.

Geology : Solum underlain by tertiary alluvium. Sandy A horizons may be partly formed from aeolianite.

Occurrence : Land Units VII c, VIII b.

Original vegetation : Woodland formation : Dominant tree : *Eucalyptus leucoxylon* F.v.M.

Land Use : Grazing, intermittent cropping.

23. Low salinity, gully-line soils

Principal Profile Forms : Dy3.82, Dd2.82

Morphology : A_1 dark brown, grey or black (dry) sandy loam - clay loam, apedal. A_2 bleached, loamy sand-clay loam. B yellow to dark brown, mottled, medium to heavy clay, dries to prismatic structure that crumbles easily, apedal when wet.

Geology : Yellow sandstone frequently occurs at the base of these soils.

Occurrence : Land Units VI c, VII d e, VIII d e

Profile description : 24

Original vegetation : Woodland Formation. Dominant tree : *Eucalyptus leucoxylon*. Common shrubs : *Calistemon* spp.

Land use : Grazing and cropping. Phalaris and subterraneum clover are the main pasture plants. Barley grass, Wimmera ryegrass, wild oat and capeweed are common. Wheat, oats and barley crops are grown. Waterlogging often limits the use of machinery.

24. Highly saline gully and valley soils

Principal Profile Forms : Dy3.83, Dd2.83

Morphology : As for SMU 23. Small areas of sand, gravel and truncated profiles occur.

Geology : As for SMU 23

Occurrence : Land Units VII e, VIII e

Original vegetation : Low shrubland. Common shrubs : *Calistemon* spp. Common herbs : *Cyperus* spp.

Land use : Light grazing. Subterraneum clover and strawberry clover (*Trifolium fragiferum* L.) grows vigorously in some areas, salt water barley grass is common.

LITHOSOL

25. Skeletal sand and gravel

Principal Profile Form : Uc1

Morphology : Variously coloured, sandy with weathering rock. Organic staining of the surface indicates an immature A_1 horizon.

Geology : Soil formed on quartzite and sandstone ridges.

Occurrence : Land Units VI a b, VII b

Original vegetation : Low woodland. Dominant tree : *Eucalyptus cladocalyx*. Common shrubs : *Melaleuca* spp. *Xanthorea* spp.

Land Use : Shelter belts.

V MATERIALS AND METHODS - FIELD EXPERIMENTS

A Factorial experiments

(1) Selection of experiment sites

Sites were selected for 24 field experiments to represent the most frequently occurring soils and to provide as wide a range of soil properties as possible. Areas affected by past application of micronutrients, erosion, vermin activity and concentrated farm activity such as sheep camps, tracks and hay stacks were avoided. The soil at each prospective site was examined for uniformity of principal profile form (Northcote 1971), depth and texture of the horizons present. The sites varied in the number of years of agricultural use from nil at Site 15 to over 30 years at Sites 8-14,17,22 and 24.

(2) Experimental design and treatments.

The experiments were of ½ replicate 2^6 factorial design where 32 of the 64 possible combinations of factors are used allowing the six main effects and the 15 first order interactions to be measured accurately. The combinations were arranged in two blocks each with 16 (Appendix 5) so that within each block eight plots were treated with each micronutrient and eight were not. For each pair of elements four plots per block were treated with neither, four plots were treated with each element by itself and four were treated with both elements.

The micronutrients Cu, Zn, Mn, Fe, B and Mo were applied in aqueous solutions to wheat and the effect on growth was observed visually and measured by sampling the plots during the growing season and at maturity. The wheat cultivars used were those recommended for the respective districts by the South Australian Government's Advisory Committee on wheat quality. Insignia was used at Wharminda in 1970 and replaced by the newly released variety Halberd in 1971. Pinnacle was used in the Stokes area in both 1970 and 1971.

The seedbed at each site was prepared for sowing by the farmer . This usually entailed ploughing following autumn rains and cultivation after later rains. The sites were sown at the same time as the rest of the paddock and the plots were orientated so that they paralled the slope of the land surface. All experiments were sown with 65 kg ha^{-1} of seed at 4 cm depth in plots 20 m long and 2 m (12 rows) wide.

Basal fertilizers were applied at all sites and these contained low concentrations of micronutrients (Appendix 6). Phosphorus (40 kg ha^{-1}) as sodium tripolyphosphate was drilled with the seed and nitrogen (50 kg ha^{-1}) as ammonium sulphate was dropped on to the soil surface and incorporated by the back tynes of the combine seed drill. An additional 7 kg ha^{-1} of nitrogen was applied as urea in foliar sprays on Sites 2,3,4,6,7 and 9 at tillering following development of N deficiency symptoms.

Avadex (40% w/v)(S-2, 3 dichloroallyl -N N-diisopropyl-thiocarbamate at one litre per hectare was used to control Wimmera ryegrass and wild oat. It was applied to the soil by boom spray immediately after sowing and incorporated into the soil by harrowing.

Wild turnip, Lincoln weed and capeweed infestations were controlled by spraying at early stem elongation of the wheat with 100 ml ha^{-1} of 50 per cent w/v Amine 2-4D (dimethylamine 2-4 dichlorophenoxy-acetic acid).

The micronutrient fertilizer treatments were applied to the wheat as foliar sprays at three growth stages: single leaf to early tillering, late tillering to early stem-extension, and at the boot stage. The sprays were applied during humid weather when the wind velocity was low and a plastic shield was carried between the plots to intercept any drifting spray.

At each time of application the micronutrients were applied either singly or in pairs in 500 l ha^{-1} of deionized water. Each plot was sprayed one, two, or three times as necessary to complete the application of the micronutrients. The different spray volumes applied to different plots were not an important source of water to the wheat because the plants were already wet with dew and the maximum volume applied was less than 1500 l ha^{-1}, equivalent to 0.15 mm rainfall. The amounts of micronutrients applied at each time of spraying are given in Table 10.

TABLE 10

Rates of micronutrients and compounds applied

Element	Amount used g ha^{-1}	Compound used	Amount of Compound used g ha^{-1}
Cu	100	$CuSO_4.5H_2O$	390
Zn	200	$ZnSO_4.7H_2O$	880
Mn	500	$MnSO_4.4H_2O$	2 030
B	200	H_3BO_3	1 150
Mo	10	$Na_2MoO_4.2H_2O$	25
Fe	500	$FeSO_4.7H_2O$	2 480

These amounts of nutrients were calculated from data of Mitchell (1963 Table III), on the assumption that the total dry matter of the crop was 10 000 kg ha^{-1}, that the crop required the amounts of nutrients quoted by Mitchell, and that the percentage recovery of nutrients from the spray was 30 per cent.

(3) Sampling and yield measurement

Soil

On each site 10 small pits were dug to the base of the solum (Northcote 1971). The depths of each horizon were measured in each pit and the mean values are given in Appendix 1. Assessments of structure and texture, wet and dry soil colour and pH were made from the pits. A sample of about 0.5 kg of soil was taken from each horizon except where an horizon was unusually deep, when samples were taken from the upper and lower parts of the horizon, or where the horizon was shallow, when it was not sampled (Appendix 1). For each horizon the samples from each pit were mixed, and a 2 kg subsample was retained for analysis. The soil samples were air dried. Soils from sandy horizons containing coarse laterite or quartz gravel were sieved (2 mm) without crushing, and the others were crushed to break hard aggregates before sieving. The less than 2 mm fraction was used for analysis.

Plant

The plants were sampled by cutting quadrats two or three times during the year at the following growth stages:

Harvest 1 (H1) late tillering (before the second application of micronutrients), Harvest 2 (H2) boot (before the third application of micronutrients),

Harvest 3 (H3) maturity. The actual harvests made at each site are given in Appendix 7.

On each occasion 10 quadrats totalling 15 or 20 m of row were taken. Plant numbers were counted at the first two harvests and the wheat was then bulked and weighed. The bulked sample was then subsampled and oven-dried at 70°C for dry weight determination.

At Harvest 3 quadrats were bulked, thrashed and grain and straw weights measured. Moisture contents were determined on subsamples taken after thrashing. The plots were reaped with an autoheader for grain determination. The statistical significance of growth effects was determined by analysis of variance.

The responses were then used to classify each site into four categories of deficiency (0-3) using the following criteria:

Not deficient - 0: No response to application of micronutrients occurred.

Marginally deficient - 1: Sites were classified here if deficiency symptoms appeared for a while but disappeared by final harvest or if main effects occurred in plant number or if responses to micronutrients occurred only in interaction with others.

Deficient - 2: Dry matter increases due to the application of micronutrients measured at Harvests 1, 2 or 3. The increase in grain yield was less than 40 per cent.

Very deficient - 3: Marked deficiency symptoms and yield increases in excess of 20 per cent occurred at these sites.

Toxic - T: Also noted were several decreases in yield measured in main effects or interactions as a result of application of micronutrients.

(4) Chemical and physical analysis

Soil

The pH of the soil was determined in 1 : 5 soil-water suspension with a glass electrode. Particle size fractionation was made using the Plummett balance method of Hutton (1955) following ultrasonic dispersion of the soil (Edwards and Bremner 1967). Bulk densities were estimated on the <2 mm fraction of the soil by weighing 50 cm^3 of soil. This method used by the South Australian Department of Agriculture laboratory has accuracy equal to field determination made with a Coile sampler (R.J. French pers. comm. 1972).

The carbonate content of the soil was estimated by rapid titration with hydrochloric acid (Piper 1947 p.135). Organic carbon was determined by wet oxidation (Walkley and Black 1934), using the spectrophotometric method of Sims and Haby (1971) to measure the residual dichromate.

Mineral content and clay types were determined from X-ray diffraction patterns of <2μ m material from selected horizons from Sites 1, 5, 8, 11, 15, 17, 20 and 22.

Total soil nitrogen was determined by sulphuric acid digestion in the presence of Na_2SO_4 and selenium (Bremner 1965) and measuring the ammonium formed using the iodophenyl reaction of Van Slyke and Hiller (1933). Total soil phosphorus was released from the soil by concentrated HCl digestion of fused soil and magnesium acetate (Beckwith and Little 1963). Available soil phosphorus was extracted using dilute acid (Bray and Kurtz 1945) for the soils of Stokes and bicarbonate (Colwell 1965) for the soils of Wharminda. The phosphorus in the soil digests and extracts was measured by the molybdenum-blue method as described by Jackson (1962) p.135, method I.

Water soluble and exchangeable cations and cation exchange capacity were determined by the methods outlined in the U.S.D.A. Agriculture Handbook No. 60. Total Cu, Zn, Mn, Fe and Mo in the soil were determined by atomic absorption spectrophotometry (Allan 1961) on HF and $HClO_4$ digests of the soil (Hanna 1964). Boron was measured with arc emission spectrography (Robinson and Lomman 1971).

Extractable Cu, Zn, Mn and Fe were determined by three methods:

EDTA Twenty grams of soil was shaken for 16 hours in 40 ml of 0.05 M Na_2EDTA and 1 M CH_3COONH_4 solution adjusted to pH 6.0 with ammonium hydroxide (Viro 1955, Tucker and Kurtz 1955).

DTPA Ten grams of soil was shaken for one hour with .001 M DTPA in $CaCl_2$ solution and triethyl amine buffer at pH 7.3 according to the method of Lindsay and Norvell (1969).

$Ca(NO_3)_2$ Twenty grams of soil were successively extracted three times with 70 ml of 0.01 M $Ca(NO_3)_2$ at pH 6.0. The first extraction period was 16 hours followed by two one hour extractions. The soil and extracts were centrifuged, the extracts decanted, bulked and made up to 200 ml.

Preliminary experiments were conducted to determine optimum pH for the complexing of Cu, Zn, Mn and Fe with APDC (ammonium pyrollidine dithiocarbamate) and concentration in MIBK (methyl isobutyl ketone). Various buffering solutions were tested as competitors with APDC for complexing of the metals. APDC was most effective as a complexing agent in acetic-acetate buffer and the optimum pH of extraction was 5.0. Cu, Zn and Fe detection were greatly improved by the method but Mn was not. Cu, Zn and Fe were complexed with APDC and concentrated into 5 ml of MIBK from 40 ml of the bulked solution that had been adjusted to pH 5.0 with acetic-acetate buffer. The concentration of Cu, Zn and Fe in the MIBK and Mn in the bulked $Ca(NO_3)_2$ solution were determined by atomic absorption spectrophotometry (Allan 1961).

Plant

Approximately 100 g of dried (70°C) tops and grain from each plot were ground in a Wiley mill fitted with stainless steel blades and 0.5 mm sieve, and were retained for analysis. Ca, Mg, P and K in this material were determined by X-ray fluorescence methods as outlined by Norrish and Hutton (1969) and N by Keldahl digestion and measuring ammonium as for soil nitrogen. Cu, Zn, Mn and Fe were measured in HNO_3 - $HClO_4$ digests of the material by atomic absorption spectrophotometry (Allan 1961). Boron was determined by the colorimetric method of Berger and Truog (1939) and Mo by the method of Johnson and Arkley (1954). The concentration techniques of Allan (1961) were used when measuring plant Cu. Soil and plant chemical analyses were fitted to yield response data in diagrams.

B Ancillary experiments

Eighteen small experiments were conducted in various areas of Eyre Peninsula to provide additional information on the extent and frequency of occurrence of micronutrient deficiencies on soils similar to those in the study areas. A detailed list of sites, wheat cultivars, and basal fertilizers used is given in Appendix 8.

Experimental design

The experiments on Sites 31 and 42 were of randomized block design with three replications. The treatments were:

Treatment Number	Treatment
1	Nil
2	Zn, Mn, B, Mo, Fe
3	Cu, Mn, B, Mo, Fe
4	Cu, Zn, B, Mo, Fe
5	Cu, Zn, Mn, Mo, Fe
6	Cu, Zn, Mn, B, Fe
7	Cu, Zn, Mn, B, Mo
8	Cu, Zn, Mn, B, Mo, Fe

In 16 experiments (Sites 25-30, 32-41), Cu, Zn and Mn were applied singly or in various unreplicated combinations. The number of treatments in each experiment depended on the number of elements used. The treated plots were separated from each other by control plots to which no micronutrient was applied as illustrated in Fig. 12. All plots received the same basal fertilizer application.

FIGURE 12

Examples of treatments on unreplicated plots

Nil
$MnSO_4$
Nil
$ZnSO_4$
Nil
$CuSO_4$
Nil
$MnSO_4$ + $ZnSO_4$
Nil
$CuSO_4$ + $ZnSO_4$
Nil

Application of micronutrients

On Sites 31, 35, 38-40 the micronutrients were applied to the plants as foliar sprays at tillering and boot stage at the same rates as those used in the factorial experiments. In the remaining experiments solid fertilizers in sulphate form were applied to the soil at the time of sowing. The fertilizers were drilled with the seed at the following rates of application: Cu (1.0 kg ha^{-1}), Mn (1.7 or 3.4 kg ha^{-1}) and Zn (1.6 kg ha^{-1}).

Assessment of yields

Three methods of yield assessment were used. In four experiments 10 quadrats per plot were cut to estimate grain yield; in three experiments headers were used; and in 11 experiments only visual estimates were made. The method used is recorded in Appendix 8. For each of the three methods of assessment described, the sites were classified similarly to the factorial experiments, into the same four categories of deficiency.

VI RESULTS AND DISCUSSION

PART 1 YIELD IN FIELD EXPERIMENTS

Part 1 describes the weather conditions at the experimental sites, describes deficiency symptoms observed and presents the vegetative and grain yields where responses occurred due to micronutrient treatments. The grain yields determined by heading are presented in the text for the factorial experiments except for Sites 15, 17, 20 and 22, where estimates of grain yield were made by quadrats only. Header yields are better estimates of grain production and generally have lower variances. Estimates of straw yields presented were determined from the quadrats. The complete results obtained at each site are given in Appendix 9. The factorial experiments were designed to test only main effects and first order interactions of the micronutrient treatments. The implications of the micronutrient interactions are discussed.

A Factorial experiments

(1) Climatic and other factors

Experiments 1, 5, 8, 11, 15, 17, 20 and 22 were conducted in 1970 and Experiments 2, 3, 4, 6, 7, 9, 10, 12, 13, 14, 16, 18, 19, 21, 23 and 24 were conducted in 1971. The mean rainfall and screen temperatures together with the 1970 and 1971 measurements at Cleve, Port Lincoln and Ungarra are given in Appendix 3. In 1970 the May-June rainfall was below average and fell in light showers before warm periods with dry north winds. This led to postponement of sowing until late June through to August. Erosion at Sites 1 and 5, and weeds at Sites 8 and 11, caused the experiments at these four sites to be discontinued after Harvest 1. Above average rains fell in August and September, but October and November were dry.

Calm conditions prevailed in May and June 1971 and prolonged rainy periods continued from May through to September. The weather produced ideal conditions for cultivating and sowing, and later in the season the rain provided ample soil water for the crop to grow unchecked until maturity. Several very hot days occurred in early October followed by further rainy periods through to December. Wheat growth was limited by N deficiency due to leaching, despite liberal N application, at sites on solodized solonetz and solodic soils with light-brown sand A_1 horizons. Wheat plants in block 1 at Site 2 were damaged by rabbits and grain yields were determined from block 2.

(2) Deficiency symptoms

Copper

Cu deficiency was observed in 14 of the factorial experiments. The symptoms were early occurrence of wilting, curved ears, dieback, whiteheads, melanism and abnormal tillering. The earlier the symptoms occurred in the season the greater was the reduction in yield. Wilting and curved ears were more obvious in cultivar Halberd than Pinnacle.

Wilting (Plate 1) was the most common deficiency symptom and occurred in 13 experiments. It appeared as early as tillering but usually was not evident until the boot stage. At two sites wilting occurred at flowering but the effect had disappeared by maturity. Different reflection patterns of sunlight from the wilted leaves allowed easy recognition of the sympton. Curved ears (Plate 2) occurred on many deficient sites appearing as late as soft dough stage and was the only symptom seen at one site. Dieback of the leaf blade and whiteheads (Plate 3) was frequent at sites where Cu deficiency was severe.

Death of the upper portions of the stems occurred resulting in white dead ears above green succulent stems. This symptom was often associated with melanism (dark straw and ears) and a second period of tiller initiation towards the end of the growing season.

Zinc

Deficiency of Zn produced few distinguishing symptoms during the growing season, with increased vigour and height after application of Zn being the only observable response. After harvest of the grain the mature deficient straw developed darker colour where Zn had not been applied, similar to the Cu melanism syndrome. At one site Zn application caused substantial reduction in yield, and melanism was evident on the Zn treated plots but not on the untreated plots. At some sites the application of Cu and Zn together resulted in lighter coloured straw than where Cu or Zn were applied alone, showing that melanism is affected by both these elements.

Manganese

Manganese deficiency appeared about three weeks after emergence as yellowing of the leaves, and dieback of the leaf tips followed by collapse of the whole plant (Plate 4). The leaves were brittle and cracking of the blade was common. These symptoms were accompanied by drastic reduction in yield.

Molybdenum, Iron and Boron

At two sites some of the plots without Mo application were yellower in colour than those with Mo applied. Intervenal chlorosis indicated Fe deficiency on some plots at two sites. Occasionally growth and height responses to Mo and Fe were observed. No symptoms of B deficiency were observed.

PLATE 1

Wilting in Halberd wheat

PLATE 2

Curved ears and melanism in Halberd wheat

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PLATE 3

Whiteheads in Halberd wheat

PLATE 4

Manganese deficiency in Halberd wheat

(3) Main effects on yield

Copper

The response of wheat to application of Cu varied greatly from site to site but was greater on the higher yielding sites (Table 11). No response occurred at six of the 20 sites continued to final harvest. At Sites 6 and 10 symptoms of deficiency (wilting) were observed but neither vegetative growth nor grain yield were affected. The occurrence of increased dry matter of tops at Harvest 2 (boot stage) was not a sure indication of grain yield response to follow. At Site 19 vegetative growth response occurred and wilting symptoms were observed at Harvest 2 but at Harvest 3 no evidence of response remained. Grain yield increase was sometimes preceded by wilting symptoms without vegetative increases as at Sites 4, 9, 12, 20, 23 and 24. At other sites (3, 15, 16, 18, 21) both dry weights of tops at Harvest 2 and grain yields at Harvest 3 were increased by Cu application. Of these, three sites were very deficient but at the other two sites both response in dry matter of tops at Harvest 2 and of grain were small. In no case did application of Cu ($P=0.05$) reduce dry matter yields of tops or grain. Fig. 13 shows the relation between the grain yields from plots with and without Cu for the 20 sites on which grain yields were determined. Response to Cu is proportionately greater and more common at the higher yielding sites. Similar relationships exist for dry matter yields of plant tops at Harvest 2.

TABLE 11

Effect of Cu on wheat yield (kg ha^{-1})

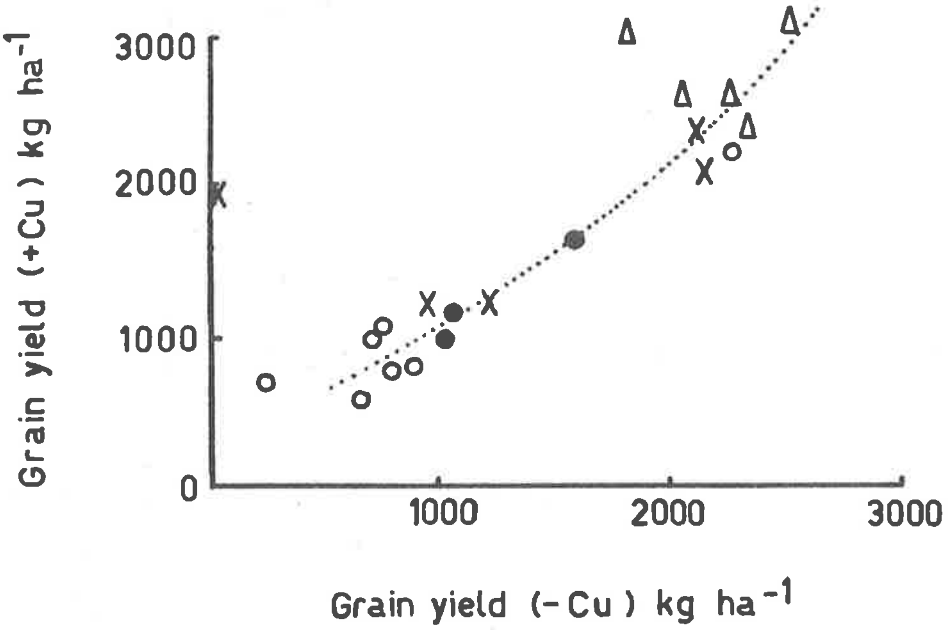
Site No.	Harvest 1		Harvest 2		Harvest 3				
	D.W.	tops	D.W.	tops	D.W.	straw	D.W.	grain	
	-Cu	+Cu	-Cu	+Cu	-Cu	+Cu	-Cu	+Cu	
1	470	480	-	-	-	-	-	-	
2	-	-	-	-	-	-	650	600	
3	-	-	1240	1500^{xxx}	1320	1800^{xxx}	230	700^{xxx}	+
4	-	-	2610	2800	2070	2250	700	1010^{x}	+
5	720	650	-	-	-	-	-	-	
6	-	-	2070	1920	2570	2470	790	800	+
7	-	-	2580	2740	-	-	890	800	
8	570	580	-	-	-	-	-	-	
9	-	-	2050	2490	2430	2760^{xx}	760	1080^{xxx}	+
10	-	-	4910	4940	5160	5370	2280	2210	+
11	830	800	-	-	-	-	-	-	
12	-	-	4390	4350	4270	4440	1050	1160^{x}	+
13	-	-	5170	5300	3510	3480	1580	1650	
14	-	-	3560	3570	3360	3280	1030	1000	
15	530	630^{xx}	2430	4020^{xxx}	2590	3080^{xxx}	15	1910^{xxx}	+
16	-	-	3450	4030^{xx}	2980	3360	950	1230^{x}	+
17	520	520	4540	4510	3810	3820	1210	1250	
18	-	-	5070	5640^{x}	3320	3710^{x}	2120	2370^{x}	+
19	-	-	4740	5240^{xx}	4340	4380	2160	2130	+
20	620	660	5140	5270	5160	5420	2050	2620^{x}	+
21	-	-	5140	6640^{xxx}	4890	6660^{xxx}	1810	3810^{xxx}	+
22	-	-	4520	4210	3910	4030	2360	2390	
23	-	-	6210	6510	6440	7030^{x}	2520	3100^{xxx}	+
24	-	-	3800	3900	3760	3970^{x}	2260	2620^{xxx}	+

Significance: x $P=0.05$, xx $P=0.01$, xxx $P=0.001$

+ Deficiency symptoms present

FIGURE 13

Effect of Cu on grain yield in the factorial experiments



○ Deep siliceous and calcareous sands and solodized solonetz and solodic soils with light-brown sand A_1 horizons

● Solodized solonetz and solodic soils with brown loamy sand horizons, and solonized brown soils

X Lateritic podzolic soils

Δ Solodic soils of Stokes

Zinc

Increased vegetative growth was seen at Sites 13 and 14, and this was accompanied by increased dry matter yield at Harvest 2 (Table 12). At maturity the visual differences at Site 13 had disappeared, and the grain yield showed only a slight but non-significant (P=0.05) increase due to Zn application, while at Site 14 response continued to be apparent at the final harvest and grain yield was significantly increased.

