1-1-1989

Soil management for sustainable agriculture: background papers from a workshop organized by the Research Review Committee of the Grains Section of the Western Australian Farmers Federation held at Perth Civic Centre, September 29-30, 1987

Western Australian Farmers' Federation

G A. Robertson

Follow this and additional works at: https://researchlibrary.agric.wa.gov.au/rmtr

Part of the Soil Science Commons

Recommended Citation

This report is brought to you for free and open access by the Natural resources research at Research Library. It has been accepted for inclusion in Resource management technical reports by an authorized administrator of Research Library. For more information, please contact jennifer.heathcote@agric.wa.gov.au, sandra.papenfus@agric.wa.gov.au, paul.orange@dpird.wa.gov.au.
Soil Management for Sustainable Agriculture

G.A. Robertson

Resource Management Technical Report No.95
Disclaimer

The contents of this report were based on the best available information at the time of publication. It is based in part on various assumptions and predictions. Conditions may change over time and conclusions should be interpreted in the light of the latest information available.

© Chief Executive Officer, Department of Agriculture Western Australia 2001
# Table of Contents

**Introduction** ................................................................................................................................. 1

1. Soil of the cereal growing areas of western australia or the problems of extreme old age ................................................................................................................................. 2
   1.1 MOST SOILS IN THE REGION ARE VERY OLD! ................................................................ 2
   1.2 THE SOIL MAP OF SOUTH-WESTERN AUSTRALIA ........................................................... 7
   1.2 CONCLUDING REMARKS AND A FEW WHINGES AND SUGGESTIONS ............................... 10

2. The farmer perception of soil management - an eastern wheatbelt perspective ........................................................................................................... 12
   2.1 SALMON GUM/GIMLET OR CLAY LOAMS ..................................................................... 13
      2.1.1 soil structure................................................................................................. 13
      2.1.2 wind and water erosion ................................................................................ 13
      2.1.3 plant nutrient availability............................................................................... 13
      2.1.4 build-up of disease....................................................................................... 14
   2.2 MALLEE SOILS OR SANDY LOAMS ............................................................................. 14
      2.2.1 wind and water erosion ................................................................................ 14
      2.2.3 plant nutrition ............................................................................................... 15
   2.3 TAMMA TEE TREE OR SANDS..................................................................................... 15
      2.3.1 soil structure................................................................................................. 15
      2.3.2 plant nutrition ............................................................................................... 15
   2.4 WODGIL OR ACID SANDS ......................................................................................... 16
      2.4.1 other issues affecting soil management....................................................... 16
   2.5 SUMMARY.............................................................................................................. 16

3. Maintenance and improvement of soil structure ............................................................................. 18
   3.1 SUMMARY.............................................................................................................. 18
   3.2 INTRODUCTION ...................................................................................................... 18
   3.3 THE PRESENT STRUCTURAL CONDITION OF WESTERN AUSTRALIAN AGRICULTURAL SOILS 19
      3.3.1 surface soils.................................................................................................... 19
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5 CARBON CYCLE</td>
<td>89</td>
</tr>
<tr>
<td>7.6 NITROGEN CYCLE</td>
<td>89</td>
</tr>
<tr>
<td>7.7 SUBSOIL ACIDIFICATION</td>
<td>91</td>
</tr>
<tr>
<td>7.8 CRITICAL LEVELS OF ACIDITY</td>
<td>94</td>
</tr>
<tr>
<td>7.9 LIME AS PART OF OUR AGRICULTURAL SYSTEM</td>
<td>95</td>
</tr>
<tr>
<td>7.10 STRATEGIES TO MINIMIZE SOIL ACIDIFICATION</td>
<td>97</td>
</tr>
<tr>
<td>7.11 RESEARCH NEEDS</td>
<td>101</td>
</tr>
<tr>
<td>7.12 LITERATURE CITED</td>
<td>101</td>
</tr>
<tr>
<td>8. Effects of agricultural practices on the soil</td>
<td>103</td>
</tr>
<tr>
<td>8.1 INTRODUCTION</td>
<td>103</td>
</tr>
<tr>
<td>8.2 WHAT IS SOIL BIOLOGY?</td>
<td>103</td>
</tr>
<tr>
<td>8.2 EFFECTS OF AGRICULTURAL PRACTICES ON SOIL BIOLOGY</td>
<td>107</td>
</tr>
<tr>
<td>8.3 RESEARCH IN SOUTH-WESTERN AUSTRALIA</td>
<td>109</td>
</tr>
<tr>
<td>8.4 ORGANISMS DIRECTLY AFFECTING PLANT GROWTH</td>
<td>110</td>
</tr>
<tr>
<td>8.5 ORGANISMS INDIRECTLY AFFECTING PLANT GROWTH</td>
<td>111</td>
</tr>
<tr>
<td>8.6 RESEARCH DIRECTIONS</td>
<td>112</td>
</tr>
<tr>
<td>9. Acknowledgements</td>
<td>114</td>
</tr>
<tr>
<td>9.1 REFERENCES</td>
<td>114</td>
</tr>
<tr>
<td>10. The farmer perception of soil management - soil and</td>
<td>119</td>
</tr>
<tr>
<td>10.1 THE PURPOSE OF THE WORKSHOP</td>
<td>119</td>
</tr>
<tr>
<td>10.2 THE REASONS WE NEED MORE RESEARCH</td>
<td>119</td>
</tr>
<tr>
<td>10.3 SOME WOOLLY LOGIC</td>
<td>122</td>
</tr>
<tr>
<td>10.4 INTEGRATION OF RESEARCH</td>
<td>124</td>
</tr>
<tr>
<td>10.5 WHAT CHANCE SUCCESS?</td>
<td>125</td>
</tr>
<tr>
<td>11. The integration of soils research - a queensland viewpoint</td>
<td>127</td>
</tr>
<tr>
<td>11.1 INTRODUCTION</td>
<td>127</td>
</tr>
<tr>
<td>11.2 DEFINITION OF INTEGRATION</td>
<td>127</td>
</tr>
<tr>
<td>11.3 ADVANTAGES AND PROBLEMS OF INTEGRATION</td>
<td>129</td>
</tr>
<tr>
<td>11.4 HOW TO INTEGRATE?</td>
<td>130</td>
</tr>
<tr>
<td>11.5 REFERENCES</td>
<td>133</td>
</tr>
</tbody>
</table>
12. Integration of soils research - directions in western australia ................. 134

12. References ..................................................................................................... 138
Introduction

In 1987 the Research Review Committee of the Grains Section of the Western Australian Farmers Federation held a workshop to define soil research direction needed to be followed if sustainable production was to be achieved in the grain producing industries of Western Australia.