TABLE 12

Effect of Zn on wheat yield (kg ha^{-1})

Site No.	Harvest 1 D.W. tops -Zn	Harvest 1 D.W. tops +Zn	Harvest 2 D.W. tops -Zn	Harvest 2 D.W. tops +Zn	Harvest 3 D.W. straw -Zn	Harvest 3 D.W. straw +Zn	Harvest 3 D.W. grain -Zn	Harvest 3 D.W. grain +Zn	
4	-	-	2940	2460	2400	1930	1210	500^{xxx}	T
8	590	560^{x}	-	-	-	-	-	-	
13	-	-	5040	5430^{x}	3440	3560	1580	1650	+
14	-	-	3050	3730^{xx}	3150	3490^{xxx}	950	1080^{x}	+

Significance: x $P=0.05$, xx $P=0.01$, xxx $P=0.001$
+ Deficiency symptoms present, T Toxicity symptoms present

At Site 4 Zn application greatly reduced vegetative dry matter yield, straw yield and grain yield. This effect was accompanied by increased melanism in the mature plants in the Zn treated plots. At Site 8 a small decrease in dry matter occurred at Harvest 1 (tillering).

Manganese

Significant increases in plant and grain yields due to Mn application occurred at Site 4 (Table 13). Vegetative yield was increased by 40 per cent and grain yield by 100 per cent. Neither the straw nor the grain yield at Site 3 were significantly reduced ($P=0.05$) by Mn application, however the combined straw and grain yield was significantly reduced. This effect of Mn at Site 3 was larger in interaction with Cu (see Cu x Mn section).

TABLE 13

Effect of Mn on wheat yield (kg ha^{-1})

Site	Harvest 2		Harvest 3				
No.	D.W.	tops	D.W.	straw	D.W.	grain	
	-Mn	+Mn	-Mn	+Mn	-Mn	+Mn	
3	1340	1400	1590	1520	490	440	
4	2280	3120^{xx}	1770	2260	560	1150^{xx}	+

Significance: xx P=0.01, + Deficiency symptoms present

Iron

Significant (P=0.05) but small increases in yield due to Fe application occurred at Sites 3, 16 and 19 (Table 14). Intervenal chlorosis was visible on plots without Fe application at Sites 20 and 24, but this had no effect on yields. At Site 17 Fe application slightly reduced the yield of the tops at Harvest 2.

TABLE 14

Effect of Fe on wheat yield (kg ha^{-1})

Site	Harvest 2		Harvest 3				
No.	D.W.	tops	D.W.	straw	D.W.	grain	
	-Fe	+Fe	-Fe	+Fe	-Fe	+Fe	
3	1370	1380	1490	1630^{xx}	440	490^{x}	
16	3530	3940^{x}	3060	3280	1010	1170	
17	4690	4360^{x}	3890	3730	1280	1170	
19	4960	5010	4340	4380	2080	2210^{x}	
20	5240	5170	-	-	2350	2320	+
24	5280	5440	3390	3640	2410	2460	+

Significance: x P=0.05, xx P=0.01, + Deficiency symptoms present

Boron

There were no increases (P=0.05) in yield due to B application. At Site 22, B application depressed growth (Table 15.)

TABLE 15

Effect of B on wheat yield at Site 22 (kg ha^{-1})

Variate	Harvest	-B	+B
Dry Weight	2	4400	4330
Grain and straw	3	6540	6140^{x}
Grain	3	2430	2310

Significance: x P=0.05

Molybdenum

Small increases in yield due to Mo application occurred at Sites 12, 19 and 23 (Table 16). The dry weight of the tops at Harvest 2 was decreased at Site 6. Neither of the effects on top growth at Harvest 2 at Sites 6 and 12 continued through to final harvest while the effects on grain yield at Sites 19 and 23 were not present at Harvest 2.

TABIE 16

Effect of Mo on wheat yield (kg ha^{-1})

Site	Harvest 2		Harvest 3				
No.	D.W.	tops	D.W.	straw	D.W.	grain	
	-Mo	+Mo	-Mo	+Mo	-Mo	+Mo	
6	2100	1890^{x}	2580	2460	760	820	
12	4200	4550^{x}	4340	4360	1130	1080	
19	5070	4910	4370	4350	2080	2210^{xx}	+
23	6450	6260	6970	6490	2700	2920^{x}	+

Significance: x P=0.05, xx P=0.01, + Deficiency symptoms present

(4) Interaction of micronutrients: effects on yield

Copper x Zinc

Cu x Zn was the most common interaction: it affected the degree of melanism exhibited at Sites 15 and 21 and the yields at Sites 3, 4, 9, 10, 13, 15, 16, 19, 21, 22 and 23. The effect of interaction appeared to become more pronounced later in the season, consequently most of the interactions were detected in the straw and grain yields.

TABLE 17

Cu x Zn interaction on wheat yield (kg ha^{-1})

Site No.		Harvest 2		Harvest 3			
		D.W. tops		D.W. straw		D.W. grain	
		-Zn	+Zn	-Zn	+Zn	-Zn	+Zn
10	-Cu	4680	5140	5250	5070	2270	2280
	+Cu	4920	4960	5100	5640	2220	2200
	LSD P=0.05	610		475		205	
15	-Cu	2630	2220	-	-	27	4
	+Cu	4000	4030	-	-	1850	1960
	LSD P=0.05	460				80	
21	-Cu	5100	5170	4990	4790	2020	1600
	+Cu	6690	6590	6490	6830	3800	3820
	LSD P=0.05	550		420		290	
23	-Cu	6460	5970	6860	6020	2690	2350
	+Cu	6280	6730	7090	6960	2970	3220
	LSD P=0.05	1030		730		300	

In Table 17 the yields at four of the nine sites where Cu x Zn interaction occurred are presented to illustrate the nature of the effects. In the absence of Cu, Zn application frequently decreased the yield, e.g. at Sites 21 (grain) and 23 (straw and grain). At Site 15 the top growth at Harvest 2 appeared to be decreased by Zn application without the effect being significant at $P=0.05$. On the other hand, Zn application frequently increased the yields in the presence of Cu, e.g. at Sites 10 (straw) and 15 (grain). Again, increases were measured that were not significant at $P=0.05$, e.g. at Sites 21 (straw) and 23 (tops at Harvest 2 and grain).

The size of the Cu x Zn interaction was not related to the severity of Cu deficiency. Only Sites 13 and 14 were Zn deficient and at both these sites Cu and Cu x Zn effects were non-significant. The Cu x Zn interaction indicated that Zn application aggravated Cu deficiency but that Cu application did not aggravate Zn deficiency. Sites where Zn application increased yields above that obtained with Cu alone were considered to be marginally deficient in Zn.

Copper x Manganese

Cu x Mn interactions had small but significant effects at Sites 3 and 24 (Table 18). At Site 3 Mn had no effect on yield when applied by itself but decreased the yield of straw and grain when applied in the presence of Cu. At Site 24 both Cu and Mn applied alone increased straw yield. At this site significant effects ($P=0.05$) similar to that in straw yield were measured in dry weight per plant at Harvest 2 and combined straw and grain yield. This site was considered to be marginally deficient in Mn while at Site 3 Mn was considered to have had a toxic effect.

TABLE 18

Cu x Mn interaction on wheat yield (kg ha^{-1})

Site No.		Harvest 2		Harvest 3			
		D.W. tops		D.W. straw		D.W. grain	
		-Mn	+Mn	-Mn	+Mn	-Mn	+Mn
3	-Cu	1210	1270	1270	1350	210	260
	+Cu	1470	1540	1910	1690	780	620
	LSD P=0.05	140		120		110	
24	-Cu	3820	3790	3590	3920	2330	2180
	+Cu	3970	3830	4130	3810	2670	2570
	LSD P=0.05	290		310		180	

Zinc x Iron

Zn x Fe interaction had small effects on yield at Sites 3, 9 and 22 (Table 19). At Sites 9 (tops at Harvest 2) and 22 (grain) the application of Zn or Fe alone decreased the yield and the application of these elements together increased the yields above that obtained with either element alone. This yield was similar to the yield without either element. Site 3 was considered to be marginally deficient in Zn and Fe because the addition of these elements increased the straw yield above that obtained where neither element was applied. Sites 9 and 22 were not deficient in either element, nor did toxicity occur when the elements were applied together.

TABLE 19

Zn x Fe interaction on wheat yield (kg ha^{-1})

Site No.		Harvest 2 D.W. tops		Harvest 3 D.W. straw		D.W. grain	
		-Fe	+Fe	-Fe	+Fe	-Fe	+Fe
3	-Zn	1350	1370	1530	1580	450	450
	+Zn	1380	1380	1440	1670	440	520
	LSD P=0.05	140		120		110	
9	-Zn	2490	1970	2650	2490	1020	850
	+Zn	2100	2510	2460	2790	850	960
	LSD P=0.05	400		320		190	
22	-Zn	4600	4370	4030	3890	2490	2210
	+Zn	4200	4280	3990	3970	2280	2500
	LSD P=0.05	530		-		170	

Manganese x Molybdenum

Significant interaction was detected at Sites 3, 4, 8, 23 and 24. The effect of the interaction on wheat growth varied (Table 20). For example, at Site 4 the application of Mo alone reduced the dry weights of tops at Harvest 2 and the grain and straw at Harvest 3 by 50 per cent but the addition of Mn and Mo together increased the grain yield by 40 per cent above that obtained with Mn alone. On the other hand, at Sites 23 and 24 both Mn and Mo, when applied alone, increased the yield but application of the elements together reduced the yields below that obtained by application of either element alone.

Mn x Mo interaction at Site 4 was a positive interaction and indicated marginal deficiency of Mo and acute deficiency of Mn.

TABLE 20

Mn x Mo interaction on wheat yield (kg ha^{-1})

Site No.		Harvest 2		Harvest 3			
		D.W. tops		D.W. straw		D.W. grain	
		-Mo	+Mo	-Mo	+Mo	-Mo	+Mo
4	-Mn	2920	1650	2250	1290	790	330
	+Mn	2960	3290	2410	2700	970	1320
	LSD P=0.05	740		770		420	
23	-Mn	6080	6680	6910	6940	2420	3090
	+Mn	6830	5850	7040	6040	2980	2740
	LSD P=0.05	1030		730		300	
24	-Mn	3780	4010	3850	3870	2440	2560
	+Mn	4010	3610	3860	3880	2470	2280
	LSD P=0.05	290		310		180	

Sites 23 and 24 were considered to be marginally deficient in both elements because each increased the yield when applied alone. It is inferred from the reduced yield when the elements were applied together that an imbalance between the Mn and Mo occurred in the plants.

Interactions with macronutrients

Interactions with major nutrients may also be important in relation to the occurrence of micronutrient deficiencies. Chaundry and Loneragan (1970) showed that Cu and Zn deficiency did not occur on Western Australian loamy sand soils unless N was first added. On these soils eight-fold increases in dry matter yields due to N occurred and Cu and Zn deficiencies were prevalent on the treated soils. The

Cu and Zn deficiencies were caused by dilution of the absorbed Cu and Zn and were aggravated by increased growth of tops relative to roots. This effect was observed in some of the factorial experiments on the solodized solonetz and solodic soils of Wharminda where basal N fertilizer increased dry matter by two-fold. Symptoms of Cu deficiency were less severe in the wheat around the experiments which had been sown without N fertilizer. Some of the smaller responses found, particularly in the factorial experiments may not have occurred without the basal N application.

The Zn x P interaction on plant growth described by Millikan (1963) and Olsen (1972) may have affected wheat growth in the factorial experiments. However, at the Zn deficient sites no differences were observed between wheat in the plots not treated with Zn and surrounding wheat crops that received less P and N than the experiment sites. It may be concluded from this that Zn x P and Zn x N interactions were equally severe in the farmers' crops and in these experiments, and consequently Zn responses obtained in the experiments would probably also occur in commercial crops.

(5) Effect of boron and molybdenum on plant numbers

The results in Tables 21 and 22 show that B and Mo applications affected the survival of wheat seedlings. However, the effects were inconsistent with both increases and decreases occurring in plant number per m^2.

TABLE 21

Effect of B on plant numbers

Site No.	Harvest No.	Plants per m^2 -B	Plants per m^2 +B
7	2	83	79^x
11	1	115	126^{xx}
19	2	80	85^x

Significance: x P=0.05, xx P=0.01

TABLE 22

Effect of Mo on plant numbers

Site No.	Harvest No.	Plants per m^2 -Mo	Plants per m^2 +Mo
2	2	58	53^x
6	2	58	53^x
20	2	78	82^x

Significance: x P=0.05

Survival of seedlings was also affected by the interaction of B and Mo with other micronutrients. At Harvest 1 all seven and at Harvest 2 four of the eight interactions measured involved B or Mo.

(6) Severity of deficiencies

In Table 23 the responses to the micronutrients have been used to indicate the severity of deficiencies and to indicate where micronutrient application had toxicity effects resulting in decreased yields at each site.

TABLE 23

Severity of micronutrient deficiencies in factorial experiments

Site	SMU	Cu	Zn	Mn	Fe	B	Mo
1	1	-	-	-	-	-	-
2	1	0	0	0	0	0	0
3	1	3	1	T	2	0	0
4	4	3	T	3	0	0	1
5	5	-	-	-	-	0	0
6	5	1	0	0	0	0	T
7	6	0	0	0	0	0	0
8	7	-	-	-	-	0	1
9	7	3	1	0	T	0	0
10	8	1	1	0	0	0	0
11	9	-	-	-	-	1	1
12	9	2	0	1	0	0	2
13	10	0	2	0	0	1	0
14	11	0	2	0	0	0	0
15	17	3	1	0	0	0	0
16	17	3	1	0	2	0	0
17	19	1	0	0	T	1	1
18	19	2	0	0	0	0	0
19	18	2	1	0	2	1	2
20	21	3	0	0	1	0	1
21	21	3	0	0	0	0	0
22	20	0	1	0	1	T	0
23	20	3	1	1	0	0	2
24	23	0	1	1	1	0	1

Severity of deficiency: not deficient - 0; marginally deficient - 1; deficient - 2; very deficient - 3. Also recorded was toxicity - T.

B Ancillary experiments

Table 24 summarizes the results of the ancillary experiments. Eleven of the 18 sites were deficient in one or more of the micronutrients added. Cu was applied at 17 sites and six responses to the treatment occurred. The yield of grain at Sites 37, 38 and 41 increased from 0 to over 2 000 kg ha^{-1} due to Cu fertilization. At Site 35 Cu decreased vegetative growth and grain yield, and increased the severity of melanism.

Yield increases due to Zn application occurred at three of the 12 sites where Zn was applied. At Sites 28 and 35 large responses occurred. At Site 36 Zn application produced taller and more vigorous plants at boot stage but this effect had disappeared by final harvest.

Increased vegetative and grain yields due to Mn application occurred at each of the three sites on calcareous sand and also on a shallow solodic soil (Site 34). No responses to Fe, B or Mo occurred at Sites 31 and 42, the only two sites where these micronutrients were applied (Appendix 8).

TABLE 24

Severity of deficiency in ancillary experiments

Site No.	SMU	Copper	Zinc	Manganese
25	1	0	0	0
26	4	0	0	1
27	4	0	-	3
28	4	0	3	3
29	5	0	0	0
30	5	0	0	0
31	6	2	0	0
32	7	0	0	0
33	9	0	0	0
34	10	-	-	2
35	12	T	3	0
36	12	0	1	0
37	13	3	-	-
38	17	3	-	-
39	18	1	-	-
40	19	0	0	0
41	19	3	-	-
42	20	0	0	0

Severity of deficiency: not deficient - 0; marginally deficient - 1; deficient - 2; very deficient - 3. Also recorded was toxicity - T.

PART 2 RELATION OF YIELD RESPONSE TO SOIL PROPERTIES

The concentrations of micronutrients in the plant and in the soil are given, and the relations between soil and plant concentrations and yield response are represented diagrammatically for all soils and for groups of soil mapping units.

A Concentration of micronutrients in plants and soils

The analysis of total tops of the plants and grain from the control plots of the factorial experiments sampled at tillering, at the boot stage and at maturity are given in detail in Appendix 10. In general the Cu, Zn, Mn, B and Mo concentrations in the plants did not vary greatly between the growth stages. The ranges in concentration were: Cu 0.9 - 6.9 ppm, Zn 8 - 35 ppm, Mn 0.8 - 139 ppm, B 1.2 - 20.8 ppm and Mo from <0.2 - 1.2 ppm. The Fe concentration at tillering ranged from 105 - 910 ppm, at boot stage 42 - 230 ppm and in the grain 42 - 108 ppm. These values are similar to those reported for micronutrients in wheat in other areas of South Australia (J.E. Schultz and R.J. French, personal communication).

Tables 25 and 26 present data for soils from certain sites of the factorial experiments selected to show the range of total and available micronutrients in the soils. The complete results are given in Appendix 1. The deep siliceous and calcareous sands and the solodized solonetz and solodic soils at Wharminda contained lower concentrations of total micronutrients in the A and B horizons than did the other soils. The concentrations reported are similar to those quoted by Tiller (1957)

TABLE 25

Total and EDTA-extractable micronutrients in selected horizons at sites of the factorial experiments

Soil	Site No.	Horizon	Total						EDTA-extractable			
			Cu	Zn	Mn	Fe	B	Mo	Cu	Zn	Mn	Fe
			ppm			%	ppm		ppm x 10^2	10^2	10^2	10
Deep siliceous sand SMU 1	3	A_1	1.5	50	10	0.20	4	2	11	34	230	450
		A_2	–	–	–	–	–	–	12	31	42	410
		B^2	1.0	40	9	0.29	3	2	9	14	9	170
Calcareous sand SMU 4	4	A_1	2.0	45	20	0.33	3	1	23	47	370	160
		B_1	1.0	40	10	0.21	2	1	14	32	29	87
Solonized brown soil SMU 11	14	A_1	3.0	95	30	0.69	2	2	50	150	660	330
		B_1	4.5	130	50	1.10	5	4	89	23	310	120
Lateritic podzolic soil SMU 17	15	A_1	4.0	10	35	18.00	-	5	14	26	420	410
		A_2	–	–	–	–	-	–	10	22	130	440
		B_1	3.0	15	25	6.00	-	1	9	25	29	270
Stokes solodic soil SMU 21	20	A_1	4.0	150	85	1.10	-	1	48	59	3800	1900
		B_1	4.0	450	100	5.50	-	1	18	21	120	550
Stokes solodic soil SMU 23	24	A_1	3.0	160	55	0.46	3	2	57	110	460	2800
		A_2	–	–	–	–	–	–	11	41	100	1100
		B_2	2.0	230	95	1.60	3	3	24	34	19	350

TABLE 26

DTPA and $Ca(NO_3)_2$-extractable Cu, Zn, Mn and Fe in selected horizons at sites of the factorial experiments

Site		DTPA-extractable				$Ca(NO_3)_2$-extractable			
No.	Horizon	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
			ppm	x			ppm	x	
		10^3	10^2	10^2	10	10^4	10^3	10^3	10^3
3	A_1	10	31	100	80	8	0	750	46
	A_2	-	-	-	-	35	5	220	190
	B	-	-	-	-	0	0	57	24
4	A_1	24	13	93	34	30	0	0	44
	B_1	-	-	-	-	43	0	0	21
14	A_1	160	190	140	37	64	0	0	130
	B_1	-	-	-	-	120	0	0	49
15	A_1	46	20	440	160	13	0	1700	26
	A_2	-	-	-	-	20	0	790	130
	B_1	-	-	-	-	0	0	75	20
20	A_1	110	45	1700	480	57	34	16000	180
	B1	-	-	-	-	0	0	85	0
24	A_1	150	66	340	930	140	350	3700	1200
	A_2	-	-	-	-	39	160	1000	17000
	B_2	-	-	-	-	3	0	30	52

for similar soils in the south-east of South Australia. Total concentrations of micronutrients found in terra rossas, rendzinas and other soils by McKenzie (1959) and Blackburn and Giles (1963) in the south-east of South Australia and in podzolic soils in Victoria (McKenzie 1966) are of the same order as concentrations found in similar soils of the study areas.

The lateritic podzolic soils, as expected, contained higher total Fe in all horizons than the other soils. The pisolitic laterite in these soils was found to contain double the concentration of Fe than the soil around it but the concentrations of Cu, Zn and Mn were only slightly higher than in the soil. The total Zn concentration is generally higher in B and C horizons, associated with higher percentage of clay minerals, but the other elements show no consistent differences in concentration between horizons. McKenzie (1957, 1959) showed no profile trends in total micronutrient concentration in terra rossas but showed increasing concentration with depth in red brown earths.

The extractable micronutrient contents varied with depth in the profiles. The A_1 horizons generally contained higher concentrations of EDTA-extractable forms than lower horizons. EDTA-extractable Mn and Fe were considerably more concentrated in A horizons, particularly at Sites 20 and 24. The concentration of Cu extractable with EDTA from the surface horizons of soils in the mapped areas ranged from 0.11 to 1.3 ppm. The range in podzolic soils is similar to that reported by McKenzie (1966) for podzolic soils of Victoria but the concentrations in solodized solonetz and solodic soils ~~was~~ were often less than half that reported by Tiller et al (1972) who found 0.6 - 1.7 ppm EDTA-extractable Cu in surface horizons of these soils. Concentrations of EDTA-extractable Zn reported by Tiller et al (1972) in the surface horizons of solonized brown soils (1.8 - 2.7 ppm) and podzolic soils (0.3 - 0.4 ppm) were similar to those obtained on these types of soils in the mapped areas.

As expected, the amounts of Zn and Mn extracted by $Ca(NO_3)_2$ solution from soils of high pH and high carbonate content were very low. Many of the alkaline soils actually removed traces of Zn and Mn from the $Ca(NO_3)_2$ extracting solutions despite purification of the extracting solution with dithizone. However, much of the total Zn and Mn in the slightly acid horizons of the soils of Stokes was extractable. For example, at Site 20 (pH 6.5 in the surface horizon) half of the total Mn was extractable with EDTA solution and one-fifth was extractable with DTPA or $Ca(NO_3)_2$. The values obtained for $Ca(NO_3)_2$-extractable Zn (Table 29) are in close agreement with analyses reported by Tiller et al (1972) for solodized solonetz, solonized brown soils and podzolic soils in South Australia.