The format chosen was for leading farmers and scientists to present review papers at a workshop. The workshop proceeded to review the main problem areas in Western Australia and define research and extension needs. A broad cross section of the farming industry participated.

The review papers prepared by the scientists and the farmer perceptions together represent the first documented attempt to assess the basis for the full range of soil management problems being experienced in Western Australia. In addition they provide a comprehensive review of previous research in each area considered and are an important statement of the current situation. This statement is of considerable importance for farmers, research administrators, scientists and students.

Recognising the on-going importance of the Background Papers the Research Review Committee sought to have them published. The Department of Agriculture agreed to publish the papers and the result is this Technical Report.
1. Soil of the Cereal Growing Areas of Western Australia or the Problems of Extreme Old Age

In a review paper such as this it is not possible to describe in detail the pattern of soils in south-western Australia. Indeed such an attempt would be limited by the realisation of how little is known about the distribution and properties of soils in the region. Instead, this paper will outline the distinctive properties of the soils that affect their management and briefly define some general principles that enable the broad patterns of soils across the landscape to be described.

1.1 Most Soils in the Region are Very Old!

David Bellamy, Earthwatch, assorted greenies, concerned farmers and others are forever telling us that soils are not a renewable resource. Strictly speaking this is not true and soils are, and always have been, renewable. Otherwise most of the land surfaces of the world would be mantled with highly leached and completely infertile soils so that agriculture would be impossible. However, soils are renewed naturally as in the cradles of civilisation in Asia and the Middle East which were all areas of high soil fertility and productive agriculture. In these places Nature regularly renewed the soils as, for example, in the case of the annual additions of mud to soils in the Nile Valley or volcanic ash in Java. In this way, fresh minerals (i.e. ‘natural fertilizers’) are eroded from rocks and added to the soil. Unfortunately, this process of soil renewal operates much more slowly in most parts of the world and often requires periods of geological time for complete renewal. Table 1 lists some of the soil-rejuvenating processes that add fresh minerals to soils together with some major cereal-growing regions where these processes operate.

Table 1. Nature’s soil rejuvenating processes for some cereal-growing regions of the world

<table>
<thead>
<tr>
<th></th>
<th>U.S.A. Canada *</th>
<th>Europe, India, China, Russia</th>
<th>Eastern States*</th>
<th>W.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain building</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Recent Volcanic Phase</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Glaciation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Loess addition</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Climate change</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes**</td>
</tr>
</tbody>
</table>

* In some parts of these regions only.
** Yes, but in the wrong direction.
It is evident from this table that the soils in cereal growing areas of Western Australia will differ considerably from those of Australia’s competitors in the world cereal market since Western Australian soils have mostly not been rejuvenated. Indeed, some of Western Australia’s soils (the laterites) have probably formed during a period of landscape stability extending back more than 50 million years, and in this time little erosion/deposition has occurred. For some of this period much of Western Australia was covered in rainforest vegetation that was growing under a wet, warm climate and so today’s soils should be regarded as fossil tropical soils (palaeosols). Unfortunately, the soils were continuously leached of minerals and clay over this long period, which has made them very sandy, and also they are chemically infertile as they have not received natural additions of minerals to restore fertility. Not surprisingly, soil scientists describe such soils as senile and the region as a nutrient desert so that quite simply many of the difficulties we experience with our soils are the inevitable problems of old age. Ten of these problems are listed in Table 2, and you may notice some affinities with problems of old age that also afflict farmers and soil scientists!

### Table 2. Ten problems of old age - some familiar symptoms?

<table>
<thead>
<tr>
<th></th>
<th>INFERTILITY</th>
<th>Low essential nutrient content (N, P, K, Cu, Zn, Mo, Se, Mn, etc.) due to losses during the great lifetime of the soil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>WATER PROBLEMS</td>
<td>Low available water, erosion, water logging. Very sandy and duplex (sand over clay) soils often do not allow plants to make the best use of rainfall and non-wetting soils are also a major problem.</td>
</tr>
<tr>
<td>3</td>
<td>DENSE</td>
<td>Subsoil compaction due to traffic over some sandy soils, inhibits root penetration reducing crop yields.</td>
</tr>
<tr>
<td>4</td>
<td>CRUSTY</td>
<td>Hardsetting surfaces form because of an absence of organic matter and the accumulation of sodium ions in the soil.</td>
</tr>
<tr>
<td>5</td>
<td>THIN ON TOP</td>
<td>Sandy surfaced soils (which include deep sands and duplex soils) may contain so little clay and organic matter that they are poorly structured and cannot retain plant nutrients or survive poor management.</td>
</tr>
<tr>
<td>6</td>
<td>SUSCEPTIBLE TO DISEASE</td>
<td>Harmful microorganisms flourish and it is difficult to introduce beneficial microorganisms due to poor soil conditions. Worms and other desirable animals do not prosper due to the low inherent fertility.</td>
</tr>
<tr>
<td>7</td>
<td>TROUBLED BY WIND</td>
<td>Wind erosion of light land, due to poor soil structure and consequent damage to crops and farm facilities and loss of fertility.</td>
</tr>
<tr>
<td>8</td>
<td>RECOVER SLOWLY</td>
<td>Structure decline, poor recovery from acidity and chemicals due to loss of minerals and clay by leaching which removes the buffering capacity of the soil.</td>
</tr>
</tbody>
</table>
Many problems that cannot be ignored, including soil structure that is poor and easily destroyed, a salt balance that is easily altered and adverse water relations resulting in waterlogging due to clearing and cultivation.

Management for sustainable agriculture is particularly difficult because of the poor nature of the soil resource and ineffective natural mechanisms for recovery and soil renewal. Mistakes in soil management might not be correctable since the soils are often unforgiving of the abuses of poor management.