B Soil mapping units and the Factual Key

In order to apply the information from the factorial and ancillary experiments, the relationships of the responses to the soil mapping units and various groups of units has to be considered. The soil mapping units are defined (after Webster 1968) as naturally occurring groups of soils with similar parent materials and soil morphology. Wherever they occur they support similar original or introduced communities of plants and have low variability in productive potential.

The Factual Key of Northcote (1971) separated some soil mapping units. For example, the principal profile forms Uc1.11 and Uc5.12 occurred as two separate units. However, in other cases the same principal profile forms occurred in several soil mapping units. The lateritic podzolic soil with grey surface and pisolitic laterite in the A horizons (SMU 19), the alluvial solodic soil (SMU 23) and some solodic soils formed on white granitic gneiss (SMU 20) have Dy3.82 profiles. Significant differences between these units in the growth of wheat and in chemical analyses of the soils were noted. Conversely, one soil mapping unit may contain several similar principal profile forms. For example, the solodized solonetz and solodic soils of Wharminda have Dy5.43 and Dy5.83 profiles and the solodic soils formed on pink granitic gneiss at Stokes have Db2.22 and Db2.62 profiles. Each pair of profiles had minor structural differences in the B horizon which were of little agronomic importance. In short, the Factual Key was not sufficient in itself to separate the soil mapping units. As pointed out by Mulcahy and Humphries (1967), the agronomic utility of the Factual Key is limited by the number of diagnostic criteria used. However, the Key was particularly useful in systematic examination of soil profiles and provided a starting point for the identification of the mapping units.

Northcote (1962) described sequences of principal profile forms that occur between mountainous areas and adjacent plains in Victoria and showed how the Key linked climate and soil development more accurately than did previous systems of classification. The Key makes similar distinctions between the soils at Wharminda and those at Stokes. Neutral duplex soils occur at Stokes and alkaline duplex, gradational and uniform soils occur at Wharminda, but within each district sequences such as described by Northcote (1962) do not occur because there is not enough climatic variation to produce them. Northcote (1962) also showed how the Key differentiated between variants of single great soil groups. For example, two forms of krasnozem with different structural properties were separated. The Key served this purpose in the study areas, differentiating between forms of great soil groups.

The deep siliceous sands and solodized solonetz and solodic soils of Wharminda were mapped in seven units that vary mainly in depth of horizons (Fig. 9). SMU 1 and 5 - 8 have very light-brown sand A_1 horizons, whereas SMU 9 and 10 have brown loamy sand A_1 horizons. The latter two soil mapping units have characteristics in common with the solonized brown soils, such as loamy sand A_1 horizons and carbonate close to the surface. The calcareous sands have some properties in common with the other sands, and may be grouped with them when Cu is considered because availability of Cu is relatively unaffected by pH and carbonate content. In contrast, these two properties have large effects on Zn and Mn availability, and the calcareous sands may then be more appropriately grouped with the other calcareous soils.

The soils of Stokes are slightly acidic and have more clay in the surface horizons than the soils of Wharminda and are usually neutral lower in the solum, whereas the soils of Wharminda are usually alkaline beneath the surface. The soils of Stokes are mainly lateritic podzolic and solodic. Three soil mapping units were recognized in the lateritic podzolic soils, varying in amount and form of laterite and in profile drainage. All three soils have similarly coloured, unstructured or poorly structured clay B horizons and have similar depths of solum and texture of horizons. The solodic soils contain five soil mapping units which differ in parent material, depth of solum, colour and texture of A horizons and drainage characteristics. These soils are usually deeper than the lateritic podzolic soils and frequently have blocky structured B horizons.

C <u>Distribution of deficiencies in different soils</u>

In Tables 27 and 28 occurrence of deficiencies is related to the nature of the soils and the 42 experimental sites are described as deficient or not deficient. This enabled the proportion of sites deficient in particular elements on each individual or group of soil mapping units to be determined. Marginal deficiencies at factorial sites were not included in this assessment. Pooling of the results of the factorial and ancillary experiments shows several clear relationships between response to micronutrients and soil mapping units. However, it should be borne in mind that in pooling the results, the accurately

TABLE 27

Soils at sites of the factorial and ancillary experiments

Soil categories	Soil Mapping Units	Site number	
		Factorial experiments	Ancillary experiments
Deep siliceous sand	1	1 - 3	25
Calcareous sand	4	4	26 - 28
Solodized solonetz and solodic soils			
(a) With light brown sand A_1 horizons	5 - 8	5 - 10	29 - 32
(b) With brown loamy sand A_1 horizons	9, 10	11 - 13	33, 34
Solonized brown soils	11, 12	14	35, 36
Red brown earth	13		37
Lateritic podzolic soils A_1 horizons:			
(a) With massive and concreted laterite	17	15, 16	38
(b) Red-brown with pisolitic laterite	18	19	39
(c) Grey with pisolitic laterite	19	17, 18	40, 41
Solodic soils A_1 horizons:			
(a) Grey with white quartz gravel: soil formed on white granitic gneiss	20	22, 23	42
(b) Brown with pink sand grains: soil formed on pink granitic gneiss	21	20, 21	-
(c) Grey: gully line soils formed on alluvium	23	24	-

TABLE 28

Separation of all experimental sites into deficient and non-deficient categories

Soil Mapping Units	Numbers of sites					
	Deficiency of Cu		Deficiency of Zn		Deficiency of Mn	
	present	absent	present	absent	present	absent
1	1	2	1	2	0	3
4	1	3	1	2	4	0
5-8	4	4	2	6	0	8
9,10	1	2	1	2	2	2
11,12	0	3	3	0	0	3
13	1	0	0	0	0	0
17	3	0	2	0	0	2
18	2	0	1	0	0	1
19	3	1	0	3	0	3
20	1	2	2	1	1	2
21	2	0	0	2	0	2
23	1	0	0	1	1	0

measured responses in factorial experiments are equated with the assessed responses of the ancillary experiments. In the latter case small responses tend to be overlooked. Moreover, five wheat cultivars were used in the 42 experiments and this may have affected the presence or the degree of deficiency at each site.

Cu deficiency occurred on a wide range of soils It occurred on the deep siliceous and calcareous sand, solodized solonetz and solodic soils at Wharminda (SMU 1, 4-8). Responsiveness of wheat to Cu application on these soils did not appear to be related to depth of sand as might have been expected if the underlying clay had been a better source of Cu; however, as indicated previously, the Cu contents of the B horizons were low. When SMU 1 and 4-8 were grouped together yield increases occurred at six of the 15 sites. The loamy sand to sandy loam soils in SMU 9 - 12 at Wharminda, which includes shallow solodized solonetz, solodic and solonized brown soils, were tested at six sites and only one was slightly deficient in Cu. From these experiments and from observations of crops on these two categories of soil, Cu deficiency would appear to be largely restricted to soils with light-brown sand A_1 horizons. These soils contained lower concentrations of organic matter in their surfaces than the brown loamy sands which may explain why the former soils contain lower concentrations of extractable Cu and were more deficient. The properties of the surface horizon had greater influence on deficiency than did the great soil groups to which the soil belonged.

In the Stokes area, nine of the 10 sites on lateritic podzolic soils were Cu-deficient. At two of the three sites on SMU 17 (with massive and concreted laterite) death of many plants occurred where no Cu was applied. Four of the six sites on the solodic soils of Stokes were deficient in Cu, with both sites on SMU 21 (derived from pink granitic gneiss) being very deficient.

Zn and Mn deficiencies appear to be confined largely to calcareous soils. The yield responses to application of Zn occurred on solonized brown soils with calcareous loam horizons at or near the surface (SMU 11 and 12) and on calcareous sand (SMU 4). One site on a shallow solodic soil at Wharminda was Zn-deficient. All sites on calcareous sand (SMU 4) and one site on a shallow solodic soil (SMU 10) were deficient in Mn.

Two sites at Stokes were Mo deficient, one on a lateritic podzolic soil and the other on a solodic soil. Deficiencies of Fe were small and occurred on a variety of soil mapping units. Responses to Mo, Fe and B were not considered to be of any agronomic importance.

D Yield responses to micronutrient application, and soil and plant concentrations

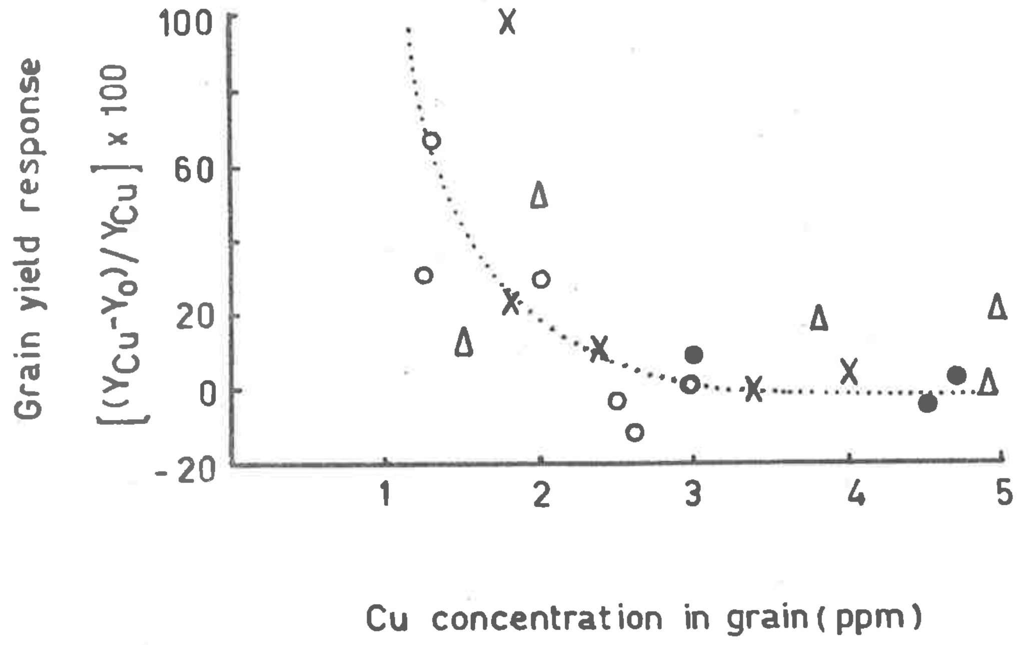
The relation of plant yield response to soil and plant concentrations of micronutrients is presented. In the diagrams, the curves have been hand fitted as not enough experiments were conducted on each group of soils to adequately test the fit statistically.

(1) Copper

Soil and plant analyses are related to per cent yield increase and to absolute increases. In the former case $\left[(Y_{Cu}-Y_o)/Y_{Cu}\right] \times 100$ (where Y_{Cu} is the mean dry matter of tops or grain yield with Cu applied and Y_o the mean yield without Cu) is used to even out the effects of the large differences in yield that occur between sites. It should be noted that data calculated from this function are not normally distributed. Y_{Cu}/Y_o is not suitable as an index of response because at sites where yield without added Cu is very low (e.g. Site 15) the values of Y_{Cu}/Y_o are very large and give a greatly exaggerated view of the response.

FIGURE 14

Per cent grain yield response to Cu and Cu concentration in the grain of control plots



o Deep siliceous and calcareous sands, solodized solonetz and solodic soils with light-brown sand A_1 horizons.

● Shallow solodized solonetz and solodic soils and solonized brown soils with brown loamy sand A_1 horizons.

X Lateritic podzolic soils.

Δ Solodic soils of Stokes.

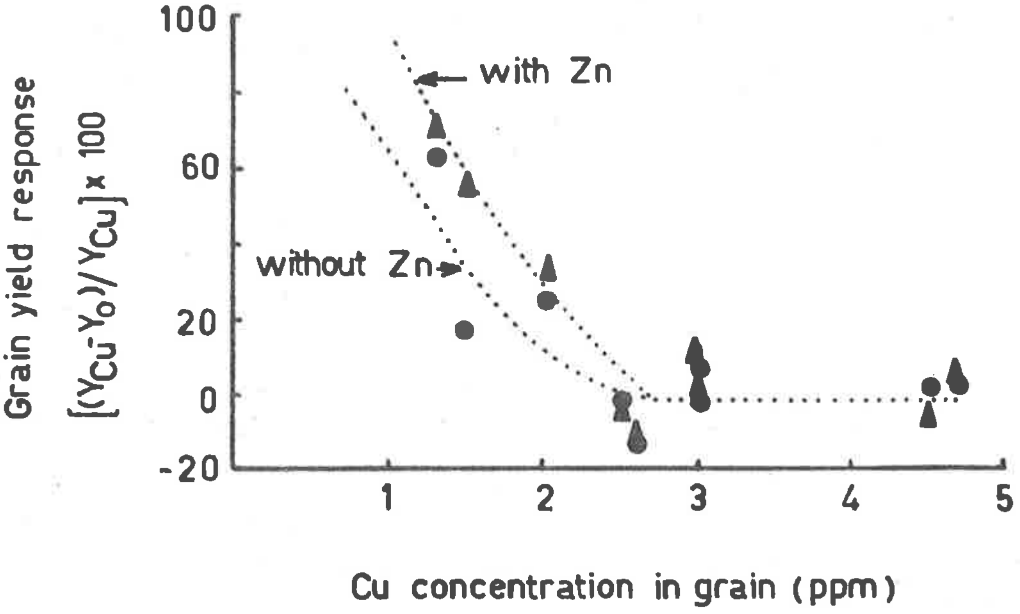
These symbols apply also in Figs. 16-18.

Cu concentration in the grain is related to per cent grain yield response in Fig. 14. The responsive and unresponsive sites are largely separated by a grain Cu concentration of 2.5 ppm although response to Cu application occurred at two sites on solodic soils of Stokes with Cu concentrations in the grain of 3.7 and 5.0 ppm.

The critical concentration of Cu in the tops at the boot stage was 3.2 ppm. The critical values in the tops and grain were affected slightly by soil type and to a lesser extent than was extractable Cu in the soil. The results for yield responses in Fig. 14 were calculated from the mean grain yield for all plots with and without Cu. Although interactions with other micronutrients occurred frequently the effect was generally small and had little effect on the critical values for Cu as illustrated in Fig. 15 for the Cu x Zn interaction on the Wharminda soils. Pizer _et al_ reported a range of 0.9 - 4.5 ppm Cu in deficient wheat grain in England and suggested that grain

FIGURE 15

Per cent grain yield response to Cu, without and with applied Zn and Cu concentration in grain of control plots



● in the absence of Zn

▲ in the presence of Zn

analysis was of little value for diagnosing deficiency. However, Caldwell (1971) stated that farm advisers in south-eastern England consider that less than 2 ppm Cu in wheat grain indicates deficiency while greater than 3 ppm indicates sufficiency. Both the range of Cu concentrations in deficient grain and the critical values reported by Pizer _et al_ (1966) and Caldwell (1971) are in close agreement with the findings of the experiments in this study.

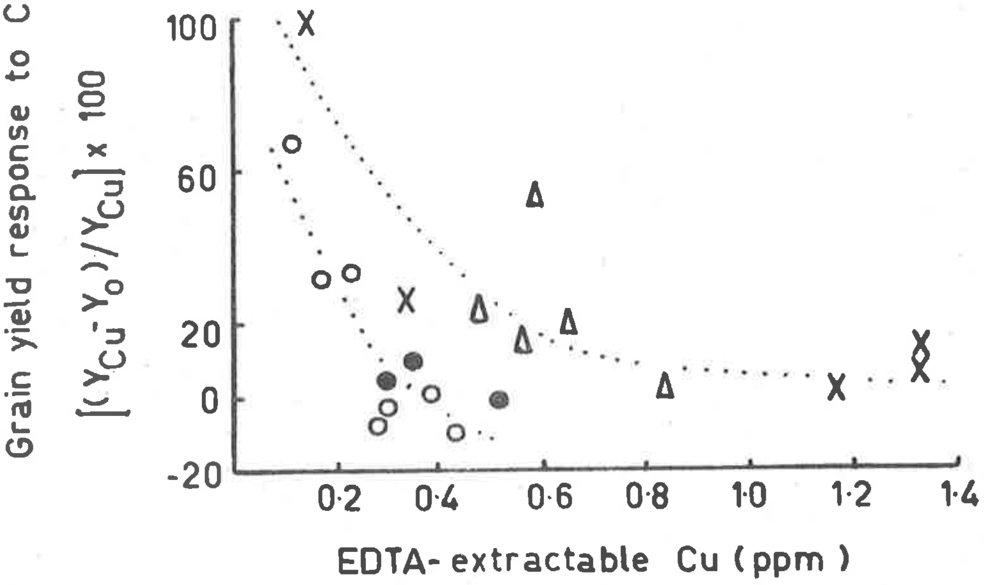
The amounts of Cu extracted from the soil by EDTA solution are related to per cent grain yield response in Fig. 16. The relationship between EDTA-extractable Cu in the surface soils and grain yield response appear to be different for Wharminda and Stokes. Responses to Cu application occurred at higher soil Cu concentrations in the surfaces of lateritic podzolic and solodic soils of Stokes. Similar relationships were observed between per cent grain yield response and DTPA - and $Ca(NO_3)_2$-extractable Cu. Critical values for extractable Cu above which little response to applied Cu occurred were:

	Wharminda ppm	Stokes ppm
EDTA-extractable Cu	0.35	0.75
DTPA-extractable Cu	0.10	0.20
$Ca(NO_3)_2$-extractable Cu	0.004	0.010

When absolute increases in yield were plotted against soil concentrations, three curves were obtained instead of two (Fig. 17). Where absolute yield increases are used, critical values for EDTA extraction are 0.4 ppm for the soils of Wharminda, 0.6 ppm for the lateritic podzolic soils and 0.85 ppm for the solodic soils of Stokes. Similar curves are produced when absolute yield increases are plotted against DTPA- or $Ca(NO_3)_2$- extractable Cu. The critical values

FIGURE 16

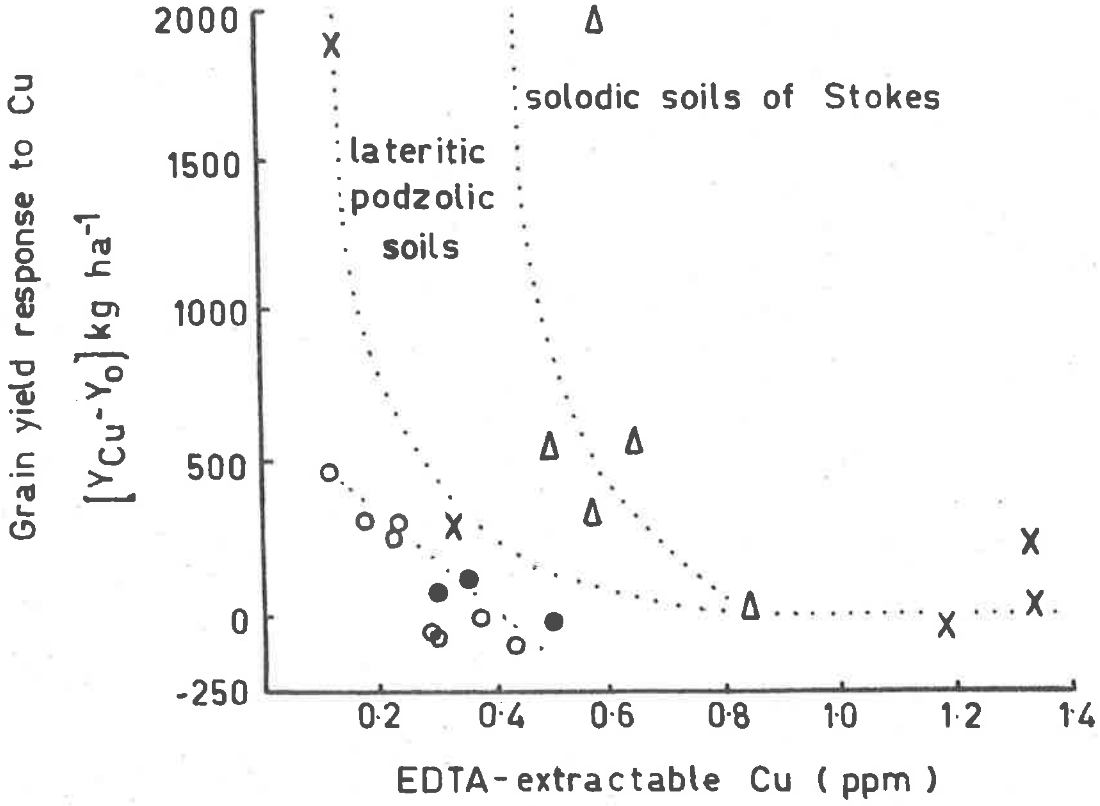
Per cent grain yield response to Cu and EDTA-extractable Cu in A_1 horizons



Legend - see Fig. 14

FIGURE 17

Absolute increase in yield due to Cu, and EDTA-extractable Cu in A_1 horizons



Legend - see Fig. 14

obtained with EDTA are similar to those reported elsewhere. A critical value of 0.75 ppm EDTA-extractable Cu was reported for a wide range of soils by McKenzie (1966), Reith (1968) and Cox and Kamprath (1972) whereas Caldwell (1971) reported 0 - 1.3 ppm EDTA-extractable Cu in deficient soils of England.

The existence of two curves in Fig. 16 may be due to the soils, climatic effects or the wheat cultivars used: differences between the soils of the two areas are considered to be mainly responsible for the existence of the two curves. Pinnacle was grown at Stokes and Halberd at Wharminda. In a greenhouse experiment with these cultivars, conducted on soil from the A horizon of a deep siliceous sand from near Site 1, Halberd was found to be more susceptible to Cu deficiency and more responsive to application of Cu than was Pinnacle (Alston, A.M. personal communication). If these differences occur widely in the field the effect of growing one cultivar at all sites would accentuate the differences between the curves. Since the relationship between per cent grain yield increase and concentration of Cu in the soil for the experiments in the Stokes area is the same in both 1970 (a dry year) and 1971 (a wet year), rainfall is unlikely to affect the relationship. Moreover, in Fig. 17, absolute yield increases form two curves for the lateritic podzolic and solodic soils of Stokes. Experiments were conducted in 1970 and 1971 on both soil groups, which are in close proximity to one another. Since Pinnacle was used at all sites it is reasonable to conclude that the relationship between yield response and extractable Cu is different for these different groups of soils.

The total Cu uptake in the grain grown on the lateritic podzolic and solodic soils of Stokes was twice that in the grain grown on the soils at Wharminda, due mainly to the higher yields obtained at Stokes (Table 29) where soil nutrient content is relatively high (Appendix 1).

The supply of $Ca(NO_3)_2$-extractable Cu in the A_1 horizons of the soil, the form most readily available to plants, was similar in the soils of both regions. The higher critical Cu values in the soils at Stokes compared with Wharminda may be caused simply by higher demand for Cu from pools approximately equal in size.

TABLE 29

Cu contents of grain and available Cu in soil

Variate		Wharminda	Stokes
mean grain yield	kg ha^{-1}	1050	2040
total Cu content of grain	g ha^{-1}	2.92	6.24
$Ca(NO_3)_2$-Cu in A_1 horizons	g ha^{-1}	9.1	10.7

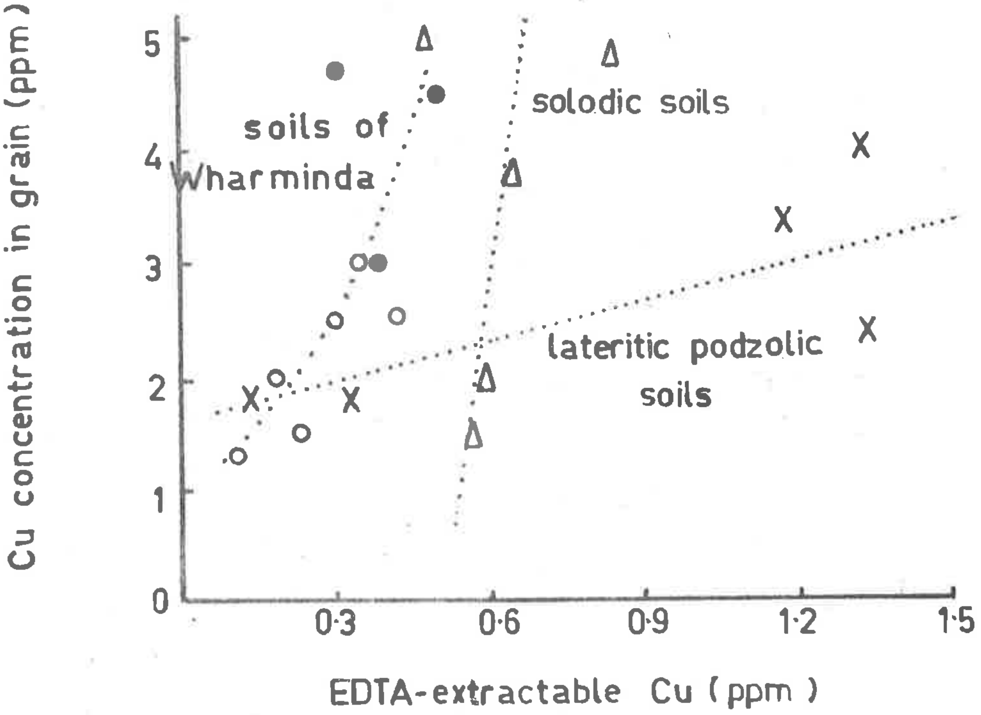
The relations between the response to Cu measured in the dry matter of the plant tops at Harvest 2 and the amounts of Cu extracted from the soil by the various solutions were similar to those for the grain. However, the critical values separating deficient and non-deficient soils were 5-10 per cent lower, and responses that occurred after boot stage were not detected.

When the concentration of Cu in the grain was plotted against the Cu extracted from the soil by EDTA (Fig. 18) all soils at Wharminda appear to fall on one curve, while the lateritic podzolic and solodic soils of Stokes appear to be on two different curves. This suggests that the extractants removed different fractions of the soil Cu available to plants on the contrasting soils. Similar relations were found between DTPA- and $Ca(NO_3)_2$-extractable Cu and concentration of Cu in the grain. The concentrations of extractable Cu in the B horizons of lateritic podzolic and solodic soils were not related to

FIGURE 18

Concentration of Cu in the grain and

EDTA-extractable Cu in A_1 horizons



Legend - see Fig. 14

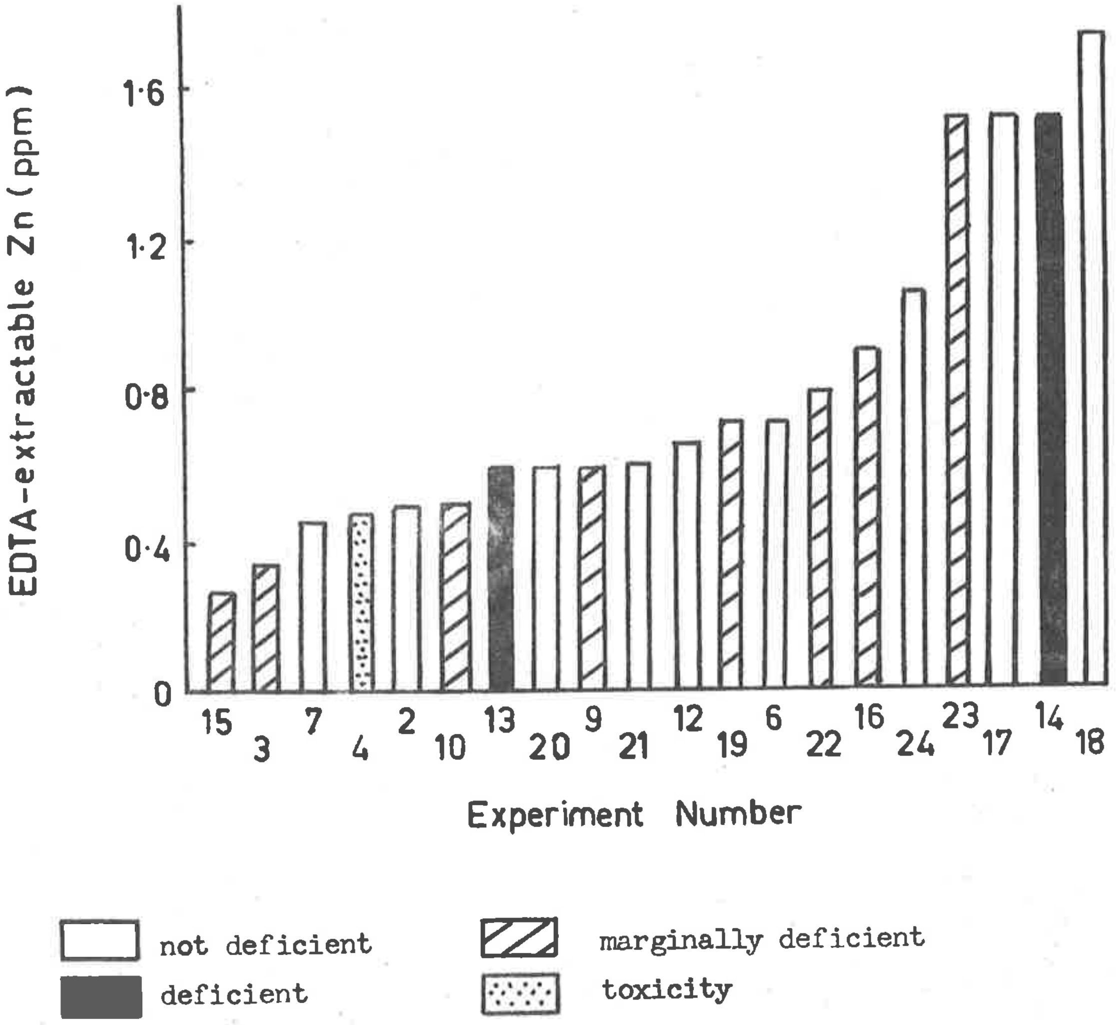
response of grain yield to application of Cu emphasizing again that A_1 horizons were the main source of plant Cu.

(2) Zinc, manganese, iron, boron and molybdenum

Few yield responses to Zn, Mn, Fe, B or Mo occurred and it was not possible to define clearly the relationship of yield response to concentration of these micronutrients in the plant or soil. There was no obvious relationship between deficiency of Zn, Mn or Fe and EDTA-, or DTPA-extractable Zn, Mn or Fe in surface soils. The relationship between EDTA-extractable Zn and Zn deficiency is given in Fig. 19. Sites not deficient in Zn contained as low as 0.26 ppm of extractable Zn in the surface while the deficient sites contained 0.6 and 1.5 ppm

FIGURE 19

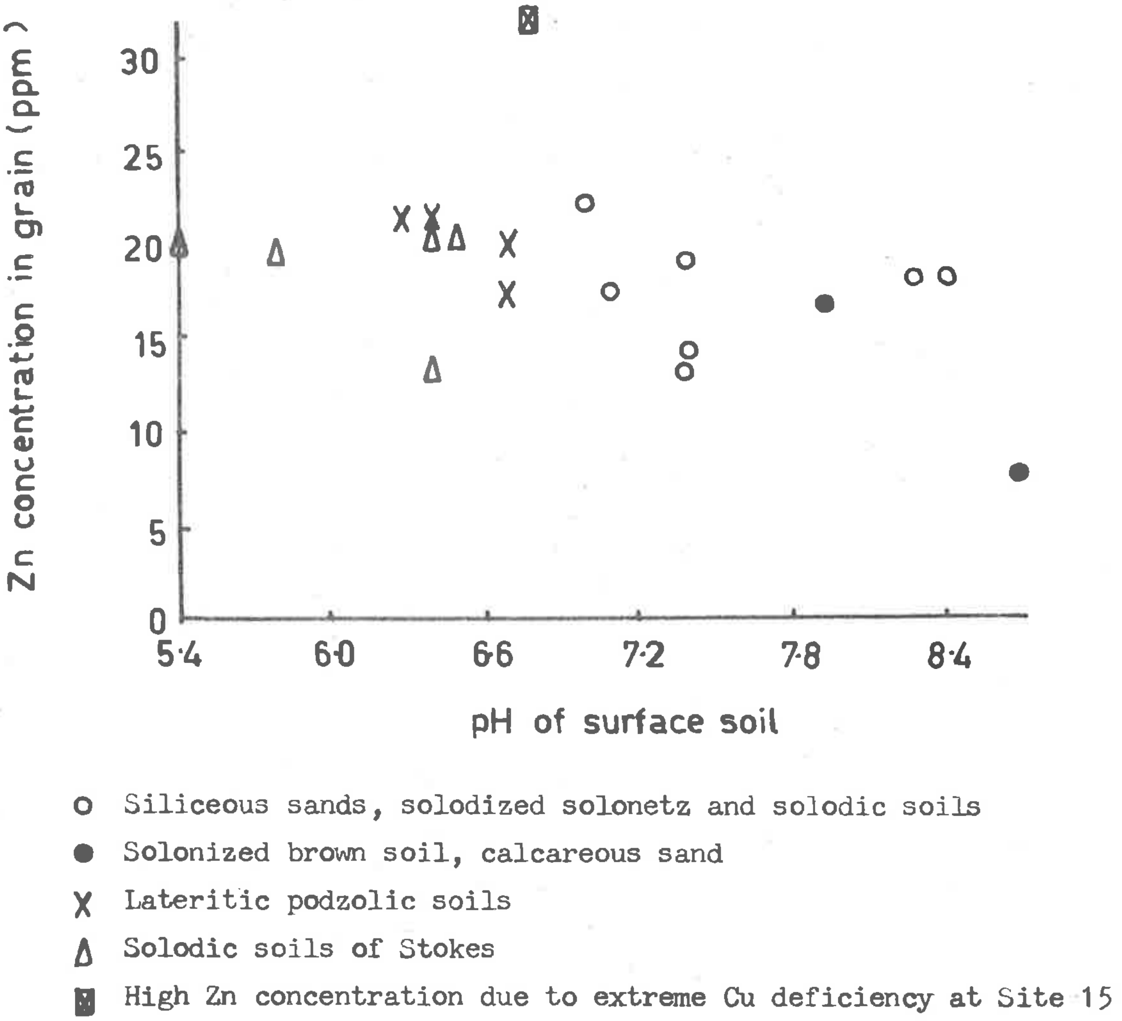
EDTA-extractable Zn in A_1 horizons and Zn deficiency at factorial experiment sites



extractable Zn. Relationships between EDTA-extractable Zn and deficiency have been shown elsewhere. For example, Trierweiler and Lindsay (1969) reported a critical value of 1.4 ppm EDTA-$(NH_4)_2CO_3$ extractable Zn. A complex relationship exists between $Ca(NO_3)_2$-extractable Zn and Mn and deficiency of these elements. It was noted that surface soils from the sites deficient in Zn (Sites 13 and 14) and Mn (Site 4) adsorbed more Zn and Mn from the extracting solution than did surface soils from the other sites. It was also observed that at Site 3 where Mn toxicity occurred the surface soil contained a higher concentration of $Ca(NO_3)_2$-extractable Mn than at any other Wharminda site. Allied to adsorption or release of Zn or Mn into neutral salt solution is the effect of pH and carbonate. Both Zn and Mn concentration in the plant and grain decreased with increase in pH and carbonate content of the surface soil. This is illustrated in Fig. 20 for the relationship between Zn concentration in the grain and pH of surface soil. The concentration of Zn in the grain appears to have decreased slightly above pH 75.

FIGURE 20

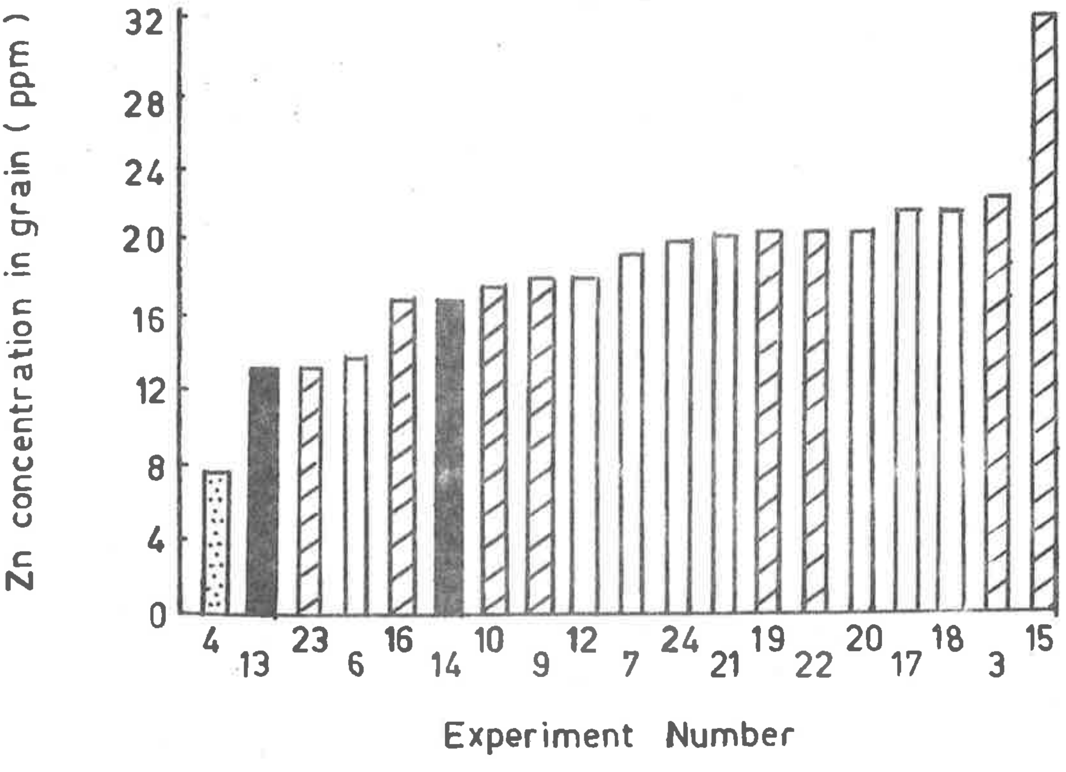
Zn concentration in grain of control plots and pH of surface soil



At Sites 13 and 14 (Zn deficient) the concentration of Zn in the grain was 13 and 17 ppm respectively and these concentrations were lower than at most sites (Fig.21) although all but one site had grain Zn concentrations of less than 22 ppm. These concentrations are all close to the critical value of 15 ppm reported by Viets (1966) and indicate that incipient Zn deficiency was likely at many sites.

FIGURE 21

Zn concentration in grain of control plots and Zn deficiency at factorial experiment sites



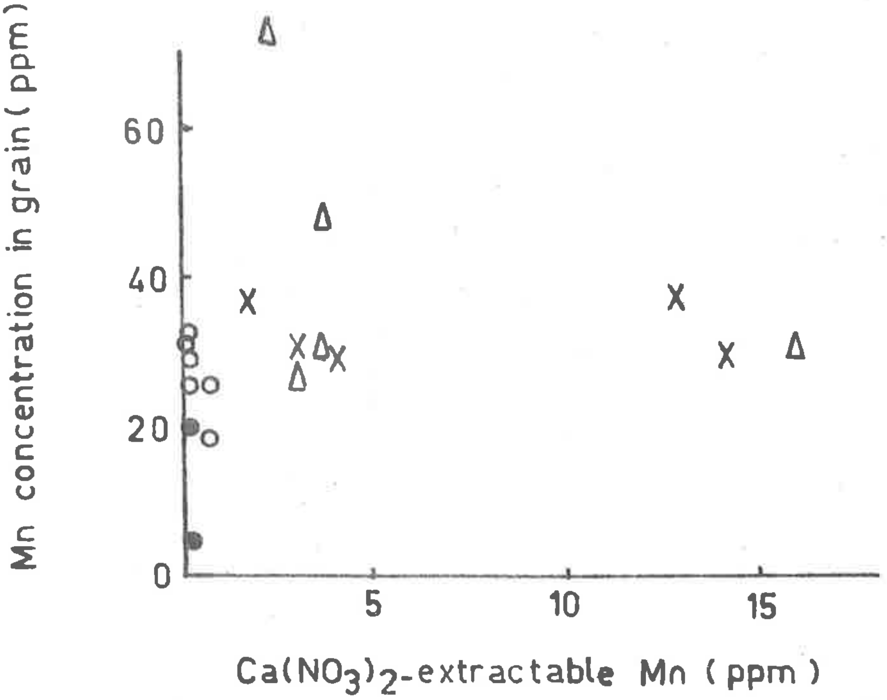
Legend - see Fig. 19

There was no obvious relationship between Zn concentration in the plants or grain and marginal Zn deficiency detected through the Cu x Zn interaction (Fig. 21). Chaundry and Loneragan (1970) indicated that Zn concentration is often higher in Cu deficient plants and this may explain the poor relationship. At Site 15 where wheat from all plots was analysed for Cu and Zn, the Zn concentration in the plant tops at Harvest 2 was 12.5 ppm where Cu was not applied and 9.0 ppm where it was applied. By Harvest 3 the Zn concentration had risen to 32 ppm in the grain from the plot to which no fertilizer had been applied. The lowest concentration of Zn in the tops at the boot stage and in the grain occurred at Site 4 (calcareous sand) but, contrary to what was expected, Zn application decreased the yields (Table 12), possibly through interaction with Cu or Mn which were both very deficient at this site. Mn deficiency at Site 4 was accompanied by the lowest concentrations of plant and grain Mn found in the experiments (Fig. 22).

FIGURE 22

Mn concentration in grain of control plots and

Mn extractable from A_1 horizons by $Ca(NO_3)_2$ solution



Legend - see Fig. 20

The plant and grain data suggest that interactions may be more important in assessing the significance of Zn concentrations in the plant than they appeared to be for Cu. Analysis of the plant tops and grain appear to be more useful than are EDTA, DTPA or $Ca(NO_3)_2$ tests for diagnosing Zn and Mn deficiency.

B and Mo contents of the vegetative and grain parts of the plant (Appendix 10) do not indicate deficiency when compared to the concentrations in healthy plants given by Chapman (1966). Williams (1971) showed that Mo deficiency occurred in a range of crops when the Mo concentration was less than 0.1 ppm. This concentration was exceeded in most of the plants in the experiments. The effects of B and Mo on plant survival were common but the reasons for them are not known. Because the effects operated after the two leaf stage of the plants (when the first spray was applied) it is likely that B and Mo treatment at sowing would have had larger effects on germination and survival. Increased growth rates of germinating wheat grain due to B were reported by Kurgzov (1972) and increased growth rate of seedlings through fungicidal action of B was shown by Rebenko (1971).

Visual examination of diagrams relating Cu, Zn, Mn or Fe concentrations in the plant tops or grain to per cent clay, organic carbon, total soil nitrogen, bicarbonate extractable P and cation exchange capacity in the soil were made but no obvious correlations were observed.

PART 3 GENERAL CONCLUSIONS

A Identification of micronutrient deficient areas

Mapping of landscape features as land units based on geomorphology and topography greatly aided identification and delineation of the soil mapping units and hence areas of likely deficiencies. Some soils occurred widely, while others were restricted to one or two land units. For example, the calcareous sands (SMU 3 and 4) were found only in LU II and the terra rossas (SMU 14) in LU V, while the solodized solonetz and solodic soils were found in all units although the area occupied varied greatly from land unit to land unit. The soils were found on particular components within the land units. For example, in LU I (Dune and swale system) deep siliceous sands occur on the tops and upper slopes of the dunes, solodized solonetz and solodic soils with light-brown sand A_1 horizons occur on middle and lower slopes of dunes and in slightly raised sandy areas on the flats, whereas shallow solodized solonetz and solodic soils with brown loamy sand A_1 horizons are found in the flats. This topographic relationship of soils is characteristic of LU I. Similar relationships exist in the other land units.

The field experiments indicated particular sites where micronutrient deficiencies occurred, and if the sites are characteristic of the particular soils they represent, the results of the field experiments can be used in conjunction with the soil survey to define soils deficient or potentially deficient in micronutrients. The results suggest that solodized solonetz, solodic and other soils at Wharminda with loamy sand to sandy loam A_1 horizons were unlikely to be deficient in Cu, but that soils with light-brown sand A_1 horizons are potentially deficient. All the lateritic podzolic and solodic soils at Stokes are considered to be potentially deficient in Cu: the observed deficiencies were most severe on the lateritic podzolic soils particularly those with A horizons dominated by massive and concreted pisolitic laterite. Areas potentially deficient in Zn are on solonized brown soils with calcareous loam surface horizons while Mn deficiency is likely on the calcareous sands. Both Zn and Mn deficiency occurred occasionally on shallow solodic soils, particularly where cultivation or erosion had brought carbonate to the soil surface. These effects are similar to those responsible for the induced Fe deficiency in Colorado reported by Follett and Lindsay (1970), where removal of surface soil by erosion or land levelling exposed soil low in available Fe content. Follett and Lindsay (1970) also reported decreased concentration of DTPA-extractable Zn and Mn with depth in the soil, and they anticipated that removal of surface soil could cause deficiencies. Erosion is not uncommon on Eyre Peninsula and the possible effects that it would have on the occurrence of deficiencies should not be overlooked.

Not all of the sites regarded as potentially deficient on the basis of the soil survey and the results of the field experiments actually responded to fertilizer application. Soil and plant analysis and, in some cases, the occurrence of micronutrient deficiency symptoms were used with varying degrees of success to separate the responsive from the unresponsive sites. It was possible to draw firm conclusions about the value of soil and plant analysis only for Cu, since relatively few yield responses occurred to application of the other micronutrients. Plant and grain analysis was more satisfactory than soil analysis for separation of Cu-deficient from non-deficient soils because the nature of the soil had little effect on the critical value of 2.5 ppm in the grain.

Before soil analysis can be used effectively, differences between soils or groups of soils must be recognized. Provided the nature of the soil is taken into account, the three extractants $Ca(NO_3)_2$, DTPA and EDTA were equally useful in diagnosing Cu deficiency. The results for $Ca(NO_3)_2$ extraction were least dependent on the properties of the soil and this extractant should have more widespread application than the others. However, extraction and measurement of Cu in EDTA extracts can be simply and quickly performed and this extractant is distinctly preferred for use in routine testing, at least for comparison of soils within groups that have similar properties.

Use can also be made of deficiency symptoms to identify deficient and non-deficient areas. Although it permits action in subsequent seasons, in any one season by the time the crop is treated, loss of yield may have occurred. The wilting symptom characteristic of Cu-deficient plants is detected easily visually. If wilted plants are treated soon after the symptom appears, the deficiency has little effect on potential grain yield (R.D. Graham, personal communication). However, dependence on deficiency symptoms as the sole criterion for diagnosis of Cu deficiency is not recommended: detection of marginally deficient soils (where the chances of treatment leading to complete recovery are high) is unreliable as the symptoms may not occur every year and may be dependent on seasonal conditions. Physiological changes in Cu deficient plants may be useful in detecting Cu deficiency. For example, Rahimi (1972) showed changes in the morphology of vascular bundles and in cell wall thickness in Cu deficient plants.

Visual symptoms in the wheat identified Mn deficient soils but symptoms appeared only when the deficiency was severe, so that any attempt to correct Mn deficiency in the same season is likely to be partially successful only. Symptoms of Zn deficiency were of little use as a diagnostic aid.

B Extrapolation of the results

The soil mapping units were relatively homogenous bodies of soil defined on the basis of easily recognizable morphological properties. These properties may be poorly correlated with micronutrient availability and further assessment of the variation of properties affecting micronutrient availability within the soil mapping units is required.