Table 2 mentions a variety of problems of soil and water management which will be discussed during the meeting by experts in these fields and need not be repeated here. This paper will restrict itself to identifying those problems that are directly due to the intrinsically poor quality of many of the soils. To do this, it is first necessary to appreciate the unusual nature of the constituents of Western Australian soils and in particular the crystals that make up these soils. Due to the predominance of quartz-rich granitic parent materials in South Western Australia, many of the soils are very sandy. The sand consists of 0.002-2 mm quartz crystals that were liberated from the granites by millions of years of weathering. Because quartz itself is very resistant to weathering, and as other constituents are lost, the soils become progressively more sandy. The clay that was also formed by weathering of the granite (and other rocks) was mostly the mineral kaolinite, but this may have subsequently:

1. dissolved and leached away in solution in drainage water,
2. been leached out of the surface soil horizons as individual clay particles (smaller than 0.002 mm) to accumulate in the lower part of the soil profile to produce texture contrast or duplex soils, or
3. been winnowed out of the near-surface soil materials when they experienced phases of wind and water erosion.

Over the very long period that Western Australian soils have formed, these processes have had a much more severe effect on the form of soil profiles than is seen in younger landscapes where soil horizons are often poorly developed. Not surprisingly, therefore, Western Australia has a much larger proportion of very sandy and duplex soils than occurs in most of the agricultural areas listed in Table 1 where Australia’s competitors are growing cereals.

Even where some clay has been retained in the soil, it consists of materials such as kaolinite and iron oxides that are much less desirable than the constituents of soil clays in regions of the world with a high native soil fertility. In these naturally fertile soils the clay has many physical and chemical properties that enhance soil fertility, structure,
drainage, etc. This point is illustrated in Table 3 by a list of six undesirable properties that are directly due to the particular constituents of Western Australian soils.

Table 3. Why the old soils are mostly infertile - six undesirable properties of the constituents of Western Australian soils

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nutrients have been removed by leaching over many millions of years leaving only the most insoluble minerals that do not contain the nutrient elements required by plants.</td>
</tr>
<tr>
<td>2</td>
<td>Iron oxides fix phosphate. Iron oxides are mostly insoluble in the soil solution and so accumulate in old soils giving them their red and orange colours. Unfortunately, iron oxides consist of very small crystals (about 0.00003 mm) which expose a large surface area to soil solution and absorb much of the P added as fertilizer thereby preventing its use by plants. It is impossible to completely saturate this surface area with P by using high rates of fertilizer since the area is so large. The total surface area of the iron oxide crystals in a hectare of a red Western Australian soil is greater than the land surface of Tasmania (i.e. more than 10,000 km²)! Other nutrients including Mo, Cu, and Zn may also be retained by iron oxides and become poorly available to plants.</td>
</tr>
<tr>
<td>3</td>
<td>Sandy soils do not retain most nutrients. Unfortunately, the sandy Western Australian soils show little capacity to retain water and dissolved nitrogen, potassium and sulfur so that these plant nutrients can be leached beyond the reach of plant roots. This is a particular problem with very sandy soils.</td>
</tr>
<tr>
<td>4</td>
<td>Low organic matter - poor structure. Our soils contain little organic matter because relatively little is produced due to low soil fertility and also because it is rapidly consumed by organisms. Higher levels of organic matter are required to develop optimum soil structure. Consequently, our soils are often poorly structured or structureless, leading to problems with wind and water erosion, seedling emergence, imperfect drainage and root penetration.</td>
</tr>
<tr>
<td>5</td>
<td>High contents of quartz sand, kaolin clay, iron and aluminium oxides result in a low CEC (cation exchange capacity) and AEC (anion exchange capacity). Even when the soils contain some clay and so can retain rainfall for use by plants, there are leaching losses of highly soluble nutrients such as nitrogen, potassium and sulfur. Leaching occurs because the surfaces of the soil constituents do not temporarily adsorb these nutrients to provide a fertility bank that can be drawn on by the plants during the growing season. Soil scientists measure the exchange capacity (CEC and AEC) of soil constituents to provide a measure of nutrient retention. The major constituents of our soils - quartz sand, kaolin clay and iron oxides - all have low to extremely low CEC and AEC values relative to the most fertile soils of the world.</td>
</tr>
</tbody>
</table>
6. High levels of quartz, kaolin and oxides lead to low buffering and a poor ability to inactivate pollutants. Soils exhibit a property known as buffering capacity which is a measure of how well the soil can withstand chemical changes brought about by the additions of acidity (H ions), fertilizers, pollutants and other chemicals. Unfortunately, the quartz, kaolin and iron oxides in many of Western Australia’s soils have a low buffering capacity so that these soils are readily affected by chemical changes. For example, quite small additions of acidity in fertilizers can produce a substantial decrease in soil pH and greatly reduced yields.

To conclude this litany of the problems of West Australian soils and to illustrate the good fortune of farmers in some other cereal-growing regions of the world, Table 4 lists a comparison of properties between a representative Western Australian soil (Merredin earthy sand) and beautiful black clay loam soil from the Darling Downs in southern Queensland which is similar to soils that are used for growing wheat in some regions of the United States of America, Canada, Europe, Russia, India, etc. It is evident from this comparison that Nature has imposed a severe penalty on Western Australian farmers. The Western Australian soil is inferior in every respect, having much less desirable chemical and physical properties than the Queensland soil. Indeed the only characteristic showing a higher score is for percentage sand and, as described above, sandy soils have many adverse properties compared to more clayey soils.

Table 4. Some properties of cereal-growing soils: Nature’s penalty on West Australian farmers

<table>
<thead>
<tr>
<th></th>
<th>1The soil you want</th>
<th>2The soil you have</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay %</td>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>Sand 5%</td>
<td>36</td>
<td>81</td>
</tr>
<tr>
<td>pH</td>
<td>5.4</td>
<td>4.3</td>
</tr>
<tr>
<td>Organic matter %</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Exchange capacity</td>
<td>41</td>
<td>4</td>
</tr>
<tr>
<td>N %</td>
<td>0.28</td>
<td>0.01</td>
</tr>
<tr>
<td>P %</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>K %</td>
<td>0.64</td>
<td>0.16</td>
</tr>
<tr>
<td>S %</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Available water</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Structure</td>
<td>good</td>
<td>none</td>
</tr>
</tbody>
</table>

1Darling Downs Black Earth  2Merredin Earthy Sand
1.2 The Soil Map of South-Western Australia

Little is known of the nature and distribution of soils in the region. Various CSIRO, WADA and University scientists have mapped some regions and at a range of detail. There is an Atlas of Australian Soils covering the entire country, but this was mostly compiled from air photos or from the window of a Land Rover travelling at 70 m.p.h. (The antique imperial unit for speed is deliberately used since this out-of-date mapping was mostly done nearly a quarter of a century ago and there are no current plans to update it. The map inevitably provides only a broad overview of the soil pattern in Western Australia and for some areas is little better than guesswork. At the other extreme there are a few very detailed maps of research stations, nature reserves, catchments, etc. that clearly illustrate the true complexity of the soil pattern at about the scale of a single farm and which demonstrate the need for much more systematic mapping and characterisation of the soils. It would therefore not be an exaggeration to note the appalling ignorance of the distribution and properties of this most vital natural resource - the soils of Western Australia.

Figure 1. Generalised soil map of southwestern Australia adapted from the more detailed soil surveys by Northcote et al. (CSIRO).
A generalised soil map based on the Atlas of Australian Soils and a compilation of maps produced by Northcote and other CSIRO workers is shown in Figure 1 with a corresponding schematic cross-sectional diagram in Figure 2. The following soil-landscape associations have been recognised:

1. **Siliceous and calcareous coastal dunes** - these grossly infertile soils are not used extensively for agriculture. These rather undesirable soils have formed on very sandy materials deposited as dunes and beach ridges and are best left to sun lovers, dugites and real estate salesmen.

2. **Low level laterites and other alluvial soils of the Swan Coastal Plain** - these soils have formed upon sediments deposited by rivers flowing from the Darling Range. They vary in texture from loamy sand to clay and are generally used for pasture. Depending on their age they range from fertile, well-structured loams (young soils) to senile, leached, infertile duplex soils.

3. **Laterites with duricrust** - these are the fully preserved, ancient fossil soils that probably formed millions of years ago under a humid, tropical climate. They occur throughout the agricultural regions but are best developed and preserved in the western agricultural and the forested regions of the Darling Range. The region supports a forest of red gum and jarrah and is mostly used for timber, water harvesting and bauxite mining. The laterite soil profiles are very deep and may consist of 20 or more of porous clay called the pallid and mottled zones passing upward into a surface horizon of duricrust (hardcap or laterite), ironstone gravels and sand. These soils generally occur on gently sloping uplands and are often bounded by small cliffs or breakaways which mark the transition into the next soil-landscape unit - the zone of dissected laterites.

4. **Dissected laterites** - to the east of the dominantly laterite zone is a zone where the majority of soils have formed from rock or laterite pallid and mottled zone materials that have been exposed on valley sides by erosion or truncation of the pre-existing laterite profiles. Consequently, the soil pattern within catchments is complex with quite fertile soils developed on granite and dolerite occurring adjacent to less fertile duplex soils formed from the preweathered pallid and mottled zones. Farmers often refer to this land as wandoo or York gum country. In this zone seasonal waterlogging and soil salinity in valleys are common and are a consequence of rising watertables due to clearing. Salt that had accumulated in the pallid zone under a forest hydrological regime and over many thousands of years is now being brought to the surface by the rising watertable.

5. **Lateritic sandplain** - the rejuvenation of drainage that was responsible for creating the zone of dissected laterites mostly does not extend east of a N-S line passing through Meckering and Katanning. A similar W-E line passes through Katanning with more incised drainage to the south and large areas of upland sandplain to the north interrupted only by broad shallow valleys containing salt lakes. The soils of the upland sandplain are commonly yellow sands and earthy sands which are
underlain by lateritic mottled and pallid zones. These soils support a native shrub vegetation that is easily cleared and the soils are used extensively for cereal growing. The Merredin soil described in Table 4 is an example of this group of soils.

(6) **Calcareaous and saline soils** - the broad, shallow valleys that traverse the lateritic sandplain and in places extend into the region of dissected laterite provide the heaviest textured soils used for cereal growing in Western Australia. The soils immediately adjacent to the salt lake (playa) surfaces are often too saline for cropping but a variety of salt tolerant pasture species may be grown. Further away from the playa lakes and occupying large areas of the valley floors and sides is a variety of heavier textured sodic and/or calcareous soils. They are often referred to as salmon gum and morrel soils, and are particularly productive in years of high rainfall. The high clay content of these soils and their sodic nature means that they are readily damaged by inappropriate cultivation.

(7) **Young soils** - in limited areas the active erosion by western and southern flowing rivers has completely removed the ancient, deeply-weathered soils creating a rejuvenated landscape and young fertile soils. For example, in the Avon Valley at York and Northazn there are well structured, fertile red bars that resemble some of the highly productive soils found elsewhere in Australia. It is no coincidence that many of our oldest towns are located on these soils since they were capable of being farmed in the nineteenth century, employing the traditional European farming methods that were used before the advent of chemical fertilizers. In the early years of settlement of Western Australia it was these naturally rejuvenated soils that helped sustain the infant colony and later fed an army of goldminers.

![Generalised cross-section of southwestern Australia](image)

Figure 2. Generalised cross-section of southwestern Australia. Low level laterites and other alluvial soils occur on the Swan Coastal Plain to the west of the Darling Fault. Gravelly and sandy laterites and other ancient soils occur on the Old
Plateau to the east of the Fault. A variety of soils have developed from mottled, pallid, saprolite and rock zones that have been exposed by erosion. (Note that the vertical scale has been exaggerated and that the exaggeration is greater for the soil horizons than for the landscape relief.)

With the advent of superphosphate, legumes and more recently of trace elements, agricultural development of the ancient highly weathered soils became possible. Farmers in Western Australia currently spend about $0.2 billion a year on chemical fertilizers to remedy nutrient deficiencies that were induced by weathering. It should be recognised that in his use of fertilizers Man has simply taken over from Nature the process of rejuvenation of soils through the addition of fresh minerals.

The above brief description of the major soil-landscape associations of the region is necessarily superficial and interested readers are referred to the several CSIRO, WADA and UWA publications that describe elements of the soil pattern in more detail. Sufficient information has been provided here to enable subsequent speakers to identify their subject matter with one or more of these distinct soil-landscape associations. Farmers should be able to determine where their soils fit into this pattern since it is only by relating soil problems and performance to individual soil types that research into soil management can progress and be extended on a regional basis.