Because few experiments were performed on each soil, the conclusions drawn about the occurrence of deficiencies on particular soils or groups of soils must be regarded as tentative, and further experiments will have to be performed before a complete assessment of deficiencies can be made. Possibly glasshouse experiments could be used. One approach would be to perform experiments on soils from sites used in this study, to test whether results similar to those obtained in the field could be obtained in the glasshouse. If there is a consistent relationship between the results of the field and glasshouse experiments then further information within the study areas could be obtained from glasshouse experiments. Otherwise, further field experiments have to be conducted.

Land units and soil associations similar to those surveyed occur widely on Eyre Peninsula and it is likely that deficiencies of Cu in particular, but also of Zn and Mn exist over much of the Peninsula. The areas studied at Stokes and Wharminda were representative of the land forms and soils in Units 3 (190 000 ha) and 13 (650 000 ha) mapped by French (1958). The soils described have been recognized in several other units of French (1958), occupying in all about half of the Peninsula. The units are:

Units 3 and 4 - Lateritic podzol, solodized solonetz, solod, skeletal and solonchak occurring in hilly, sloping and low-lying areas.

Unit 10 - Solodized solonetz, terra rossa, leached sands, solonized brown soils.

Unit 13 - Solodized solonetz and leached sandhills, red brown earths, solonized brown soils, terra rossa.

Unit 14 - Solodized solonetz and leached sandhills, solonized brown soil, terra rossa.

Unit 16 - Grey calcareous sand, terra rossa.

Unit 18 - Leached sands, solodized solonetz, skeletal shallow and stony red brown earth.

The topographic relationships of the soils within the land units provide a basis for extending the investigation and the application of its results to the units mapped on Eyre Peninsula by French, and possibly to other parts of South Australia where similar patterns of soil and climatic conditions exist. Many of the land units and soils recognized at Wharminda occur in the Murray mallee (Potter et al 1973). Land units and soils similar to those at Stokes occur on Kangaroo Island and the southern Mt. Lofty ranges.

The general approach used in this study for the identification of areas deficient in micronutrients through the use of soil survey, field experiments and chemical analysis of soils and plants should have widespread application.

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APPENDIX 1 - Description of soil profiles at the sites of the factorial experiments.

Terms used in the following description:

(1) Section and Hundred from county plans of South Australia.

(2) Land unit and component where the profile occurs.

(3) Principal profile form and soil mapping unit of the profile.

Profile drainage.

Excessively drained: Soil is loose, developed on extremely permeable material of very poor moisture retaining capacity.

Freely drained: No mottling due to gleying occurs less than 60 cm of the surface and any mottling just below this is sparse.

Imperfectly drained: Water penetration is slowed by impermeable layers. Mottling of the B horizon is marked.

Poorly drained: A dominantly grey layer or zone, sometimes with ochreous colours, is present at less than 60 cm depth.

Horizon names and boundary conditions, and structure of B horizons are defined according to Northcote (1971). Colours, names and designations are taken from the Munsell colour chart. The analytical techniques used are described in Materials and Methods, pp. 92-94.

Abbreviations used: I - illite, K - kaolinite, Q - quartz.

The profile numbers correspond to the numbers of the experiment sites referred to in the text.

Profile 1

(1) Sn 20 Butler (2) LU Ia (3) Uc2.21 (SMU 1)

Location: 801 150yN 423 100yE

Parent material: Aeolian siliceous sand

Profile drainage: Excessively drained.

Description

Horizon	Depth cm	
A1	-15	Greyish brown (10YR 5/3 moist 7/3 dry); unconsolidated sand. Abrupt to -
A2(1)	-25	Pale brown (10YR 6/3 moist 8/2 dry); unconsolidated sand, pockets of decaying organic matter.
A2(2)	-60	Light yellowish brown (10YR 6/4 moist 8/3 dry); unconsolidated sand. Diffuse to -
B	-90	Very pale brown (10YR 7/3 moist 8/4 dry); unconsolidated sand. Abrupt to -
C	-104	Light brown (7.5YR 6/4 moist, 10YR 8/6 dry); light sandy clay, massive.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.5	6.6	40	59	1	0	0.0	0.45	0.025	35	14
A2(1)	6.5	7.6	28	69	3	0	0.3	0.09	0.005	20	8
A2(2)	6.5	8.3	30	55	14	1	0.3	0.06	0.005	15	3
B	6.5	7.8	36	58	2	4	0.0	0.03	0.005	15	3
C	7.0	8.6	26	53	1	20	0.0	0.09	0.015	30	4

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.55	2.0	1.4	0.2	0.14	0.14	1	5	0.50
A2(1)	1.55	1.2	0.5	0.0	0.37	0.21	-	-	-
A2(2)	1.55	1.0	0.6	0.0	0.12	0.17	-	-	-
B	1.55	1.0	0.3	0.2	0.23	0.26	2	10	0.40
C	1.30	9.5	5.6	1.2	0.95	0.78	17	10	0.30

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	<5	5	10	-	3	0.1	3	0	360	63
A2(1)	-	-	-	-	-	-	5	0	120	61
A2(2)	-	-	-	-	-	-	4	0	120	27
B	<5	5	5	-	<3	0.1	2	0	38	25
C	<5	5	15	-	<3	1.4	2	0	45	4

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	1.2	2.4	8.9	380	4	15	42	710
A2(1)	0.6	2.6	3.9	350	-	-	-	-
A2(2)	0.6	1.6	3.7	240	-	-	-	-
B	0.5	1.5	3.0	200	-	-	-	-
C	0.7	3.0	1.3	190	-	-	-	-

Profile 2

(1) Sn 14 Verran (2) LU LU Ic (3) Uc2.21 (SMU 1)

Location: 812 600yN 420 300yE

Parent material: Aeolian siliceous sand

Profile drainage: Excessively drained

Description

Horizon	Depth cm	
A1	-11	Dark greyish brown (2.5Y 4/2 moist 6/2 dry); unconsolidated sand. Abrupt to -
A2	-54	Light grey (2/5Y 7/2 moist, 7.5YR 8/0 dry); unconsolidated sand. Gradual to -
B	-94	Pale yellow (2.5Y 7/4 moist 8/4 dry); unconsolidated sand. Bands of strong brown (7.5YR 5/8 moist 6/8 dry) sandy clay occur particularly in the lower part of this horizon.
C	-116	Reddish yellow (7.5YR 6/6 moist, 10YR 6/6 dry); light sandy clay loam, massive, underlain by carbonate rich layer.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.5	7.3	44	54	2	0	0.0	0.56	.033	60	18
A2	7.0	7.2	40	58	1	1	0.0	0.15	.012	15	5
B	7.0	7.7	34	63	3	0	0.0	0.03	.005	10	1
B^+	7.0	8.0	32	55	1	12	0.0	0.09	.015	25	1
C	9.0	9.0	20	55	1	24	3.8	0.15	.013	25	1

B^+ - Bands of strong brown sandy clay from B horizon

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	$\%<2\mu$	%Q	$^I/_K$
		m-equiv./100 g O.D. soil							
A1	1.55	1.8	3.9	1.5	0.10	0.10	-	-	-
A2	1.55	0.3	1.8	2.1	0.07	0.03	-	-	-
B	1.55	0.8	2.7	1.4	0.12	0.06	-	-	-
B^+	1.40	7.1	5.6	0.5	0.43	0.43	-	-	-
C	1.30	9.9	38.2	3.3	0.97	0.71	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	2.0	8	15	2	<1	0.2	7	6	640	57
A2	-	-	-	-	-	-	5	0	30	47
B	2.0	7	8	3	2	0.2	6	0	75	22
B^+	-	-	-	-	-	-	6	0	0	0
C	4.5	10	25	3	<1	1.0	4	0	0	23

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	2.9	4.8	23.0	350	7	55	98	780
A2	0.8	2.0	2.1	260	-	-	-	-
B	0.5	1.3	1.2	190	-	-	-	-
B^+	1.0	1.2	1.9	230	-	-	-	-
C	2.2	2.2	9.0	100				

$B+$ - Bands of strong brown sandy clay from B horizon

Profile 3

(1) Sn 45 Verran (2) LU Ia (3) Uc2.21 (SMU 1)

Location: 809 000yN 428 600yE

Parent material: Aeolian siliceous sand

Profile drainage: Excessively drained

Description

Horizon	Depth cm	
A1	-13	Greyish brown (10YR 5/2 moist 6/3 dry); unconsolidated sand. Abrupt to -
A2	-60	Light grey (10YR 7/2 moist 8/2 dry); unconsolidated sand. Diffuse to -
B	-120	Brownish yellow (10YR 6/6 moist 7/6 dry); unconsolidated sand with bands of strong brown sandy clay in the lower parts of this horizon.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.5	7.0	32	60	7	1	0.0	0.63	.030	55	12
A2	6.5	7.3	52	45	2	1	0.0	0.21	.015	15	4
B	6.5	7.6	42	55	1	2	0.0	0.03	.006	10	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	$g\ cm^3$	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.55	1.7	1.4	0.2	0.06	0.08	-	-	-
A2	1.55	0.7	0.7	1.0	0.03	0.04	-	-	-
B	1.55	0.4	0.7	1.0	0.09	0.04	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	1.5	5	10	4	2	0.2	1	0	750	46
A2	-	-	-	-	-	-	4	5	220	190
B	1.0	4	9	3	2	0.3	0	0	57	24

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	1.1	3.4	23.0	450	1	31	100	800
A2	1.2	3.1	4.2	410	-	-	-	-
B	0.9	1.4	0.9	170	-	-	-	-

Profile 4

(1) Sn 20 Butler (2) LU IIa (3) Uc1.11 (SMU 4)

Location: 799 250yN 419 600yE

Parent material: Aeolian calcareous sand

Profile drainage: Excessively drained

Description

Horizon	Depth cm	
A1	-9	Dark yellowish brown (10YR 4/4 moist 6/3 dry); unconsolidated calcareous sand. Abrupt to -
B1	-44	Very pale brown (10YR 7/4 moist 8/2 dry); unconsolidated calcareous sand. Gradual to -
B1(2)	-140	Light yellowish brown (10YR 6/4 moist 8/4 dry); unconsolidated calcareous sand.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A	9.0	8.7	38	58	3	1	9.7	0.78	.053	110	21
B1	9.0	8.7	42	55	0	3	23.0	0.48	.029	55	3
B1(2)	9.0	9.3	37	59	2	2	20.0	0.33	.010	80	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	$g\ cm^3$	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.50	5.3	37.0	1.7	0.24	0.26	-	-	-
B1	1.25	4.4	40.0	2.6	0.17	0.05	-	-	-
B1(2)	1.50	2.3	34.0	6.0	0.25	0.04	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	2.0	4	20	3	<1	0.3	3	0	0	44
B1	1.0	4	10	2	<1	0.2	4	0	0	21
B1(2)	1.5	3	15	3	<1	0.3	1	0	0	18

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	2.3	4.7	37.0	160	2	13	93	340
B1	1.4	3.2	2.9	87	-	-	-	-
B1(2)	1.4	2.6	5.3	49	-	-	-	-

Profile 5

(1) Sn 4 Verran (2) LU Ic (3) Dy5.83 (SMU 5)

Location: 801 550yN 422 800yE

Parent material: Aeolian siliceous sand

Profile drainage: Freely drained

Description

Horizon	Depth cm	
A1	-10	Dark greyish brown (10YR 4/2 moist 6/2 dry); unconsolidated sand. Diffuse to -
A1(2)	-19	Brown (10YR 5/3 moist 6/3 dry); unconsolidated sand. Abrupt to -
A2	-30	Pale brown (10YR 6/3 moist 8/2 dry); unconsolidated sand. Diffuse to -
A2(2)	-50	Light yellowish brown (10YR 6/4 moist 8/3 dry); unconsolidated sand. Abrupt to -
B1	-55	Light yellowish brown (10YR 6/4 moist 7/4 dry); sandy clay loam, massive. Diffuse to -
B2	-70	Reddish yellow (7.5YR 6/6 moist 7/5 dry); sandy clay loam, massive, some soft carbonate.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	-	7.6	58	38	1	3	0.0	0.45	.055	80	19
A1(2)	-	7.2	46	49	3	2	0.0	0.33	.020	40	11
A2	-	7.0	30	67	2	1	0.0	0.12	.010	20	5
A2(2)	-	8.0	32	65	2	1	0.0	0.03	.005	20	4
B1	-	8.6	21	54	2	23	0.0	0.14	.020	35	5
B2	-	9.3	22	47	7	24	5.5	0.20	.020	40	4

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
		CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
	g cm^3	m-equiv./100 g O.D. soil							
A1	1.55	1.7	1.0	0.2	0.19	0.17	2	5	0.50
A1(2)	1.55	1.9	1.3	0.1	0.09	0.12	-	-	-
A2	1.55	1.3	0.7	0.4	0.06	0.10	-	-	-
A2(2)	1.55	0.9	0.7	0.0	0.05	0.07	-	-	-
B1	1.35	14.0	5.3	2.2	1.10	0.94	12	5	0.70
B2	1.25	14.0	40.0	4.6	2.20	1.70	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	<5	5	15	-	<3	0.3	13	0	280	28
A1(2)	-	-	-	-	-	-	1	0	490	44
A2	-	-	-	-	-	-	5	0	65	79
A2(2)	-	-	-	-	-	-	6	0	0	18
B1	<5	5	15	-	<3	1.2	6	0	0	24
B2	-	-	-	-	-	-	11	0	0	8

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	6.5	5.5	24.0	420	22	31	85	670
A1(2)	1.8	3.3	16.0	310	-	-	-	-
A2	1.9	2.3	6.6	290	-	-	-	-
A2(2)	1.7	2.1	4.1	290	-	-	-	-
B1	1.3	3.3	2.0	370	-	-	-	-
B2	2.2	3.0	4.8	130	-	-	-	-

Profile 6

(1) Sn 14 Verran (2) LU Ic (3) Dy5.83 (SMU 5)

Location: 812 250yN 420 950yE

Parent material: Aeolian siliceous sand

Profile drainage: Freely drained

Description

Horizon	Depth cm	
A1	-19	Greyish brown (10YR 5/2 moist 7/2 dry); unconsolidated sand, channels of dark organic matter. Abrupt to -
A2	-46	Pale brown (10YR 6/3 moist 8/2 dry); unconsolidated sand, channels of dark organic matter in upper parts. Diffuse to -
A2(2)	-64	Discontinuous, pale yellow (2.5Y 8/4 moist); sand. Abrupt to -
B1	-87	Mottled reddish yellow (5YR 6/8, 10YR 7/8 moist); sandy clay, massive. Changes within 5 cm to -
B2	-99	Yellowish brown (10YR 5/8 moist); medium clay with some soft carbonate, apedal.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.0	7.4	30	68	1	1	0.0	0.45	.040	70	26
A2	6.8	7.2	25	72	3	0	0.0	0.03	.012	15	6
A2(2)	7.0	7.5	28	71	0	1	0.0	0.09	.007	10	2
B1	7.7	8.1	22	53	4	21	0.8	0.06	.020	25	2
B2	8.5	9.4	27	52	2	19	2.0	0.12	.013	30	2

Horizon	Bulk dens. $g\ cm^3$	Exchangeable cations					Mineralogical analysis		
		CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.55	1.5	3.3	0.3	0.11	0.09	-	-	-
A2	1.55	1.1	0.7	1.1	0.07	0.03	-	-	-
A2(2)	1.55	0.6	0.6	2.2	0.09	0.03	-	-	-
B1	1.35	-	3.2	5.5	1.90	0.88	-	-	-
B2	1.25	13.0	27.0	7.1	2.40	1.00	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	9.0	7	15	4	2	0.2	7	2	140	39
A2	-	-	-	-	-	-	7	8	160	70
A2(2)	-	-	-	-	-	-	0	20	120	44
B1	2.5	15	25	2	2	1.4	7	0	0	33
B2	3.0	16	35	8	2	1.5	3	0	0	8

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.8	7.2	23.0	310	9	64	100	670
A2	0.6	1.5	1.5	250	-	-	-	-
A2(2)	0.7	7.0	1.4	210	-	-	-	-
B1	0.9	2.3	1.5	360	-	-	-	-
B2	2.0	2.2	3.7	110	-	-	-	-

Profile 7

(1) Sn 4 Verran (2) LU Ic (3) Dy5.83 (SMU 6)

Location: 801 500yN 422 900yE

Parent material: Aeolian siliceous sand

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-17	Pale brown (10YR 6/3 moist 7/3 dry); unconsolidated sand. Abrupt to -
A2	-44	Very pale brown (10YR 8/3 moist 8/2 dry); unconsolidated sand. Abrupt to -
B1	-65	Mottled, brownish yellow (10YR 6/6, 6/8 moist); sandy clay loam, apedal. Diffuse to -
B2	-80	Mottled reddish yellow (7.5YR 6/8, 2.5Y 7/4 moist); sandy clay loam, apedal with soft carbonate.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.0	7.0	46	52	0	2	0.0	0.54	0.45	70	15
A2	6.5	7.5	33	65	1	1	0.0	0.15	.010	15	5
B1	9.0	9.0	18	54	2	26	0.9	0.15	.020	30	3
B2	10.0	9.5	30	44	6	20	20.0	0.41	.018	30	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	$^I/_K$
		m-equiv./100 g O.D. soil							
A1	1.60	2.5	0.6	2.3	0.22	0.14	-	-	-
A2	1.55	0.6	0.7	0.2	0.14	0.04	-	-	-
B1	1.35	13.0	6.8	3.5	1.20	0.84	-	-	-
B2	1.30	14.0	44.1	8.3	2.30	1.10	-	-	-

Horizon	**Total micronutrients**						**$Ca(NO_3)_2$-extractable**			
	Cu	**Zn**	**Mn**	**B**	**Mo**	**Fe**	**Cu**	**Zn**	**Mn**	**Fe**
	ppm					**%**	**ppm x 10^3**			
A1	2.5	4	10	2	<1	0.2	5	0	300	34
A2	-	-	-	-	-	-	5	0	0	0
B1	-	-	-	-	-	-	6	0	0	0
B2	2.5	13	55	5	3	1.5	4	0	0	7

Horizon	**EDTA-extractable**				**DTPA-extractable**			
	Cu	**Zn**	**Mn**	**Fe**	**Cu**	**Zn**	**Mn**	**Fe**
	ppm x 10				**ppm x 10^2**			
A1	4.3	4.5	15.0	280	12	31	60	680
A2	0.7	1.0	1.2	220	-	-	-	-
B1	1.0	1.6	1.5	380	-	-	-	-
B2	2.7	2.4	4.1	120	-	-	-	-

Profile 8

(1) Sn 20 Butler (2) LU Ib (3) Dy5.43 (SMU 7)

Location: 801 300yN 423 200yE

Parent material: Aeolian siliceous sand

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-13	Dark greyish brown (10YR 4/2 moist 6/3 dry); unconsolidated sand. Abrupt to -
A2	-27	Light brownish grey (2.5Y 6/2 moist, 10YR 8/2 dry); unconsolidated sand. Abrupt to -
B1	-38	Light yellowish brown (10YR 6/4 moist 7/4 dry), mottled; sandy clay, columnar and blocky, A2 between columns, clay skins on ped faces.
B2	-46	Light yellowish brown (10YR 6/4 moist 7/4 dry); sandy clay, apedal, patches of soft carbonate. Underlain by calcrete.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	-	7.4	38	56	3	3	0.0	0.78	.055	70	15
A2	-	8.5	40	55	0	5	0.0	0.09	.015	20	6
B1	-	8.1	27	45	0	28	0.9	0.30	.025	35	4
B2	-	9.6	27	41	1	31	1.5	0.21	.020	45	3

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.55	4.0	3.1	0.2	0.18	0.23	2	5	0.50
A2	1.55	1.4	0.7	0.2	0.26	0.17	-	-	-
B1	1.30	12.0	4.5	3.5	2.40	0.96	12	5	0.70
B2	1.30	17.0	19.0	5.4	4.50	2.00	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	<5	5	15	-	<3	0.3	4	0	640	41
A2	-	-	-	-	-	-	6	0	40	47
B1	<5	5	15	-	<3	1.1	6	0	0	32
B2	-	-	-	-	-	-	11	0	0	12

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	2.8	5.5	38.0	540	6	31	180	760
A2	1.5	2.5	6.9	280	-	-	-	-
B1	1.3	2.6	2.0	420	-	-	-	-
B2	2.0	3.3	13.0	260	-	-	-	-

Profile 9

(1) Sn 4 Verran (2) LU Ic (3) Dy5.43 (SMU 7)

Location: 804 200yN 421 500yE

Parent material: Aeolian siliceous sand

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-12	Greyish brown (10YR 5/2 moist 6/3 dry); unconsolidated sand. Abrupt to -
A2	-28	Light grey (10YR 7/2 moist 8/2 dry); unconsolidated sand. Abrupt to -
B1	-50	Mottled brownish yellow (10YR 6/6 and 5/3 moist); sandy clay loam, columnar to 33 cm then blocky. Gradual to -
B2	-68	Mottled yellow (10YR 7/8, 5YR 6/8 moist); light sandy clay loam, apedal, containing soft carbonate.

Chemical and Physical Analysis

Hor-izon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.5	6.8	41	56	2	1	0.0	0.72	.051	60	11
A2	8.0	8.2	41	56	2	1	0.0	0.15	.013	15	5
B1	8.5	9.0	32	46	1	21	1.2	0.21	.020	25	2
B2	9.5	9.5	24	51	10	15	31.3	0.33	.017	30	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2	%Q	$^I/K$
		m-equiv./100 g O.D. soil							
A1	1.55	0.8	2.3	0.7	0.24	0.11	-	-	-
A2	1.55	1.0	1.1	1.2	0.23	0.06	-	-	-
B1	1.30	12.0	3.9	-	1.90	1.10	-	-	-
B2	1.30	16.0	44.0	6.6	3.30	1.50	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	2.0	5	15	5	<1	0.3	4	0	660	63
A2	-	-	-	-	-	-	2	0	0	79
B1	3.0	14	35	5	<1	1.5	4	0	0	10
B2	-	-	-	-	-	-	2	0	0	15

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	1.8	5.9	28.0	460	5	29	130	760
A2	1.0	1.3	1.9	300	-	-	-	-
B1	1.5	2.7	2.5	450	-	-	-	-
B2	2.9	2.0	8.4	120	-	-	-	-

Profile 10

(1) Sn 4 Verran (2) LU Id (3) Dy5.43 (SMU 8)

Location: 801 450yN 420 700yE

Parent material: Calcrete, aeolian siliceous sand

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-8	Dark greyish brown (10YR 4/2 moist 6/3 dry); unconsolidated sand. Abrupt to-
A2	-15	Very pale brown (10YR 7/3 moist 8/2 dry); unconsolidated sand. Abrupt to -
B1	-37	Reddish yellow (7.5YR 6/8, 2.5Y 6/4 moist); sandy clay, domed surface breaking to blocky structure. Diffuse to -
B2	-51	Reddish yellow (7.5YR 6/8, 2.5Y 6/4 moist); sandy clay with much soft carbonate.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.5	6.9	42	57	0	1	0.0	1.02	.066	105	16
A2	7.5	7.6	31	66	3	0	0.0	0.18	.016	20	4
B1	9.0	9.3	25	40	3	32	3.0	0.18	.032	40	2
B2	10.0	9.6	29	30	9	32	41.7	0.09	.025	50	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.50	3.8	3.9	0.5	0.19	0.27	-	-	-
A2	1.60	1.8	0.6	1.4	0.20	0.09	-	-	-
B1	1.30	21.0	15.0	8.3	4.00	2.00	-	-	-
B2	1.20	23.0	43.0	11.0	8.30	2.70	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	2.5	7	15	3	<1	0.3	5	0	67	46
A2	-	-	-	-	-	-	2	0	120	41
B1	3.5	17	50	8	<1	1.9	7	0	0	15
B2	6.0	27	110	8	2	2.4	14	0	0	12

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.0	5.0	33.0	540	9	32	130	1400
A2	0.8	2.0	5.1	270	-	-	-	-
B1	2.0	4.9	10.0	470	-	-	-	-
B2	4.6	2.5	22.0	150	-	-	-	-

Profile 11

(1) Sn 20 Butler (2) LU IVc (3) Dy5.83 (SMU 9)

Location: 801 300yN 424 050yE

Parent material: Calcrete, aeolian siliceous sand

Profile drainage: Freely drained

Description

Horizon	Depth cm	
A1	-8	Very drak brown (10YR 2/2 moist 6/3 dry); unconsolidated loamy sand. Abrupt to-
A2	-9	Brown (10YR 5/3 moist, 7.5YR 8/4 dry); unconsolidated sand. Abrupt to -
B1	-14	Yellowish-red (5YR 4/6 moist 5/6 dry); mottled sandy clay, massive. Diffuse to -
B2	-22	Yellowish-red (5YR 4/6 moist 7/6 dry); mottled sandy clay, massive underlain by calcrete.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	-	7.2	30	65	1	4	0.2	0.96	.085	90	17
B1	-	8.7	29	53	2	16	0.5	0.57	.040	40	8
B2	-	8.8	28	45	7	22	7.0	0.51	.045	40	5

Horizon	Bulk dens. g cm^3	Exchangeable cations CEC	Ca	Mg	Na	K	Mineralogical analysis %<2µ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.55	6.5	5.3	0.3	0.15	0.55	4	3	0.70
B1	1.30	12.0	17.0	2.0	0.47	0.59	14	3	0.20
B2	1.30	16.0	42.0	2.7	0.78	0.64	-	-	-

Horizon	Total micronutrients Cu	Zn	Mn	B	Mo	Fe	$Ca(NO_3)_2$-extractable Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	<5	5	15	-	<3	0.4	6	0	520	28
B1	<5	5	20	-	<3	1.4	8	0	30	43
B2	-	-	-	-	-	-	13	0	0	37

Horizon	EDTA-extractable Cu	Zn	Mn	Fe	DTPA-extractable Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.3	6.6	49.0	490	7	25	230	880
B1	2.6	2.7	22.0	490	-	-	-	-
B2	3.9	3.2	31.0	240	-	-	-	-

Profile 12

(1) Sn 9 Verran (2) LU IVb (3) Dy5.83 (SMU 9)

Location: 806 600yN 425 450yE

Parent material: Calcrete, aeolian siliceous sand

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-11	Dark brown (10YR 4/3 moist 6/3 dry); unconsolidated loamy sand. Abrupt to -
A2	-15	Brown (10YR 5/3 moist, 7.5YR 8/4 dry); unconsolidated sand. Abrupt to -
B1	-30	Mottled, strong brown (7.5YR 5/6 moist); sandy clay, slightly domed at interface with A2 horizon. Diffuse to -
B2	-49	Reddish yellow (7.5YR 6/6 moist 8/4 dry); sandy clay loam, apedal contains nodular calcrete.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.0	7.8	31	67	0	2	0.0	0.84	.070	135	46
A2	7.0	7.9	38	59	0	3	0.0	0.15	.022	35	16
B1	9.0	8.6	26	45	0	29	1.0	0.36	.038	70	15
B2	9.0	9.5	40	33	8	19	39.0	0.21	.032	60	2

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	$^I/_K$
		m-equiv./100 g O.D. soil							
A1	1.55	4.5	3.6	1.8	0.41	0.79	-	-	-
A2	1.60	2.7	1.9	0.9	0.38	0.22	-	-	-
B1	1.30	19.0	4.8	11.0	4.20	1.60	-	-	-
B2	1.25	21.0	44.0	12.0	8.00	2.00	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	3.0	7	25	3	<1	0.5	4	0	190	22
A2	-	-	-	-	-	-	2	0	95	40
B1	-	-	-	-	-	-	11	0	0	13
B2	9.0	31	115	10	4	1.8	38	0	0	19

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.5	6.5	46.0	440	9	41	160	810
A2	1.5	2.4	16.0	250	-	-	-	-
B1	3.3	2.7	18.0	550	-	-	-	-
B2	15.0	3.2	22.0	130	-	-	-	-

Profile 13

(1) Sn 20 Butler (2) LU IIIa (3) Dy5.83 (SMU 10)

Location: 799 100yN 421 700yE

Parent material: Calcrete

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-5	Dark brown (7.5YR 3/4 moist 6/3 dry); unconsolidated loamy sand. Much free calcrete mixed by cultivation into the horizon. Abrupt to -
A2	-6	Discontinuous light brown (7.5YR 6/4 moist, 10YR 8/3 dry), unconsolidated sand. Abrupt to -
B1	-10	Yellowish red (5YR 5/6, 7.5YR 5/6 moist), mottled; fine sandy clay loam, apedal. Abrupt to -
C	-12	Sheet calcrete

Chemical and Physical Analysis

Hor-izon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	7.0	7.4	41	55	1	3	0.0	0.78	.071	120	28
B1	7.0	8.0	31	48	1	20	0.0	0.54	.045	45	5

Horizon	Bulk dens. g cm^3	Exchangeable cations CEC	Ca	Mg	Na	K	Mineralogical analysis %<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.40	5.1	2.8	2.0	0.26	0.62	-	-	-
B1	1.30	13.0	9.0	3.4	0.66	0.95	-	-	-

Horizon	Total micronutrients Cu	Zn	Mn	B	Mo	Fe	$Ca(NO_3)_2$-extractable Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	2.5	9	25	8	<1	0.6	4	0	0	17
B1	3.0	13	35	5	3	1.3	8	0	0	21

Horizon	EDTA-extractable Cu	Zn	Mn	Fe	DTPA-extractable Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.0	5.9	52.0	420	10	25	200	880
B1	2.8	2.5	50.0	500	-	-	-	-

Profile 14

(1) Sn 9 Verran (2) LU IVa (3) Gn1.83 (SMU 11)

Location: 808 300yN 425 000yE

Parent material: Calcrete

Profile drainage: Excessively drained

Description

Horizon	Depth cm	
A1	-11	Dark brown (10YR 4/3 moist 6/3 dry); unconsolidated loamy sand. Abrupt to -
B	-32	Reddish yellow (7.5YR 6/6 moist 7/4 dry); sandy loam, apedal, much soft carbonate. Abrupt to -
C	-50	Light yellowish brown (10YR 6/4 moist, 2.5YR 8/4 dry); apedal, much soft and nodular carbonate underlain by sheet calcrete.

Chemical and Physical Analysis

Hor-izon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	9.0	8.4	34	59	3	4	0.75	0.93	.090	135	22
B	9.0	8.6	28	61	5	6	17.0	0.51	.047	50	4
C	10.0	9.5	29	46	2	23	40.0	0.33	.028	50	3

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.40	6.4	17.0	2.5	0.21	1.10	-	-	-
B	1.20	15.0	52.0	2.6	0.42	0.81	-	-	-
C	1.30	12.0	44.0	9.2	2.30	0.87	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	3.0	9	30	2	2	0.7	6	0	0	130
B	4.5	13	50	5	4	1.1	12	0	0	49
C	7.5	14	70	5	2	1.1	13	0	0	31

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	5.0	15	66.0	330	16	190	140	370
B	8.9	2.3	31.0	120	-	-	-	-
C	7.6	2.0	15.0	73	-	-	-	-

Profile 15

(1) Sn bk.12C Stokes (2) LU not identified (3) Dy3.82 (SMU 17)

Location: 777 900yN 388 250yE

Parent material: Ferruginous sandstone

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-8	Reddish brown (2.5YR 4/4 moist, 5YR 5/4 dry); sandy loam, crumb, 32% concreted laterite. Abrupt to -
A2	-13	Brown (7.5YR 5/4 moist 7/4 dry); sandy loam, hard and brittle dry, 40% concreted laterite. Abrupt to -
B1	-25	Strong brown (7.5YR 5/6 moist 7/6 dry); mottled, medium clay, blocky on surface of B1 then massive. Diffuse to -
B2	-41	Brown yellow (10YR 6/8 moist 7/6 dry); mottled, light medium clay overlying ferruginous sandstone.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.0	6.2	41	38	10	11	0.0	0.63	.040	130	2
A2	6.5	5.7	41	40	6	13	0.0	0.62	.040	128	2
B1	6.0	6.0	14	24	7	55	0.0	0.80	.045	140	1
B2	6.0	6.0	32	23	2	43	0.1	0.24	.040	130	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	$^I/_K$
		m-equiv./100 g O.D. soil							
A1	1.20	6.7	2.0	0.2	0.17	0.45	7	3	0.50
A2	1.20	7.5	1.7	1.5	0.15	0.44	-	-	-
B1	1.40	19.0	4.7	2.1	0.66	0.72	60	1	0.03
B2	1.20	13.0	4.5	1.3	0.51	0.63	66	0	0.03

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	4.0	10	35	-	5	18.0	1	1	1700	26
A2	-	-	-	-	-	-	2	0	790	130
B1	3.0	15	25	-	1	6.0	0	0	75	20
B2	3.5	15	20	-	1	6.2	0	0	20	22

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	1.4	2.6	43.0	410	5	20	440	1600
A2	1.0	2.2	13.0	440	-	-	-	-
B1	0.9	2.5	2.9	270	-	-	-	-
B2	0.3	2.4	2.0	160	-	-	-	-

Profile 16

(1) Sn 4c Stokes (2) LU not identified (3) Dy3.82 (SMU 17)

Location: 770 900yN 398 450yE

Parent material: Ferruginous sandstone

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-12	Very dark greyish brown (10YR 3/2 moist 5/3 dry); loamy sand with much concreted laterite (40%), apedal. Abrupt to -
A2	-30	Very pale brown (10YR 7/4 moist 7/1 dry); loamy sand with concreted and pisolitic laterite (60%), apedal. Abrupt to -
B	-47	Mottled strong brown (7/5YR 5/8, 10YR 6/8 moist); medium clay, apedal underlain by weathering ferruginous sandstone.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.0	6.3	42	52	3	3	0.0	1.38	.085	190	21
A2	5.5	6.5	49	42	6	3	0.0	0.24	.018	50	1
B	7.0	7.5	32	22	9	37	0.0	0.09	.021	55	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	$g\ cm^3$	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.20	7.00	1.9	4.8	0.25	0.38	-	-	-
A2	1.40	2.60	1.1	1.2	0.29	0.13	-	-	-
B	1.30	22.00	5.0	10.0	3.30	0.88	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	4.0	8	90	8	2	4.3	2	0	3000	37
A2	5.0	7	65	6	3	6.3	4	15	350	46
B	6.5	18	50	5	4	5.3	0	0	28	5

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	3.3	8.9	160.0	790	7	48	570	2000
A2	1.3	4.1	9.7	370	-	-	-	-
B	1.7	1.9	40.0	420	-	-	-	-

Profile 17

(1) Sn Bk 81 Koppio (2) LU VIIIb (3) Dy3.82 (SMU 19)

Location: 760 700yN 389 850yE

Parent material: Ferruginous sandstone

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-12	Dark brown (7.5YR 3/3 moist 5/4 dry); sandy loam with 3% pisolitic lateritic gravel, massive. Abrupt to -
A2	-32	Strong brown (7.5YR 5/6 moist 6/6 dry); sandy clay loam with 34% pisolitic laterite, massive. Abrupt to -
B1	-38	Mottled yellowish brown (7.5YR 5/6 moist 6/6 dry); medium clay, structureless when wet, weak crumbs when dry. Diffuse to -
B2	-58	As for B1 with weathering sandstone.

Chemical and Physical Analysis

Hor-izon	pH		Particle size				$CaCO_3$	Org	Total	Total	Avail.
								C	N	P	P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	5.5	6.4	35	49	7	9	0.0	1.53	.200	270	34
A2	6.0	6.5	26	45	6	23	0.0	0.45	.060	100	4
B1	7.0	6.9	33	16	12	39	0.0	0.27	.040	100	1
B2	7.0	6.9	24	27	8	41	0.0	0.09	.025	80	1

Horizon	Bulk dens. g cm^3	Exchangeable cations					Mineralogical analysis		
		CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.35	13.0	5.7	0.7	0.31	1.50	12	3	0.20
A2	1.65	11.0	5.1	1.3	0.23	0.70	22	5	0.10
B1	1.25	16.0	7.0	1.4	0.54	0.79	50	3	0.08
B2	1.25	19.0	8.1	2.2	0.80	0.80	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	5.0	15	130	-	1	6.0	18	18	14000	140
A2	4.5	15	65	-	1	10.0	1	0	3600	19
B1	4.0	15	35	-	2	7.2	2	0	160	12
B2	-	-	-	-	-	-	0	0	260	28

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	13.3	15.0	640.0	3000	34	96	2400	6900
A2	4.2	3.8	200.0	520	-	-	-	-
B1	2.5	2.8	20.0	320	-	-	-	-
B2	1.6	2.1	27.0	210	-	-	-	-

Profile 18

(1) Sn 168 Koppio (2) LU VIIIb (3) Dy3.82 (SMU 19)

Location: 761 200yN 391 400yE

Parent material: Ferruginous sandstone

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-12	Dark reddish brown (5YR 3/2 moist, 10YR 5/3 dry); sandy loam with pisolitic laterite gravel (5%), apedal. Abrupt to -
A2	-42	Brown (7.5YR 5/4 moist 7/4 dry); sandy loam with much pisolitic laterite (40%). Abrupt to -
B1	-50	Mottled brownish yellow (10YR 6/8, 2.5YR 4/6 moist); medium clay with some pisolitic laterite, apedal. Diffuse to -
B2	-58	Whole colored brownish yellow (10YR 6/8 moist); apedal medium clay underlain by ferruginous sandstone.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	5.5	6.0	21	58	10	11	0.0	1.65	.161	175	29
A2	5.7	6.6	58	32	1	9	0.0	0.18	.025	40	2
B1	6.0	6.3	11	22	5	62	0.0	0.33	.043	65	1
B2	7.0	6.9	19	26	4	51	0.0	0.09	.018	50	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.35	13.0	4.6	1.1	0.28	0.82	-	-	-
A2	1.65	6.7	1.8	1.0	0.43	0.29	-	-	-
B1	1.25	21.0	5.5	6.3	1.10	0.84	-	-	-
B2	1.25	23.0	4.9	6.8	1.40	0.73	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	6.0	14	140	6	2	5.8	9	100	13000	220
A2	-	-	-	-	-	-	0	0	820	19
B1	6.5	94	40	3	5	6.3	1	0	47	11
B2	4.0	28	70	1	7	6.8	0	0	0	26

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	13.4	17.0	430.0	2700	34	97	1400	6700
A2	1.5	3.2	32.0	450	-	-	-	-
B1	1.5	3.2	7.0	390	-	-	-	-
B2	1.2	4.5	4.1	210	-	-	-	-

Profile 19

(1) Sn 57 Stokes (2) LU VIa (3) Dr2.62 (SMU 18)

Location: 768 200yN 394 100yE

Parent material: Ferruginous sandstone

Profile drainage: Freely drained

Description

Horizon	Depth cm	
A1	-8	Dark reddish brown (5YR 3/2 moist, 7.5YR 5/4 dry); sandy loam, some pisolitic laterite, apedal. Abrupt to -
A2	-20	Reddish brown (5YR 4/4 moist, 7.5YR 6/4 dry); sandy loam with pisolitic laterite (20%), apedal. Abrupt to -
B1	-32	Yellowish red (5YR 4/8 moist); medium clay, blocky to 25 cm grading to apedal below. Diffuse to -
B1(2)	-62	Yellowish red (5YR 5/6 moist, 10YR 6/8 moist), mottled; clay loam apedal. Diffuse to -
B2	-83	Yellow (10YR 7/9, 2.5YR 4/8 moist), mottled; clay loam, apedal underlain by ferruginous sandstone.

Chemical and Physical Analysis

Hor-izon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.0	6.1	31	53	9	7	0.0	2.34	.207	200	22
A2	6.0	6.0	43	40	10	7	0.0	0.63	.062	60	3
B1	7.0	7.1	14	17	12	57	1.7	0.57	.054	60	2
B1(2)	7.0	6.8	19	21	12	48	0.0	0.39	.026	50	1
B2	7.0	6.7	14	22	16	48	0.0	0.06	.014	40	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	g cm^3	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.25	15.0	6.5	1.7	0.41	1.20	-	-	-
A2	1.40	11.0	2.2	2.9	0.39	0.51	-	-	-
B1	1.30	16.0	2.6	4.6	0.76	0.73	-	-	-
B1(2)	1.25	7.8	2.7	2.9	0.83	0.63	-	-	-
B2	1.25	11.0	2.2	2.4	0.72	0.46	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	12.0	24	75	2	2	4.9	8	4	4000	120
A2	-	-	-	-	-	-	3	1	130	190
B1	3.5	27	55	3	5	5.2	0	0	85	19
B1(2)	-	-	-	-	-	-	0	0	38	13
B2	4.0	28	100	<1	5	4.7	0	0	0	12

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	11.8	7.2	120.0	1800	33	52	560	4500
A2	1.7	3.3	5.6	460	-	-	-	-
B1	1.6	2.9	4.9	260	-	-	-	-
B1(2)	0.9	2.1	2.5	180	-	-	-	-
B2	0.8	1.7	0.9	170	-	-	-	-

Profile 20

(1) Sn 57 Stokes (2) LU VIc (3) Db2.22 (SMU 21)

Location: 769 100yN 393 500yE

Parent material: Pink granitic gneiss

Profile drainage: Freely drained

Description

Horizon	Depth cm	
A1	-8	Very dark grey brown (10YR 3/2 moist 5/3 dry): sandy loam hard and unstructured when dry. Diffuse to -
A1(2)	-15	Dark brown (7.5YR 3/2 moist, 10YR 5/3 dry); sandy loam, hard, unstructured when dry. Diffuse to -
	-28	Reddish brown (5YR 4/4 moist 6/4 dry); gravel, sand and stone (granite) single grained. Abrupt to -
B1	-43	Dark yellowish brown (10YR 3/4, 2.5Y 5/4, 4/2 moist), mottled; medium clay, blocky, smooth clay skins on peds. Diffuse to -
B2	-61	As for B1 - contains carbonate, mica, weathering granite gneiss fragments.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	5.5	6.2	38	48	8	6	0.0	1.23	.105	200	13
A2	5.7	6.1	33	51	5	11	0.0	0.57	.055	110	7
X	6.0	6.3	56	33	5	6	0.0	0.21	.025	75	4
B1	6.5	7.0	23	28	8	49	0.0	0.30	.040	100	2
B2	7.5	8.3	21	13	11	55	4.5	0.21	.045	90	2

X - layer of stones and gravel at base of A_2 horizon

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
		CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
	g cm^3	m-equiv./100 g O.D. soil							
A1	1.35	7.0	4.1	0.2	0.14	0.45	7	5	3.00
A2	1.45	5.5	3.2	0.3	0.12	0.30	-	-	-
X	1.50	3.7	1.9	0.3	0.11	0.21	-	-	-
B1	1.25	34.0	14.0	4.7	1.00	1.10	62	5	1.00
B2	1.35	24.0	39.0	4.3	1.30	1.00	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	4.0	15	85	-	<1	1.1	6	34	16000	180
A2	-	-	-	-	-	-	6	18	11000	120
X	-	-	-	-	-	-	0	6	2800	89
B1	4.0	45	100	-	1	5.5	0	0	85	1
B2	-	-	-	-	-	-	2	0	0	1

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	4.8	5.9	370.0	1900	11	45	1700	4800
A2	3.9	3.3	230.0	1200	-	-	-	-
X	2.4	2.8	50.0	510	-	-	-	-
B1	1.8	2.1	12.0	550	-	-	-	-
B2	2.0	3.0	35.0	190	-	-	-	-

X - layer of stones and gravel at base of A_2 horizon

Profile 21

(1) Sn 15 Stokes (2) LU VIc (3) Db2.62 (SMU 21)

Location: 765 050yN 390 500yE

Parent material: Pink granitic gneiss

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-6	Dark reddish brown (5YR 3/3 moist, 7.5YR 5/4 dry); loamy sand, apedal. Diffuse to -
A1(2)	-32	As for A1.
A2	-56	Dark reddish brown (5YR 3/3 moist, 7.5YR 5/4 dry); loamy sand with gravel and granitic gneiss fragments. Abrupt to -
B1	-93	Mottled dark brown (10YR 3/3, 7.5YR 3/6 moist); heavy clay, apedal. Diffuse to -
B2	-110	Dark reddish brown (5YR 3/3 moist); medium clay with occasional carbonate, apedal underlain by weathering granitic gneiss.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.0	5.4	40	50	5	5	0.0	1.08	.125	520	36
A1(2)	5.8	5.9	45	44	6	5	0.0	0.36	.048	505	7
B1	7.3	7.0	18	25	5	52	2.5	0.33	.057	295	1
B2	9.0	9.2	27	32	7	34	8.4	0.18	.034	430	2

Horizon	Bulk dens. g cm^3	Exchangeable cations					Mineralogical analysis		
		CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.35	6.50	2.6	0.6	0.38	0.34	-	-	-
A2	1.45	-	-	-	-	-	-	-	-
B1	1.25	29.0	4.3	9.7	5.00	0.87	-	-	-
B2	1.35	25.0	37.0	12.0	5.50	0.60	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	6.5	52	330	<1	<1	3.3	4	94	2300	300
A2	-	-	-	-	-	-	2	26	2100	82
B1	10.5	63	300	1	4	6.8	1	7	65	21
B2	8.0	49	300	2	4	5.2	0	0	0	6

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	5.9	6.0	41.0	1710	15	31	2100	5400
A2	5.5	2.2	57.0	1380	-	-	-	-
B1	3.8	3.6	9.1	960	-	-	-	-
B2	3.5	3.3	27.0	220	-	-	-	-

Profile 22

(1) Sn 56 Stokes (2) LU VIIb (3) Dy3.81 (SMU 20)

Location: 770 200yN 394 600yE

Parent material: White granitic gneiss

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-9	Very dark greyish brown (10YR 3/2 moist, 7.5YR 7/2 dry); sandy loam with coarse quartz gravel and rock, massive. Abrupt to -
A2	-18	Light brownish grey (2.5Y 6/2 moist, 10YR 8/1 dry); sandy loam with coarse gravel. Abrupt to -
B1	-38	Mottled (10YR 6/8, 6/3, 10YR 4/8 moist); heavy clay, massive. Abrupt to -
B2	-46	Light brown (7.5YR 6/5 moist, 10YR 8/3 dry); heavy clay, massive, contains weathering rock.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total	Avail.
										P	P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	5.7	6.4	42	48	3	7	0.0	1.23	.110	195	36
A2	6.0	6.4	45	39	8	8	0.0	0.33	.020	100	10
B1	5.5	6.0	16	24	8	52	0.0	0.63	.050	70	3
B2	5.5	6.2	22	20	9	49	0.5	0.39	.030	55	2

Horizon	Bulk dens. g cm^3	Exchangeable cations CEC	 Ca	m-equiv./100 g O.D. soil Mg	 Na	 K	Mineralogical analysis %<2μ	 %Q	 $^I/_K$
A1	1.25	5.3	2.2	1.1	0.09	0.27	4	5	0.20
A2	1.50	1.7	0.8	0.5	0.08	0.11	-	-	-
B1	1.30	20.0	5.5	2.2	1.80	0.53	57	0	0.02
B2	1.25	21.0	5.9	5.1	3.20	0.60	52	2	0.02

Horizon	Total micronutrients Cu	 Zn	ppm Mn	 B	 Mo	% Fe	Ca(NO$_3$)$_2$-extractable Cu	ppm x 10^3 Zn	 Mn	 Fe
A1	4.5	15	15	-	1	0.3	12	74	3600	1500
A2	-	-	-	-	-	-	10	38	1500	6700
B1	4.5	15	20	-	3	1.7	6	36	580	1900
B2	4.5	15	20	-	<1	1.5	2	360	440	30

Horizon	EDTA-extractable Cu	ppm x 10 Zn	 Mn	 Fe	DTPA-extractable Cu	ppm x 10^2 Zn	 Mn	 Fe
A1	8.4	7.7	57.0	2500	24	42	340	7500
A2	1.9	2.5	7.4	1100	-	-	-	-
B1	1.7	2.3	6.6	1600	-	-	-	-
B2	2.2	30.0	9.4	470	-	-	-	-

Profile 23

(1) Sn 29 Stokes (2) LU VIIc (3) Dy3.43 (SMU 20)

Location: 466 300yN 393 150yE

Parent material: White granitic gneiss

Profile drainage: Imperfectly drained

Description

Horizon	Depth cm	
A1	-8	Dark reddish brown (5YR 2/2 moist, 10YR 5/2 dry); loamy sand with some quartz gravel and rock, apedal. Abrupt to -
A2	-16	Grey (5YR 6/1 moist 8/1 dry); loamy sand with quartz gravel, apedal. Abrupt to -
B1	-51	Reddish yellow (5YR 6/8, 2.5Y 5/2 moist), mottled; sandy clay loam, coarse blocky structure, peds tightly fitting, some clay skins. Abrupt to -
B2	-68	Mottled grey and white (2.5Y 6/0, 8/0); sandy clay loam, apedal underlain by weathering white granitic gneiss.