1.2 Concluding Remarks and a few whinges and suggestions

It will be apparent from the above brief summary of the distribution and properties of the soils that very little is known about Western Australian soils and that soils and soil science are not in a healthy state in Western Australia. The soils present mostly have chemical and physical properties that are inferior to those of many of Australia’s competitors in the international market place. In addition, agriculture is carried out under a climate that in some areas is not conducive to the long-term stability of soils so that the prospects of desertification and a loss of sustainable agriculture are real and immediate considerations for some Western Australian farmers. It is vital to know much more about the distribution and properties of the soils, yet the research effort that is devoted to this purpose is small. In the entire history of agriculture in Western Australia it is probable that less money has been spent on soil research than on gambling at the Casino or on the local challenge for the Americas Cup. This lack of soil research is also a form of gambling, but with the future of agriculture as the stake. If the catastrophies due to soil loss that devastated some of the great agricultural civilisations of North Africa are to be avoided, a better understanding of the soils is urgently needed. Farmers and scientists should unite in obtaining a better deal for soil and land management research and extension. In conclusion there are three areas that need to be addressed with urgency:

**Problem 1** - There is no soil map of Western Australia and little current mapping at a scale that is directly useful to farmers or to most research workers. Although the Resource Management Division of the Department of Agriculture is making a fine effort at classifying the land capability of some regions, this can be little more than a reconnaissance and there is a need for detailed soil maps. There is no Western
Australian organisation that is able to undertake such mapping and the associated characterisation of our soils.

**Solution** - CSIRO Division of Soils should re-establish a soil mapping and characterisation unit in Western Australia. Prior to 1970 there was a productive unit that was dismembered for mostly CSIRO-political reasons and the soils experts dispersed to other non-agricultural activities.

**Problem 2** - Most WADA, UWA and other agricultural scientists make little effort to relate results of agronomic, fertility, hydrological, etc. research to the properties and distribution of soils. For example, the characterisation of soils at fertilizer trial sites by WADA and CSBP scientists is usually either non-existent or grossly inadequate. The results of such research are of little value if they cannot be transferred to other locations, and to this end the soils and sites need to be fully characterised.

**Solution** - Some of the blame for this situation must rest with the Soil Science and Plant Nutrition Department at TJWA where many of these scientists received their basic training in Soil Science. Evidently teaching will have to be improved, but other action is also required including such activities as the workshops organised by WADA for staff retraining. A simple, quick but enduring solution would be for the WADA (and other organisations) to employ soil scientists to characterise all sites used for field experiments. In addition, organisations (including producer organisations) should insist that all research plans and proposals, publications and seminars by agronomists, plant nutritionists, microbiologists, etc. should include essential soils information before their submissions can be accepted by funding bodies, journals, conferences, etc.

**Problem 3** - Industry funding bodies (wheat, wool, etc) are reluctant to support areas of soils research that investigate the more fundamental properties of soils, presumably because there is unlikely to be a resultant short-term, clearly identified gain in production or profit. This is a short-sighted view since, as pointed out earlier, many Western Australian soils are quite different from those being researched by scientists in Europe, U.S.A. and even in the eastern states. Consequently, and in marked contrast with most areas of technology, it cannot be assumed that the results and advances made elsewhere can be adopted, or that others will solve our problems. There is no choice but to define and solve our own problems, and the sooner this is recognised the better will be our chance of preserving our agricultural land.

**Solution** - Some research funds generated by Western Australian farmers should be allocated to building up knowledge of the fundamental properties of soils. If the Western Australian farming industry does not support research into the fundamental pedology, chemistry, physics and biology of Western Australian soils, no-one else will!
2. The Farmer Perception of Soil Management - An Eastern Wheatbelt Perspective

The title, “The Farmer Perception of Soil Management - Eastern Wheatbelt Perspective”. For who ever wrote the title, the use of the word “perspective” is very adept. I find measuring, assessing and trying to improve soil management a very subjective process.

When first approached to speak on this subject, my first reaction was “Hell, how am I going to talk for 20 minutes on this”. Then on one or two days of subconscious thought - “Hell, I need all day to talk on this”. Therefore the following presentation is a little abbreviated so as to cover as much as possible.

To start with I will outline the soil types on my farm and factors which affect them.

Soil types: 1. Salmon Gum - gimlet soils or clay loams.
            2. Mallee - or sandy clay loams.
            3. Tainar Tea Tree - or sandy loam.
            4. Wodjil - or acid sandy loam.

Before outlining factors which affect these soil types I should say my prime consideration in soil management is to increase what I call “latent soil fertility”. Whether you are a wool producer, grain producer or horticulturist this is the main objective you strive to achieve. If you have this “latent soil fertility” the extra production that is achieved off a soil type is usually profit.

Common factors which I consider to effect fertility are:

1. Soil structure.
2. Wind and water erosion.
3. Salt encroachment.
4. Plant nutrient availability.
5. Level of disease present in soil.

The listing of soils into four types is a broad generalization. The five factors all apply to these soils but to differing degrees depending upon soil type.
2.1 Salmon Gum/Gimlet or Clay Loams

2.1.1 Soil structure

The controlling factor which affects soil fertility in the Salmon Gum gimlet soils is “Soil Structure”. When the structure is degraded this leads to problems with penetration at the break of season (i.e. poor infiltration, hard to cultivate, becomes too wet or too dry). A very descriptive term for this soil is “Sunday Country” - can only be worked after lunch on Sunday. You then plant a crop, it rains again, you get surface sealing which leads to poor germination. The crop usually suffers moisture stress in the spring because of poor moisture penetration which causes greater losses from evaporation from the top soil. The structure of this soil is the most fragile of the four soil types. It is also the easiest to improve with:

- reduced working;
- gypsum applications;
- using tyne implements instead of ploughs; and
- reducing speed of machines i.e. from 15 km/hr to 10 km/hr.

is critical at time of cultivation. The soil cannot be too wet otherwise pugging occurs or it can’t be too dry otherwise the crumb structure is destroyed making it susceptible to sealing. It becomes a very subjective judgement on what methods can be used to establish a crop. Consideration are weeds to be controlled, the moisture status of soil and impending wet weather or lack of. The prime aim is to establish a crop with the minimum of workings possible in this soil type. So far comments have been cropping oriented. The effect of sheep with their four compactors can not be ignored. During and after rain the effect of sheep running on this type of country can be detrimental. If at all possible I try to run sheep on the soils only when it has some pasture cover or when the ground has dried out a little.