Hor-izon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	
A1	6.0	6.3	37	54	2	7	0.0	2.25	.245	245	48
A2	5.8	5.9	32	48	12	8	0.0	0.45	.040	50	11
B1	6.0	6.0	19	30	6	45	0.0	0.54	.045	50	5
B2	8.5	8.2	18	22	17	43	7.8	0.15	.023	40	1

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	$g\ cm^3$	CEC	Ca	Mg	Na	K	%K2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.25	12.0	5.4	3.0	0.21	0.74	-	-	-
A2	1.50	3.4	1.4	0.9	0.17	0.20	-	-	-
B1	1.30	14.0	4.9	3.0	0.39	0.58	-	-	-
B2	1.25	18.0	42.0	3.6	0.91	0.62	-	-	-

Horizon	**Total micronutrients**						**$Ca(NO_3)_2$-extractable**			
	Cu	**Zn**	**Mn**	**B**	**Mo**	**Fe**	**Cu**	**Zn**	**Mn**	**Fe**
	ppm					**%**	**ppm x 10^3**			
A1	5.5	9	70	7	<1	0.6	5	16	3000	162
A2	-	-	-	-	-	-	4	40	1300	11000
B1	9.0	29	95	8	5	1.5	2	0	350	1100
B2	20.5	24	120	4	7	1.8	5	0	0	2

Horizon	**EDTA-extractable**				**DTPA-extractable**			
	Cu	**Zn**	**Mn**	**Fe**	**Cu**	**Zn**	**Mn**	**Fe**
	ppm x 10				**ppm x 10^2**			
A1	6.5	13.0	120.0	2700	13	82	520	6700
A2	1.9	3.3	17.0	1100	-	-	-	-
B1	3.2	2.4	4.9	520	-	-	-	-
B2	6.4	3.3	27.0	220	-	-	-	-

Profile 24

(1) Sn 13 Stokes (2) LU VIId (3) Dy3.82 (SMU 23)

Location: 763 950yN 391 750yE

Parent material: Alluvium and sandstone

Profile drainage: Poorly drained

Description

Horizon	Depth cm	
A1	-11	Dark greyish brown (10YR 4/2 moist 6/2 dry); loamy sand, apedal. Abrupt to -
A2	-25	Light yellowish brown (10YR 6/4 moist 8/1 dry); clayey sand, apedal. Abrupt to -
B1	-31	Mottled, pale olive (5Y 6/3, 2.5YR 4/8, 10YR 6/8); medium clay, apedal. Diffuse to -
B2	-86	As for B1, but including rotting sandstone.

Chemical and Physical Analysis

Horizon	pH		Particle size				$CaCO_3$	Org C	Total N	Total P	Avail. P
	Fld	Lab	CS	FS	S	C	%	%	%	ppm	ppm
A1	5.5	5.8	42	45	8	5	0.0	1.53	.125	225	54
A2	6.0	6.2	47	35	11	7	0.0	0.27	.030	75	2
B1	5.5	5.8	23	18	10	49	0.0	0.42	.042	110	4
B2	7.0	7.2	28	18	7	47	1.8	0.30	.013	100	2

Horizon	Bulk dens.	Exchangeable cations					Mineralogical analysis		
	$g\ cm^3$	CEC	Ca	Mg	Na	K	%<2μ	%Q	I/K
		m-equiv./100 g O.D. soil							
A1	1.40	6.20	2.5	0.3	0.21	0.22	-	-	-
A2	1.60	2.90	1.1	0.5	0.15	0.07	-	-	-
B1	1.25	13.00	2.4	3.3	0.42	0.36	-	-	-
B2	1.25	8.20	1.6	4.3	0.79	0.38	-	-	-

Horizon	Total micronutrients						$Ca(NO_3)_2$-extractable			
	Cu	Zn	Mn	B	Mo	Fe	Cu	Zn	Mn	Fe
	ppm					%	ppm x 10^3			
A1	3.0	16	55	3	2	0.5	14	350	3700	1200
A2	-	-	-	-	-	-	4	160	1000	18000
B1	-	-	-	-	-	-	2	15	350	2600
B2	2.0	23	95	3	3	1.6	3	0	30	52

Horizon	EDTA-extractable				DTPA-extractable			
	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
	ppm x 10				ppm x 10^2			
A1	5.7	11.0	46.0	2800	15	66	340	9300
A2	1.1	4.1	10.0	1100	-	-	-	-
B1	1.4	4.2	2.8	650	-	-	-	-
B2	2.4	3.4	1.9	350	-	-	-	-

APPENDIX 2 - Botanical and common names of species

Arctotheca calendula (L.) Levyns	capeweed
Arthrocnemum spp.	samphire
Avena barbata Brotero	wild oat
Brassica tornefortii Govan	wild turnip
Bromus rigidus Roth	rigid brome
Calistemon spp.	bottlebrush
Casuarina stricta Ait	sheoak
Cyperus spp.	sedge
Danthonia spp.	wallaby grass
Diplotaxis tenuifolia (L.) DC	Lincoln weed
Ehrharta calycina Sm.	perennial veldt grass
Erodium botrys (Cav.) Bertol	geranium
Eucalyptus cladocalyx F.v.M.	sugar gum
Eucalyptus gracilis F.v.M.	yorrel
Eucalyptus incrassata Labill	ridge fruited mallee
Eucalyptus leptophylla F.v.M.	
Eucalyptus leucoxylon F.v.M.	blue gum
Eucalyptus odorata Behr. et Schlechtd	peppermint gum
Eucalyptus oleosa F.v.M.	red mallee
Hordeum leporinum Link	barley grass
Hordeum murinum L.	salt water barley grass
Leptospermum spp.	tea-tree
Lolium rigidum Gaud	Wimmera ryegrass
Lupinus pilosus L.	blue lupin
Medicago denticulata Willd.	burr medic
Medicago littoralis	strand medic cv. Harbinger
Medicago minima (L) Grufb.	woolly burr medic
Medicago truncatula Gaertn.	barrel medic cv. Hannaford
Medicago sativa L.	lucerne
Melaleuca uncinata R. Br.	broom bush
Oenothera spp.	evening primrose
Phalaris tuberosa L.	phalaris
Themeda spp.	kangaroo grass
Trifolium fragiferum L.	strawberry clover
Trifolium glomeratum L.	cluster clover

APPENDIX 2 - Continued

Trifolium subterraneum L.	subterraneum clover
Triodia irritans R. Br.	porcupine grass
Vulpia myuros (L.) Gmel.	silver grass
Xanthorea spp.	yakka

APPENDIX 3 - Climatological data

1. Rainfall (mm)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Cleve													
Av. (77y)	14	23	19	31	41	46	45	48	43	38	29	22	399
1970	18	0	14	42	39	34	30	71	51	3	23	30	356
Decile	7	1	6	8	5	4	3	9	7	1	5	8	4
1971	3	11	74	54	46	42	35	57	45	79	46	33	455
Decile	3	5	9	9	7	5	3	7	6	2	9	8	8
Ungarra													
Av. (63y)	10	21	14	27	46	57	64	54	46	37	25	21	420
1970	12	1	1	38	31	55	34	80	56	6	15	5	334
Decile	7	2	1	7	4	6	2	9	7	1	4	2	3
1971	5	5	27	84	51	37	27	98	82	22	41	41	533
Decile	4	4	8	>9	7	4	2	>9	>9	3	9	9	9
Pt. Lincoln													
Av. (107y)	13	15	19	36	57	76	77	66	49	36	23	18	484
1970	25	0	5	51	49	52	45	113	51	13	23	5	435
Decile	8	1	2	7	5	3	2	9	6	2	6	1	4
1971	1	7	38	97	108	60	51	121	85	33	56	39	698
Decile	1	4	9	>9	>9	4	3	>9	>9	6	7	9	9

Decile rating number indicates probability of receiving the recorded rainfall or less in a 10-year period.

APPENDIX 3 - Continued

2. Temperatures (^{o}C)

		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean
Cleve +														
Av.(32y)	Min	15	15	15	12	10	8	7	7	8	10	12	14	11
	Max.	28	27	26	22	18	16	15	16	19	22	24	27	21
Pt. Lincoln														
Av.(38y)	Min.	15	16	15	13	11	9	9	8	9	11	12	14	12
	Max.	25	25	24	21	19	16	16	16	18	20	21	23	20
1970	Min.	14	16	14	13	11	10	8	8	9	10	12	14	12
	Max.	24	26	23	23	18	17	17	15	16	20	22	24	20
1971	Min.	16	16	18	13	11	9	8	8	9	10	11	13	12
	Max.	25	24	26	21	18	16	16	15	18	20	20	23	20

+ Data for 1970 and 1971 not available.

APPENDIX 4 - Mineralogical analysis of granitic gneiss

Samples of white and pink granitic gneisses from Stokes were examined in thin section and were found to be similar. They contained approximately 45 per cent microcline, 5 per cent alkaline felspar, 35 per cent quartz, 10 per cent biotite, and 1 per cent zircon. Disintegration of felspar produced kaolinite and illite. The shape and disposition of quartz in the specimens was similar in both rock forms and zircon was the only accessory mineral in both cases.

APPENDIX 5 - Treatments used in factorial experiments

Treatment No.	Block 1	Treatment No.	Block 2
1	Nil	17	Cu, Zn
2	Zn, B	18	Cu, B
3	B, Fe	19	Cu, Zn, B, Fe
4	Zn, Fe	20	Cu, Fe
5	Cu, Mn	21	Zn, Mn
6	Cu, Zn, Mn, B	22	Mn, B
7	Cu, Mn, B, Fe	23	Zn, Mn, B, Fe
8	Cu, Zn, Mn, Fe	24	Mn, Fe
9	Cu, Mo	25	Zn, Mo
10	Cu, Zn, B, Mo	26	B, Mo
11	Cu, B, Mo, Fe	27	Zn, B, Mo, Fe
12	Cu, Zn, Mo, Fe	28	Mo, Fe
13	Mn, Mo	29	Cu, Zn, Mn, Mo
14	Zn, Mn, B, Mo	30	Cu, Mn, B, Mo
15	Mn, B, Mo, Fe	31	Cu, Zn, Mn, B, Mo, Fe
16	Zn, Mn, Mo, Fe	32	Cu, Mn, Mo, Fe

APPENDIX 6 - Micronutrient concentrations in basal fertilizers

Fertilizer	Cu	Zn	Mn	B	Mo	Fe
			ppm			%
Sodium tripolyphosphate	2	5	5	-	1	.01
Superphosphate	5	350	35	-	0.4	.45
Ammonium sulphate	< 0.5	4	1.5	-	-	.002
Urea	< 0.2	< 1	0.5	-	-	.005

APPENDIX 7 - Harvests made in each factorial experiment

Harvest No.	Measurements	Sites
1	Wet and dry weights of whole plant tops, plant numbers	1,5,8,11,15,17,20
2	Wet and dry weights, plant numbers	2,3,4,6,7,9,10,12-24
3	Grain and straw yield determined from quadrat cutting	2,3,4,6,7,9,10,12-24
	Grain yield determined by reaping whole plots	2,3,4,6,7,9,10,12-14,16,18-21,23,24

APPENDIX 8 - Description of ancillary experiments

Site No.	Location (section)	Year	Soil (SMU)	Wheat cultivar	Elements examined	Basal P kg ha^{-1}	Method^{+} of Assessment
25	39 Rudall	1970	1	Halberd	Cu Zn Mn	10	V
26	c Wrensfordly	1970	4	Insignia	Cu Zn Mn	10	Q
27	18 Haslam	1970	4	Insignia	Cu Mn	10	V
28	4 Nicholls	1970	4	Halberd	Cu Zn Mn	10	Q
29	32 Verran	1970	5	Halberd	Cu Zn Mn	10	H
30	23 Brooker	1970	5	Halberd	Cu Zn Mn	10	V
31	4 Verran	1969	6	Insignia	Cu Zn Mn B Mo Fe	17	H
32	29 Brooker	1968	7	Heron	Cu Zn Mn	10	V
33	32 Dixon	1970	9	Halberd	Cu Zn Mn	6	H
34	23 Brooker	1970	10	Halberd	Mn	8	V
35	45 Wright	1969	12	Insignia	Cu Zn Mn	16	Q
36	43 Wright	1971	12	Halberd	Cu Zn Mn	13	V
37	12C Stokes	1971	13	Halberd	Cu	10	V
38	140 Koppio	1969	17	Raven	Cu	10	V
39	35 Stokes	1970	18	Halberd	Cu	10	V
40	182 Koppio	1968	19	Heron	Cu Zn Mn	10	V
41	42 Stokes	1971	19	Raven	Cu	10	V
42	90 Stokes	1969	20	Insignia	Cu Zn Mn B Mo Fe	17	Q

+ Method of assessment: Q - Quadrat cutting; H - Header yield;
V - Visual assessment only.

Nitrogen was applied as ammonium sulphate with the seed at Sites 31 (42 kg ha^{-1}N) 32 (20 kg ha^{-1}N), and 40 (16 kg ha^{-1}N)

APPENDIX 9 Yields and plant numbers in factorial experiments

Treatment No.	Site 1		Site 2		
	Harvest 1		Harvest 2		Harvest 3
	Plants per m^2	D.W. tops kg ha^{-1}	Plants per m^2	D.W. tops kg ha^{-1}	D.W. grain kg ha^{-1}
1	141	470	-	-	-
2	151	460	-	-	-
3	137	530	98	1 440	500
4	145	470	90	1 570	430
5	147	440	-	-	-
6	164	540	-	-	-
7	154	520	-	-	-
8	132	510	-	-	-
9	140	550	-	-	-
10	66	640	82	950	570
11	111	370	-	-	-
12	147	470	-	-	-
13	145	550	-	-	-
14	112	330	-	-	-
15	129	380	97	880	-
16	138	-	86	1 240	480
17	137	360	94	2 140	650
18	139	450	96	1 480	550
19	148	470	85	1 640	520
20	152	430	94	1 660	610
21	160	500	98	2 320	800
22	131	410	89	2 350	860
23	129	380	88	1 880	920
24	152	390	95	2 420	570
25	139	-	100	2 470	530
26	157	520	100	1 660	660
27	152	510	99	1 870	870
28	141	490	97	1 880	480
29	142	560	80	1 770	520
30	141	460	89	2 050	680
31	148	500	96	2 120	720
32	148	450	89	1 960	560

APPENDIX 9 - Continued

Treatment No.	Site 3			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	88	910	1 260	200
2	96	1 250	1 190	150
3	99	1 270	1 230	310
4	101	1 210	1 270	260
5	103	1 600	1 910	680
6	102	1 420	1 610	450
7	102	1 610	1 710	830
8	97	1 450	1 820	800
9	104	1 300	1 940	650
10	87	1 440	1 900	800
11	96	1 280	1 970	590
12	113	1 800	2 150	900
13	98	1 320	1 300	370
14	103	1 190	1 200	250
15	100	1 310	1 520	310
16	97	1 360	1 490	330
17	97	1 610	1 720	940
18	91	1 600	1 870	830
19	96	1 400	1 770	880
20	93	1 320	1 940	640
21	92	1 140	1 060	90
22	98	1 310	1 410	280
23	98	1 370	1 580	250
24	93	1 130	1 290	160
25	97	1 430	1 220	180
26	94	1 280	1 230	160
27	94	1 190	1 490	200
28	98	1 170	1 320	200
29	103	1 580	1 640	640
30	92	1 500	1 340	430
31	93	1 280	1 830	570
32	97	1 860	1 680	590

APPENDIX 9 - Continued

Treatment No.	Site 4			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	82	2 240	1 770	590
2	90	3 050	2 030	310
3	89	3 780	2 550	1 200
4	80	1 990	1 520	160
5	99	3 720	3 210	1 490
6	85	2 420	1 840	610
7	84	3 170	2 020	1 170
8	98	2 690	2 160	560
9	88	2 350	2 070	720
10	84	1 760	1 030	120
11	80	1 490	1 650	760
12	74	1 260	680	170
13	93	4 180	3 220	1 690
14	90	3 170	2 320	500
15	81	3 120	2 520	1 400
16	78	2 260	2 230	540
17	85	2 400	1 880	570
18	90	4 220	3 440	2 090
19	95	2 880	2 800	800
20	97	2 790	2 020	630
21	88	2 190	1 410	190
22	89	3 710	3 380	1 660
23	82	2 100	1 680	120
24	86	3 650	3 610	1 940
25	89	2 510	1 800	400
26	93	940	580	110
27	86	1 960	1 870	210
28	76	920	630	150
29	95	3 430	3 130	1 620
30	89	3 150	2 900	2 000
31	88	3 340	2 470	1 120
32	86	3 690	2 850	1 730

APPENDIX 9 - Continued

Treatment No.	Site 5		Site 6			
	Harvest 1		Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain kg ha^{-1}
1	142	680	52	2 090	2 770	840
2	92	540	51	2 150	3 480	900
3	158	870	57	1 970	2 510	600
4	88	610	52	2 010	2 240	780
5	170	1 130	53	1 980	2 490	750
6	87	610	49	1 800	2 090	870
7	79	350	46	1 940	2 820	970
8	89	520	62	2 600	2 800	910
9	183	1 170	57	1 780	2 170	710
10	53	290	54	2 090	2 150	900
11	54	330	55	1 770	2 140	770
12	73	300	42	1 570	2 420	1 000
13	68	300	46	1 850	2 620	760
14	154	1 310	44	1 800	2 480	810
15	81	540	44	1 940	2 670	930
16	88	640	56	1 940	2 090	660
17	98	950	51	1 970	2 350	770
18	100	720	62	1 920	2 680	710
19	72	510	70	2 010	2 700	690
20	89	760	64	1 930	2 490	790
21	90	860	71	2 190	2 670	950
22	73	670	67	2 530	2 370	900
23	86	630	65	2 220	2 390	540
24	72	730	63	2 290	2 370	300
25	84	640	58	1 970	2 470	790
26	72	810	64	2 020	2 740	810
27	87	880	58	2 030	2 720	970
28	83	850	60	2 150	2 490	1 040
29	100	750	56	1 920	3 010	710
30	78	570	50	1 580	2 300	750
31	87	590	63	2 300	2 570	780
32	91	820	43	1 580	2 370	690

APPENDIX 9 - Continued

Treatment No.	Site 7			Site 8	
	Harvest 2		Harvest 3	Harvest 1	
	Plants per m^2	D.W. tops kg ha^{-1}	D.W. grain kg ha^{-1}	Plants per m^2	D.W. tops kg ha^{-1}
1	74	2 270	1 000	140	420
2	81	2 760	890	84	590
3	75	2 440	580	86	560
4	87	2 390	570	120	360
5	96	2 870	480	151	570
6	95	2 340	870	194	560
7	88	2 650	530	57	620
8	92	3 720	400	80	580
9	77	3 780	650	86	500
10	84	2 560	780	167	510
11	78	2 530	780	219	610
12	79	3 240	810	85	490
13	88	2 520	970	195	600
14	86	3 870	870	181	510
15	85	2 750	640	104	570
16	88	2 540	680	64	450
17	80	2 030	910	97	600
18	75	2 690	1 030	46	640
19	67	2 380	1 020	92	650
20	79	2 520	920	99	-
21	84	2 270	1 020	79	590
22	67	1 170	710	95	620
23	75	3 010	1 060	101	580
24	78	1 740	740	94	620
25	83	1 680	770	77	550
26	70	2 290	1 090	91	730
27	78	3 600	1 420	88	730
28	83	3 950	1 300	93	640
29	87	3 210	1 130	92	610
30	80	1 900	760	93	600
31	85	2 470	710	101	580
32	74	2 920	1 080	87	610

APPENDIX 9 - Continued

Treatment No.	Site 9			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw	D.W. grain
			kg ha^{-1}	
1	70	2 130	2 070	680
2	79	1 570	1 920	550
3	79	1 970	2 390	690
4	82	2 000	2 240	570
5	89	2 820	2 930	1 280
6	75	2 220	2 120	870
7	85	-	2 570	910
8	90	3 180	3 040	1 220
9	89	2 950	2 700	1 220
10	88	2 790	2 740	1 080
11	85	2 090	1 910	790
12	80	2 840	3 080	1 050
13	89	2 480	2 530	970
14	74	1 590	2 130	560
15	89	2 260	2 220	890
16	79	2 210	2 580	760
17	82	2 250	2 810	1 080
18	87	2 420	2 860	970
19	73	2 790	3 160	1 290
20	81	2 860	2 830	1 370
21	79	2 520	2 640	920
22	90	2 170	2 500	830
23	69	2 220	2 740	820
24	71	2 050	2 910	720
25	64	880	1 850	560
26	69	2 490	2 750	970
27	76	2 490	2 820	990
28	81	1 710	2 630	650
29	77	2 990	3 510	1 200
30	79	2 500	2 870	1 240
31	81	2 350	2 630	950
32	76	1 810	2 450	790

APPENDIX 9 - Continued

Treatment No.	Site 10				Site 11	
	Harvest 2		Harvest 3		Harvest 1	
	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain	Plants per m^2	D.W. tops kg ha^{-1}
1	68	4 710	5 450	2 460	116	750
2	76	4 710	5 120	2 580	131	860
3	83	4 700	5 620	2 500	135	960
4	62	4 910	5 510	2 660	116	710
5	61	6 030	5 050	2 330	111	690
6	65	5 580	5 370	2 080	118	730
7	71	4 660	5 410	2 420	141	900
8	66	3 820	6 010	2 430	114	750
9	72	4 180	5 130	2 420	121	720
10	81	5 160	6 210	2 290	133	950
11	63	5 560	5 490	2 380	123	1 030
12	60	5 500	5 400	2 640	121	940
13	62	4 780	5 130	2 700	129	950
14	68	4 980	5 300	2 400	131	780
15	65	5 160	5 390	2 500	118	930
16	69	5 760	5 190	2 280	120	790
17	61	4 820	5 660	2 270	86	630
18	67	4 830	4 720	2 030	120	800
19	67	4 510	5 120	1 880	125	870
20	65	4 680	4 860	2 070	137	830
21	70	5 860	5 480	2 170	105	780
22	67	4 840	5 530	2 120	113	780
23	61	5 440	3 660	1 870	125	950
24	63	4 320	4 960	2 050	124	900
25	64	4 860	5 010	2 060	112	720
26	71	4 440	5 090	1 720	117	850
27	65	4 590	5 280	2 240	113	-
28	67	4 500	4 860	2 090	107	760
29	66	4 900	5 230	2 000	108	720
30	67	4 930	5 550	2 250	126	910
31	73	5 430	6 100	2 030	145	730
32	62	4 500	4 590	1 900	113	650