2.1.2 Wind and water erosion

With regard to wind and water erosion this soil type is fairly stable but still needs some protection. I hate to see dust lifting or muddy water running away but there has to be a balance of considerations when establishing a crop. The main consideration is to establish a healthy vigorous crop which can be a little difficult if your seeding or cultivation equipment cannot handle the trash you left to protect the soil from wind and rain. This balance will obviously vary from farm to farm but the main objective should be to have as much protection as possible.

2.1.3 Plant nutrient availability

With Salmon-gum/gimlet soils, adequate phosphorus levels are easily established and maintained with low application rates. Soil tests every 2-3 years are only necessary for
monitoring the level of phosphorus. Nitrogen application is an “opportunity only” situation. If the soil has moisture reserves from summer rains, then nitrogen can be used carefully. Obviously previous cropping and pasture history will influence the nitrogen decision along with the outlook for the season.

Trace elements are not considered to be a problem with these soils so far. The next factor in this soil type is “salt”. You can adopt varied position on this problem depending on the current vogue. I am in the fortunate position of having very little salt affected soil. However I am concerned at what is happening throughout the district with salt encroachment and can see that I will not enjoy my good fortune forever. While constructing banks, drainage lines and planting trees to control water movement through the soil, I see these measures as short term answers only. I cannot see any major way of halting the degradation of soil by salt encroachment. Because the process is slow and insidious it is not given a very high immediate priority by the community, by both farmers and researchers. What the solutions may be, I simply do not know but it worries me greatly.

2.1.4 Build-up of disease

Foliar and root disease seem not to be as great a worry in the Eastern Wheatbelt as in the wetter wheat growing areas. Longer rotations can be maintained without much build up of disease. The only acceptable avenue of control is by rotations i.e. wheat/legume rotation.

A side effect of cultivation fallow for moisture retention is to break the disease cycle but I feel the long term degradation of soil structure makes this option a short term one only. Chemical f allowing is an option but at this stage is expensive relative to tillage. Returns in the eastern wheatbelt simply do not allow chemical treatment of any of these diseases.

2.2 Mallee Soils or Sandy Loams

The structure of these soils is more stable than that of the Salmon-gum soils. Basically the same principles apply to these soils as to clay soils. The cultivation timing is a lot more flexible as the soil will stay in a friable state longer.

2.2.1 Wind and water erosion

These problems become more important in these soils, especially wind erosion. Again the problem of balance between cover and establishing a crop comes into play. One point of clarification I should make is between retention and incorporation. I cannot afford to incorporate trash with cereals because of the short time moisture is available for soil micro-fauna to break down this trash and hence adversely affect the growing crop while being broken down. With retention on the surface, there seems to be positive advantages in the prevention of moisture loss from the surface and the obvious control of wind erosion.
2.2.3 Plant nutrition

Phosphorus applications required in these soils are higher than clay loams. A phosphate “bank” can be built and maintained but it needs closer scrutinizing by way of regular soil testing.

Nitrogen applications produce excellent responses from this soil type. Management of nitrogen is far more important than on clay loams and it is well worthwhile to get it right with both leguminous N as well as bagged N. Trace element monitoring is necessary, though only infrequently. Copper and zinc deficiencies seem to be the ones to watch for. Build up of disease in this soil type seems to be quicker than in clay loams hence a cereal/legume rotation is essential. Whether it is a disease break, the fixation of nitrogen or the translocation of nutrients from depth, the increase yield of cereal crop following a legume gives makes it well worth persevering with legumes.

Salt - the comments made already apply but to a lesser degree here. As you move up the profile of the landscape, salt becomes a lesser problem.

2.3 Tamma Tee Tree or Sands

2.3.1 Soil Structure

There is usually very little structure in these soils hence little to degrade. They are more friable to work than the first two soil types but it can be worked too dry, which predispose to problems with wind erosion. A “catch 22’s situation arises here, a primary cultivation will give an increase in yield of about 10-15%. Again the balance question comes into play.

Over grazing will make this soil very prone to wind erosion. Because it is sloping ground, tunnelling and eddying of wind will make certain parts of the paddock more erosion prone than other parts. Careful management of grazing and cultivation is needed.

Water erosion, because of slopes, can be a problem. Usually working to the contour is all that is necessary to control this problem. In higher risk areas banks are used at strategic points to control run-off.

2.3.2 Plant nutrition

Phosphorus application is heavier on these sands than on the previous two soil types. Soil testing for levels of P is a must on these soils. Nitrogen application is usually higher also. Again the cereal/legume rotation works well on this soil. Trace elements need closer monitoring. Molybdenum as well as copper and zinc need to be watched. Though higher rates of fertilizer are used, this soil will consistently perform in dry as well as wet years. It is what I call “low risk” ground therefore can be invested in with more confidence on a year in - year out basis.
2.4 Wodgil or Acid Sands

The actual physical problem of acid sands can be rectified to some degree with liming. It is however very uneconomic to do so. The only hope I see of these soils being productive is by adapting plant species to grow on them. If it is to be farmed, structure and erosion characteristics are the same as for Tamar sands. You just have to use more inputs and accept less in return. They can be summarized as to be “farmed with caution”.

2.4.1 Other Issues Affecting Soil Management

Economics versus ideals

Seventy per cent of problem of soil degradation of soil management.

If you wanted to do the very best thing for your soil you would walk away from it and not graze or cultivate it. This practice would however, make earning a living a bit hard, so life becomes a compromise. This is where it becomes very subjective and hazy in trying to manage your soil. Degradation problems arise when a detrimental practice is used in the interests of economy

i.e. excess cultivation for weeds; cultivation for retention of moisture;
    high speed work to beat a weather event or to make your capital cost/hectare lower;
    nil retention of trash because machines cannot handle it;
    over grazing of paddocks during summer because of factors beyond control
i.e. falling market prices, shearing problems, etc.

The very act of farming causes degradation. This compromise varies from farm to farm and is necessary to survive. The question I ask here “What level is the best compromise”? The only answer I can give is that it becomes a subjective judgment by an individual when he or she considers every factor I have spoken about so far.