APPENDIX 9 - Continued

Treatment No.	Site 12			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	75	4 570	4 720	1 400
2	95	4 000	4 800	1 110
3	71	4 100	4 880	1 190
4	92	4 400	4 270	1 070
5	98	4 470	4 760	1 220
6	83	4 210	4 240	1 340
7	85	4 590	4 650	1 270
8	82	4 520	4 910	1 230
9	79	5 560	4 590	1 370
10	78	4 290	4 510	1 100
11	77	4 140	4 630	1 050
12	92	5 100	4 780	1 150
13	81	4 700	-	910
14	94	4 780	4 410	1 050
15	88	4 590	4 380	1 150
16	88	5 680	4 620	850
17	81	3 430	4 380	1 040
18	79	4 090	4 020	880
19	84	3 670	3 820	1 120
20	91	4 120	4 400	1 110
21	82	3 850	4 290	840
22	78	3 860	3 420	970
23	86	4 250	3 920	1 110
24	87	5 050	4 040	1 090
25	72	3 620	3 740	1 050
26	91	4 280	3 960	1 040
27	82	4 530	4 170	880
28	82	3 960	4 620	1 060
29	85	4 130	4 390	1 120
30	89	4 950	4 640	1 280
31	81	3 940	4 260	1 060
32	87	4 480	3 980	1 180

APPENDIX 9 - Continued

Treatment No.	Site 13			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	87	5 790	3 610	1 650
2	83	5 380	3 590	1 660
3	74	5 630	3 890	1 730
4	83	5 340	3 740	1 430
5	80	4 800	3 150	1 640
6	82	5 490	3 120	1 740
7	84	5 300	3 790	1 760
8	76	4 770	3 520	1 540
9	82	4 990	3 350	1 720
10	80	5 370	3 240	1 610
11	85	4 960	3 150	1 670
12	75	4 820	3 680	1 780
13	80	4 630	3 230	1 630
14	93	5 590	3 590	1 650
15	75	5 210	3 500	1 320
16	84	4 930	3 160	1 390
17	85	5 670	3 530	1 680
18	80	5 910	3 460	1 860
19	82	5 870	3 790	1 890
20	72	4 040	3 280	1 080
21	88	5 820	3 810	1 550
22	63	4 360	3 230	1 500
23	81	5 860	3 740	1 670
24	77	4 720	3 730	1 700
25	77	4 520	3 370	1 520
26	77	4 380	3 230	1 220
27	87	5 520	3 440	1 960
28	83	5 070	3 420	1 690
29	77	5 690	3 750	1 570
30	71	5 390	3 710	1 700
31	76	6 180	3 850	1 750
32	82	5 480	3 310	1 440

APPENDIX 9 - Continued

Treatment No.	Site 14			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		$kg\ ha^{-1}$	$kg\ ha^{-1}$	
1	94	3 670	3 100	800
2	84	3 600	3 360	910
3	94	3 450	2 910	1 050
4	76	3 630	3 620	1 090
5	91	3 030	2 760	1 000
6	87	3 570	3 330	1 170
7	93	3 540	3 010	1 020
8	91	3 810	3 500	1 070
9	86	3 240	3 160	950
10	87	3 620	3 650	1 020
11	93	3 180	2 900	880
12	89	4 130	3 440	920
13	84	3 300	3 170	980
14	85	2 930	3 380	1 260
15	92	3 090	3 030	1 120
16	82	3 670	3 420	1 000
17	75	3 790	3 340	990
18	92	3 210	3 140	890
19	83	3 510	3 200	1 050
20	92	3 480	3 560	1 090
21	89	3 680	3 710	1 270
22	87	3 650	3 010	920
23	96	4 210	3 330	910
24	83	3 630	3 470	1 000
25	89	3 980	3 950	1 340
26	93	3 480	3 540	900
27	85	3 790	3 630	1 120
28	78	3 290	3 140	800
29	96	4 050	3 590	1 140
30	87	3 550	3 450	960
31	80	3 780	3 370	960
32	92	3 680	3 030	900

APPENDIX 9 - Continued

Treatment No.	Site 15					
	Harvest 1		Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain kg ha^{-1}
1	71	550	80	2 490	3 120	31
2	101	610	82	2 390	1 960	0
3	88	620	89	2 850	3 210	1
4	91	510	83	2 470	2 000	7
5	109	720	101	4 030	3 280	1 450
6	107	620	99	4 090	3 210	1 930
7	104	620	92	4 020	3 130	1 770
8	95	570	98	3 980	3 230	2 020
9	98	620	87	3 950	3 120	1 980
10	101	680	101	4 160	2 950	1 840
11	105	600	102	4 150	3 280	1 890
12	92	580	81	3 730	3 280	2 000
13	102	570	87	2 860	3 230	2
14	99	640	86	2 510	2 730	0
15	96	610	87	2 890	2 470	40
16	92	530	86	2 510	2 590	0
17	110	860	97	4 530	-	2 140
18	106	530	104	3 420	3 330	1 990
19	108	760	98	3 900	3 060	1 900
20	96	580	87	3 930	3 030	1 960
21	111	450	81	1 930	2 140	10
22	89	410	91	3 050	2 850	92
23	105	550	81	1 970	2 650	0
24	99	380	77	1 420	2 540	0
25	98	490	91	2 460	1 990	0
26	103	550	114	2 620	2 360	37
27	62	400	62	1 520	2 820	13
28	115	580	96	2 880	2 810	14
29	102	640	88	4 030	3 270	2 000
30	106	550	100	4 460	3 090	1 850
31	94	550	91	3 840	2 890	1 910
32	108	600	98	4 050	3 140	1 890

APPENDIX 9 - Continued

Site 16

Treatment No.	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops $kg\ ha^{-1}$	D.W. straw $kg\ ha^{-1}$	D.W. grain
1	92	3 200	3 040	1 160
2	80	2 910	2 720	760
3	94	3 360	2 830	1 030
4	88	3 640	3 380	1 340
5	86	3 510	2 970	1 030
6	91	3 550	3 360	1 240
7	94	4 290	3 390	1 500
8	86	3 610	3 170	1 320
9	80	3 650	3 420	1 470
10	85	3 560	3 030	960
11	82	3 820	2 780	1 370
12	82	3 550	2 570	890
13	91	3 380	2 810	960
14	84	3 270	2 610	1 030
15	89	3 250	2 700	970
16	88	2 980	2 210	810
17	80	3 130	2 830	620
18	95	5 350	4 090	1 470
19	85	5 150	4 290	1 280
20	93	4 460	3 900	1 310
21	88	3 390	2 710	660
22	92	3 040	2 660	790
23	89	4 800	3 780	1 390
24	86	3 850	4 270	930
25	89	3 620	3 140	990
26	88	3 070	2 540	540
27	90	4 660	3 710	1 250
28	90	2 760	2 590	560
29	87	4 260	3 950	1 490
30	91	3 620	3 170	980
31	84	5 110	4 090	1 710
32	89	3 780	2 840	1 000

APPENDIX 9 - Continued

Site 17

Treatment No.	Harvest 1		Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain
1	63	400	66	4 530	4 220	1 700
2	66	510	72	4 290	3 750	1 020
3	86	580	62	4 170	4 010	1 280
4	73	440	67	-	4 050	1 700
5	89	660	71	3 790	3 660	960
6	62	430	54	4 270	3 440	1 090
7	72	490	58	4 380	3 370	1 160
8	77	590	72	4 010	3 300	760
9	73	510	66	4 230	4 030	1 300
10	68	500	50	3 740	3 800	1 450
11	56	380	61	4 370	4 770	1 980
12	68	410	61	4 490	3 900	1 530
13	60	410	66	5 080	4 240	1 700
14	70	430	56	4 670	3 700	1 220
15	75	510	59	4 020	3 550	1 010
16	73	530	42	3 910	3 180	710
17	76	520	70	5 050	3 130	930
18	87	550	72	5 090	4 110	1 320
19	99	540	76	4 850	3 890	1 310
20	97	530	68	4 910	4 130	1 410
21	72	540	67	4 190	3 440	960
22	78	510	73	5 560	4 360	1 660
23	97	580	75	4 830	3 980	1 090
24	84	580	73	4 380	3 840	1 230
25	83	510	66	5 110	4 150	1 540
26	91	650	69	4 780	3 330	940
27	90	600	74	4 150	3 570	680
28	78	570	80	4 250	3 510	930
29	84	600	82	5 080	4 630	1 310
30	88	510	84	5 530	4 340	1 460
31	78	580	78	4 290	3 210	970
32	81	580	69	4 100	3 440	980

APPENDIX 9 - Continued

Treatment No.	Site 18			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	103	5 990	3 940	2 520
2	92	5 230	3 230	1 980
3	89	5 580	3 790	2 420
4	87	5 320	3 570	2 710
5	90	5 030	3 550	2 950
6	94	6 390	3 990	2 460
7	89	5 730	3 680	2 640
8	89	6 020	3 750	2 750
9	87	5 760	4 140	2 490
10	94	6 230	4 380	2 820
11	84	5 700	4 120	2 570
12	91	5 800	3 940	2 880
13	93	4 730	3 680	2 170
14	95	5 110	3 530	2 270
15	90	5 180	2 790	1 940
16	92	5 250	4 860	2 220
17	88	5 890	3 340	2 150
18	86	5 890	3 700	1 820
19	90	5 710	3 570	2 490
20	82	5 700	3 670	1 820
21	86	5 100	3 300	2 290
22	82	4 940	2 560	1 790
23	76	4 220	2 330	2 010
24	82	4 920	2 720	1 940
25	82	4 660	2 780	1 820
26	79	4 490	2 590	2 020
27	89	5 560	3 720	1 800
28	80	4 860	3 780	2 050
29	75	4 520	2 860	2 120
30	79	4 480	2 700	2 120
31	82	5 190	3 820	1 960
32	94	6 240	4 200	1 900

APPENDIX 9 - Continued

Treatment No.	Site 19			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	86	4 470	4 650	2 090
2	87	4 780	3 780	2 030
3	93	5 260	4 690	2 260
4	87	4 940	4 690	2 360
5	86	5 000	4 110	2 090
6	72	5 040	4 680	2 420
7	82	5 580	4 180	2 250
8	90	4 750	4 180	2 250
9	84	5 180	4 180	2 220
10	90	6 710	3 530	2 190
11	91	5 110	4 470	2 230
12	84	5 060	4 590	2 340
13	73	4 210	4 490	2 460
14	94	3 640	4 420	2 470
15	84	4 920	4 420	2 500
16	72	4 410	4 320	2 580
17	69	4 960	4 990	2 180
18	93	5 450	4 570	1 670
19	84	5 940	4 720	1 890
20	83	4 970	4 070	2 060
21	83	4 920	4 010	1 800
22	88	5 130	3 800	1 940
23	75	4 670	4 260	1 970
24	77	5 210	4 600	2 000
25	75	4 400	4 570	1 920
26	88	5 230	4 630	1 840
27	81	4 920	4 050	2 160
28	75	4 770	4 130	2 200
29	81	5 190	4 210	2 150
30	83	5 130	4 780	1 900
31	79	4 760	4 410	2 050
32	82	4 980	4 340	2 190

APPENDIX 9 - Continued

Site 20

Treatment No.	Harvest 1		Harvest 2	Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain
1	70	460	4 640	4 330	2 290
2	74	400	3 720	3 770	2 210
3	82	440	4 330	3 980	2 190
4	83	590	5 240	5 730	2 780
5	81	440	3 970	4 170	2 290
6	79	660	5 540	5 810	2 950
7	79	670	5 570	5 500	2 580
8	73	480	4 000	3 490	2 060
9	83	790	5 800	5 590	2 460
10	90	470	4 690	4 110	2 460
11	76	600	5 670	5 350	2 520
12	91	710	4 370	5 830	2 850
13	86	550	4 850	4 930	2 530
14	90	750	6 350	6 820	1 030
15	82	530	3 840	4 130	2 370
16	64	430	3 560	4 250	2 460
17	72	670	4 560	6 000	2 730
18	78	850	6 060	5 700	2 530
19	83	740	5 770	5 500	2 500
20	83	660	6 190	5 520	2 910
21	73	720	5 530	6 510	1 400
22	82	630	5 590	4 160	2 450
23	83	640	5 490	5 760	1 510
24	79	750	6 530	5 880	1 620
25	78	780	5 330	5 420	2 240
26	90	820	5 690	5 470	2 520
27	81	600	5 890	5 200	1 970
28	77	820	5 690	6 040	1 150
29	89	780	6 350	5 960	2 570
30	90	700	5 110	6 260	2 860
31	72	660	5 160	6 270	2 840
32	78	700	5 460	5 640	2 780

APPENDIX 9 - Continued

Treatment No.	Site 21			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops $kg\ ha^{-1}$	D.W. straw $kg\ ha^{-1}$	D.W. grain
1	72	4 530	4 820	1 820
2	79	6 000	4 880	2 060
3	70	5 260	5 170	2 410
4	73	5 040	5 550	2 020
5	80	6 930	6 840	3 920
6	75	6 820	7 130	3 850
7	71	6 010	6 030	3 600
8	84	6 210	6 520	3 500
9	79	7 130	5 960	3 690
10	79	6 460	7 030	3 740
11	71	6 150	5 590	3 860
12	74	6 590	6 000	3 830
13	74	4 830	4 050	2 020
14	75	4 650	3 790	1 150
15	74	5 410	5 450	1 720
16	74	4 840	4 830	1 910
17	70	5 980	7 680	3 980
18	72	7 000	6 640	3 870
19	73	6 830	6 370	3 740
20	70	6 660	7 180	3 780
21	71	5 360	5 070	1 630
22	67	4 790	4 980	1 780
23	69	4 910	4 530	1 450
24	66	4 950	5 160	2 240
25	74	5 440	4 880	1 390
26	72	5 590	5 020	2 170
27	74	5 150	4 790	1 190
28	79	5 430	5 250	1 970
29	72	7 070	7 200	4 060
30	75	6 500	7 180	3 840
31	80	6 730	6 730	3 850
32	77	7 130	6 530	3 820

APPENDIX 9 - Continued

Treatment No.	Site 22			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops kg ha^{-1}	D.W. straw kg ha^{-1}	D.W. grain kg ha^{-1}
1	87	5 220	4 850	2 770
2	60	3 780	3 460	2 110
3	50	4 530	4 070	2 350
4	78	4 500	3 840	2 580
5	67	4 350	4 010	2 400
6	72	3 930	3 770	2 260
7	68	4 270	3 810	2 160
8	66	4 110	4 360	2 860
9	82	4 400	3 960	2 370
10	56	3 800	4 610	2 220
11	62	4 330	4 070	2 060
12	65	3 470	3 920	2 510
13	83	4 270	4 130	2 490
14	75	4 060	3 760	2 410
15	73	3 800	3 280	2 060
16	57	3 990	4 460	2 610
17	71	4 220	4 150	2 330
18	81	3 740	3 860	2 360
19	64	4 810	4 350	2 570
20	73	4 140	4 210	2 220
21	69	5 070	3 700	1 990
22	82	4 030	3 800	2 420
23	72	4 230	3 450	2 080
24	92	5 690	4 060	2 570
25	72	4 430	4 520	2 470
26	85	5 220	3 910	2 630
27	97	4 790	3 420	2 090
28	78	4 640	3 780	2 070
29	95	4 340	3 960	2 440
30	97	5 590	3 690	2 530
31	89	4 330	3 980	2 730
32	69	3 540	3 830	2 230

APPENDIX 9 - Continued

Treatment No.	Site 23			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	79	5 590	6 830	2 070
2	79	5 070	5 280	1 600
3	87	6 100	7 430	2 010
4	76	3 870	5 300	1 240
5	77	5 280	5 500	2 520
6	75	6 250	6 380	3 180
7	84	6 510	8 200	2 720
8	91	6 310	6 920	3 430
9	82	6 470	7 320	2 880
10	75	5 410	6 170	3 290
11	74	5 480	6 060	3 380
12	89	5 730	6 310	3 490
13	84	4 870	5 840	2 250
14	75	4 050	-	2 080
15	79	4 870	4 620	2 850
16	77	4 350	4 790	2 500
17	77	7 840	7 830	3 270
18	72	4 700	7 500	3 030
19	78	8 210	7 740	3 070
20	77	7 250	7 360	3 040
21	81	7 800	6 970	2 640
22	82	7 830	8 210	3 210
23	75	7 200	7 240	3 170
24	72	7 470	6 910	3 020
25	79	8 340	7 710	3 030
26	65	7 140	7 210	3 010
27	72	7 060	6 900	2 530
28	78	7 800	7 840	3 110
29	75	6 770	7 160	2 880
30	81	8 050	7 270	3 100
31	82	7 310	7 170	3 170
32	73	6 510	7 530	3 120

APPENDIX 9 - Continued

Treatment No.	Site 24			
	Harvest 2		Harvest 3	
	Plants per m^2	D.W. tops	D.W. straw	D.W. grain
		kg ha^{-1}	kg ha^{-1}	
1	71	3 620	3 640	2 160
2	76	3 860	3 310	2 360
3	83	4 260	3 720	2 410
4	80	4 200	4 030	2 640
5	80	4 400	4 060	2 770
6	74	4 190	3 920	2 870
7	77	4 290	4 030	2 600
8	72	4 180	4 220	2 950
9	74	4 240	3 970	2 890
10	79	4 680	4 680	3 000
11	71	4 430	4 260	2 760
12	75	4 160	4 040	2 770
13	72	3 920	4 460	2 350
14	62	3 480	3 960	2 010
15	73	4 090	4 340	2 210
16	78	3 830	3 980	2 280
17	79	3 750	3 990	2 540
18	79	3 700	4 300	2 770
19	77	3 100	3 780	2 250
20	79	3 710	4 040	2 370
21	76	3 640	3 190	1 890
22	73	3 610	3 440	1 800
23	76	3 660	3 730	2 470
24	77	4 080	4 280	2 450
25	82	3 670	3 580	1 780
26	79	3 740	3 410	2 440
27	77	3 480	3 940	2 390
28	78	3 680	3 110	2 470
29	78	3 050	3 440	2 320
30	80	3 360	3 980	2 650
31	79	3 600	3 310	2 180
32	79	3 570	3 570	2 250

APPENDIX 10 - Analyses of plants from control plots of factorial experiments

Site No.	Analysis conducted on	Micronutrients						Macronutrients				
		Cu	Zn	Mn	Fe	B	Mo	N	P	K	Ca	Mg
		ppm of oven dry material						% of oven dry material				
1	tops H1	3.6	24	22	105	5.0	1.0	-	-	-	0.25	0.18
2	tops H2	1.4	18	15	-	13.5	0.4	0.8	0.23	1.2	0.13	0.12
3	tops H2	1.8	19	28	115	5.2	0.7	3.0	0.47	2.5	0.31	0.23
	grain	1.3	22	26	88	5.5	0.4	2.3	0.36	0.5	0.05	0.20
4	tops H2	2.6	10	0.8	68	6.2	0.2	2.0	0.26	2.6	0.29	0.25
	grain	1.5	8	5.3	46	8.2	0.4	2.2	0.31	0.5	0.05	0.18
5	tops H1	2.7	23	38	150	8.5	0.5	-	-	-	0.45	-
6	tops H2	3.3	17	18	42	4.5	0.4	1.4	0.22	1.7	0.15	0.12
	grain	3.0	14	20	45	3.5	0.4	1.6	0.28	0.5	0.04	0.15
7	tops H2	1.6	9	14	46	1.2	0.9	1.7	0.28	2.1	0.15	0.14
	grain	2.6	19	26	46	6.0	0.5	1.9	0.38	0.6	0.05	0.16

APPENDIX 10 - Continued

Site No.	Analysis conducted on	Micronutrients						Macronutrients				
		Cu	Zn	Mn	Fe	B	Mo	N	P	K	Ca	Mg
		ppm of oven dry material						% of oven dry material				
8	tops H1	2.0	23	35	118	7.0	1.0	-	-	-	0.43	-
9	tops H2	0.9	12	14	52	9.0	0.8	1.4	0.25	1.2	0.26	0.18
	grain	2.0	18	19	44	-	-	1.8	0.37	0.5	0.05	0.19
10	tops H2	2.8	17	27	78	9.2	1.2	2.1	0.32	3.1	0.13	0.18
	grain	2.5	18	32	72	9.5	0.7	2.3	0.38	0.5	0.04	0.19
11	tops H1	4.5	35	31	133	8.0	0.9	-	-	-	0.41	0.35
12	tops H2	4.4	16	24	84	5.0	0.9	2.3	0.34	3.5	0.11	0.17
	grain	3.0	18	29	94	7.5	0.8	3.1	0.45	0.7	0.04	0.23
13	tops H2	2.9	8	13	62	20.8	0.9	1.3	0.19	2.4	0.11	0.16
	grain	4.7	13	31	108	10.2	0.7	2.6	0.33	0.5	0.03	0.17

APPENDIX 10 - Continued

Site No.	Analysis conducted on	Micronutrients						Macronutrients				
		Cu	Zn	Mn	Fe	B	Mo	N	P	K	Ca	Mg
		ppm of oven dry material						% of oven dry material				
14	tops H2	4.9	10	21	115	2.8	0.5	2.0	0.27	3.1	0.20	0.20
	grain	4.5	17	20	46	6.2	0.5	2.6	0.39	0.6	0.03	0.17
15	tops H1	3.5	24	55	910	7.5	0.4	-	-	-	0.35	-
	tops H2	1.8	12	35	233	5.0	ND	-	-	-	0.29	0.21
	grain	1.8	32	37	-	-	-	-	-	-	0.04	0.19
16	tops H2	1.6	15	36	93	6.0	0.2	1.8	0.26	2.5	0.17	0.21
	grain	1.8	17	31	51	7.5	0.4	2.0	0.32	0.6	0.03	0.17
17	tops H1	4.7	35	84	720	5.0	0.7	-	-	-	0.35	-
	tops H2	6.9	17	48	83	5.0	0.6	-	-	-	0.19	0.13
	grain	4.0	22	30	66	-	-	-	-	-	0.03	0.15
18	tops H2	3.5	17	60	45	4.8	0.3	1.8	0.31	3.1	0.17	0.17
	grain	2.4	22	37	43	5.8	0.3	2.6	0.31	0.5	0.03	0.14

ND - Not detectable

APPENDIX 10 - Continued

Site No.	Analysis conducted on	Micronutrients						Macronutrients				
		Cu	Zn	Mn	Fe	B	Mo	N	P	K	Ca	Mg
		ppm of oven dry material						% of oven dry material				
19	tops H2	2.9	17	37	57	3.8	0.8	1.8	0.30	3.3	0.14	0.16
	grain	3.4	20	30	71	7.2	0.3	2.3	0.32	0.5	0.03	0.16
20	tops H1	3.5	35	103	400	6.0	0.8	-	-	-	0.38	-
	tops H2	3.5	18	89	162	5.0	0.6	-	-	-	0.24	0.14
	grain	5.0	20	31	62	-	0.4	-	-	-	0.03	0.14
21	tops H2	1.8	16	139	91		0.5	2.5	0.41	2.1	0.37	0.25
	grain	2.0	20	74	68	7.5	0.2	2.4	0.33	0.5	0.04	0.17
22	tops H2	4.0	16	74	83	4.0	0.7	-	-	-	-	0.19
	grain	4.9	20	31	62	-	0.6	-	-	-	0.03	0.14
23	tops H2	3.4	17	52	78	5.2	0.3	2.4	0.35	3.5	0.29	0.19
	grain	3.8	13	27	42	3.2	0.3	2.2	0.27	0.6	0.03	0.12
24	tops H2	1.7	15	78	43	9.0	0.3	1.8	0.29	2.2	0.22	0.17
	grain	1.5	20	48	47	5.2	0.3	2.3	0.32	0.5	0.03	0.16