2.5 Summary

In addressing the seminar title “soil management for sustainable agriculture” I will summarize by saying that I try to:

1. understand and recognize soil types;
2. farm soil types individually not as dirt in a paddock;
3. try and consider long term effects of farm practices;
4. be flexible when farming these soil types i.e. cultivate at optimum moisture level, in clays;
5. because they are not immediately achievable do not ignore long term goals in soil management.
In closing I think that we still have a lot to learn about dry land soil management. The fact that we have taken out farming principles from established practices in wetter areas has caused some hang ups in the system. We are still evolving practices for the management of our soil. This evolution should be approached with an open mind.

I find facets of soil science very exact but like many farmers have trouble applying all these concepts in a balanced, practical way. My experience has been gained by trial, observations and error. However, I feel incomplete in my understanding of soil management and look forward to opportunities to learn more.
3. Maintenance and Improvement of Soil Structure

3.1 Summary

Management of soil structure for long-term plant productivity requires consideration of both surface soil and subsoil. The surface forms the critical interface which must be kept open and porous enough to allow the passage of water and air. The subsoil must provide a store of water and nutrients and allow for the development of a large enough root system to maximise their utilisation. Few Western Australian soils have satisfactory structures on this basis, even in the virgin state. Many have been substantially degraded by relatively short periods of agricultural activity. Irrespective of the additional degradation caused by water and wind erosion and secondary salinity it is probable that surface soil structural deterioration will continue on many finer-textured soils if current systems of land management are not modified. The majority of such soils, comprising some 30% of agricultural land in Western Australia, have surfaces which readily slake, disperse and either crust or set massively when dry. In addition most arable soils, particularly those in the sand to loamy sand classes, have some degree of induced compaction at the base of the A horizon. Many Western Australian subsoils have massive structures which drain very poorly, in the case of clays, or excessively in the case of deep sands and earths. Chemical and engineering methods of ameliorating drainage problems are not likely to be economic in the long term, although substantial benefits are found from the judicious use of gypsum as a corrective to aggregation at the surface or within the profile. Effective management systems for optimising water use will need to rely more closely on matching appropriate plant types and associated agronomic practice to specific soil and climatic ecosystems. Stabilisation in many instances may then be maintained by conservation tillage practices.

This paper attempts to identify where gaps in knowledge exist concerning the hydraulic behaviour of these soils. There is, for example, a dearth of research on the grey-yellow duplex soils compared with that relating to the earthy sands and red-duplex soils. The significance of pasture phases and of existing and potential new plant species is assessed. Some suggestions are made for integrated plant soil systems which may optimise long-term soil structural conditions.

3.2 Introduction

It is well recognised that land clearing and intensive cultivation can degrade soil structure (Clarke and Russell 1977; Greenland 1971). However most soils altered through agriculture can provide stable ecosystems which are well adapted to sustaining crop production over many millenia, as in Western Europe or south east Asia. Historically agricultural systems which fail have been located in irrigated river basins or in semi-arid regions (Reifenberg 1955). Failure has normally occurred through excessive
deforestation, salinization, overgrazing and poor soil management. Small oscillations in rainfall have been identified as the trigger to this collapse.

Changes in soil chemical and microbial behaviour which occur as a result of major shifts in management may take between 50 and 100 years to establish new equilibria (Jenkinson and Rayner 1977). Changes topsoil physical and physico-chemical properties are less well documented over such time periods. However, the long-term rotation experiments on the Urrbrae loam (Dr 2.23) (Northcote, 1979) in South Australia have provided a well-characterised site for the wetter Australian cropping environment. The effect of cultivation on the surface structure of that soil has been related to organic matter content and its constituents (Greenland et al., 1962; Emerson 1959), the behaviour of earthworms (Barley 1959), grass roots and fungal hyphae (Tisdall and Oades 1980), raindrop impact (Millington 1959), fallowing (Greacen 1958), and wetting-and-drying (Utomo and Dexter 1981). Some physical changes are almost instantaneous, such as the creation of cracks through tillage, or compaction by wheeling; others, such as the creation and stabilisation of biopores, take years. Most surface alterations are reversible. Some subsoil alterations are to all intents irreversible (eg: clay illuviation). Subsoil alterations resulting from land management changes are seldom documented, although concern about soil compaction has been expressed in western countries for over three decades (Russell, 1945). The poor hydraulic properties of the top of the B horizons of many red brown earths has been the subject of much research in the irrigated areas of the Riverina. In Western Australia documentation on soil structural alterations from agricultural practices has been less intensive. Nevertheless the picture which emerges is clear enough, and parallels the experience from other parts of Australia.

3.3 The Present Structural Condition of Western Australian Agricultural Soils

3.3.1 Surface soils

The nature and extent of surface structural degradation in the wheatbelt of Western Australia was first given by Stoneman twenty five years ago, (Stoneman 1962). He compared cleared and virgin-bush soil conditions (Table 1). Land cleared for an average of 40 years had a reduced organic matter content, macro-porosity and water-stable aggregation compared with soil still under native bush. A similar survey has recently been conducted by Henderson (1986 pers.comm.) in the northern wheatbelt. He found widespread occurrence of surface crusting and subsoil compaction on the massive red and yellow earths of the district, with increased downslope surface-flooding and waterlogging of cleared areas compared with adjacent bushland.

An estimated 30% of the southern agricultural region of Western Australia (Carder and Grasby 1986) is occupied by soil types particularly prone to this type of surface degradation. Such soils have 10% clay at the surface and can be roughly defined in terms of surface texture and colour (red, red-brown and grey), in the textural categories sandy-loanxns to clays. These correspond to Northcote (1979) categories of Um, Ud, Gn, Dr and Db. Current soil classification schemes are frequently inadequate or
anomalous however, for suitable diagnosis to be made by mapping criteria alone. Visual soil and plant symptoms form a better basis for diagnosis (Hainblin 1987).

The key to the vulnerability of these soils lies in their behaviour to wetting and mechanical force. The main effect of the collapse of surface aggregates is to reduce infiltration and redistribution of rain within the profile. Water is lost by evaporation through surface ponding, run-off, and from transient waterlogging and lateral migration from seeps. Surface sealing can restrict crop emergence, and the soil may be untrafficable even after light rain. When dry these soils tend to set hard, requiring high energy tillage systems to break them up for re-cropping. Plant growth from such degraded soils is seriously reduced.

Table 1. Structure measurements on wheatbelt soils. (T.C. Stoneman, 1962)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Condition</th>
<th>Organic carbon %</th>
<th>WSA* %</th>
<th>Bulk density g/cm³</th>
<th>Non capillary porosity cm³/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salmon-gum! 'gimlet' Merredin (loam)</td>
<td>Virgin</td>
<td>1.33</td>
<td>19.64</td>
<td>1.24</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>Cleared 40 years</td>
<td>0.85</td>
<td>18.50</td>
<td>1.68</td>
<td>9.3</td>
</tr>
<tr>
<td>'Tamma' scrub sandplain Merredin (sandy loam)</td>
<td>Virgin</td>
<td>0.85</td>
<td>56.48</td>
<td>0.125</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>Cleared 9 years</td>
<td>1.01</td>
<td>16.47</td>
<td>1.39</td>
<td>21.4</td>
</tr>
<tr>
<td>'Morrel' soil Corrigin (silt loam)</td>
<td>Virgin</td>
<td>2.79</td>
<td>40.40</td>
<td>1.05</td>
<td>18.53</td>
</tr>
<tr>
<td></td>
<td>Cleared 37 years</td>
<td>1.19</td>
<td>11.29</td>
<td>1.38</td>
<td>8.25</td>
</tr>
<tr>
<td>'Jam' soil Yealering (sandy loam)</td>
<td>Virgin</td>
<td>1.51</td>
<td>51.20</td>
<td>1.46</td>
<td>19.76</td>
</tr>
<tr>
<td></td>
<td>Cleared 36 years</td>
<td>0.88</td>
<td>34.29</td>
<td>1.53</td>
<td>19.59</td>
</tr>
<tr>
<td>Salmon-gum soil Quairading (sandy loam)</td>
<td>Virgin</td>
<td>0.88</td>
<td>33.73</td>
<td>1.52</td>
<td>14.39</td>
</tr>
<tr>
<td></td>
<td>Cleared</td>
<td>1.06</td>
<td>15.79</td>
<td>1.67</td>
<td>6.22</td>
</tr>
<tr>
<td>Mallee soil Quairading (sandy loam)</td>
<td>Virgin</td>
<td>1.34</td>
<td>37.66</td>
<td>1.57</td>
<td>9.82</td>
</tr>
<tr>
<td></td>
<td>Cleared 44 years</td>
<td>0.99</td>
<td>15.54</td>
<td>1.78</td>
<td>4.03</td>
</tr>
</tbody>
</table>

*WSA = water stable aggregates.

Note: Salmon-gum, gimlet, tamma, morrel, mallee and jam refer to vegetational types or species associated with particular soil types.
3.3.2 Subsoil Deterioration

In this paper the subsoil is defined as that part of the profile which lies below the depth of normal tillage, seeding and harvesting operations. The lower limit to the rooting zone varies widely with soil type (Hamblin and Tennant 1987), plant species (Hamblin and Hamblin 1985) and season (Tennant 1976). It is important to remember that while roots can only exploit the soil to the depth of wetting in any season, many subsoils have such unfavourable chemical properties that full root development is restricted by excessive alkalinity (pH 8.4) acidity (pH < 4.2) or salinity (Cl- > 50 mmol).

There have been few studies on the effect of clearing and cropping which have considered the subsoil. Some effects can be inferred from changes which have taken place in the top soil. Abbott et al. (1979) showed that macrofaunal populations were substantially reduced by clearing and cropping at three wheatbelt sites, with closely related reductions in soil porosity and increases in soil strength. Such macrofaunal activity is known to increase the number of vertically continuous large pores which open at the soil surface and rapidly conduct water into the profile.

However, the most significant mechanism for transmitting rain deep into the profiles of otherwise massive subsoils is undoubtedly the native vegetation, Nulsen et al. (1986) found convincing evidence of preferred pathway flow in mallee-grove vegetation developed on yellow-duplex soils (Dy 3, Dy 5 soils, according to Northcote) near Newdegate, Western Australia. This rapid infiltration occurred through leaf trap, stem-flow and then to flow down root surfaces from saturation around the bole. Land clearance disrupts this pathway and results in water ponding at the interface of the sand and clay, and reduces rainfall redistribution by 30%.

It is possible that this change to the hydrology of duplex soils has occurred throughout the wheatbelt since clearance of deep-rooted, perennial vegetation. The differences in flow rate which have taken place are two to three orders of magnitude, (Nulsen et al. 1986). Saturated conductivity values of only 10 mm per day are common in the B horizon of cleared yellow-duplex soils (Sudzneyer 1987). In that study only pediments and their slopes had higher values (100 cm per day). Preferred pathway flow has been well documented in jarrah (Eucalyptus marginata, Maiden) forest (Johnston et al. 1983), and the consequence of its disruption on groundwater levels, salinity and drainage are well known (Peck 1978). Although the extent and magnitude of such reduction in subsoil hydraulic conductivity is difficult to establish, the adverse effects of perched water tables on root growth, water use, and secondary salinity are appreciated (Barrett-Lennard 1986, Greenwood et al. 1979).

Dispersion of surface clay can accelerate the process of clay illuviation and may compound the problem of the B horizon impermeability in fine-textured subsoils. The loss of a litter layer which absorbs the raindrop energy and acts as a low pressure head for infiltration also affects subsoil hydrology. Even when the original vegetation and soil association is non-wetting, McGhie (1980) has shown that litter can allow water to percolate into the soil. When the mallet (Eucalyptus astringens, Maiden) vegetation and
litter was removed run-off increased greatly and wetting of the clay subsoil hardly occurred.

Soil compaction resulting from the effects of mechanised traffic and tillage operations was only recently identified in wheatbelt soils of Western Australia (Hamblin and Tennant 1979), although Smith et al. (1969) recognised the phenomenon in a Swan Valley vineyard in 1964. Such traffic pans are now known to be widespread and are present in earthy and sandy soils (Ucl) in particular (Jarvis 1986). Jarvis and Porritt (1985) and Henderson (1985) have demonstrated that such compaction zones can develop after only eight to ten passes of a tractor on newly cleared sands and earths, at Esperance and Northampton respectively. Again it is probable that such pans have been present in many of these soils since the introduction of large scale tillage equipment in the post-war era.

3.3.3 Effects of Structural Decline on Productivity

The implications of the structural degradation for crop production as described by Stoneman (1962) could only be inferred. Since then effects of altering surface soil structure on wheat yield have been very fully studied on the Merredin soil series, (Bettenay and Hingston 1964). Long-term tillage and rotation experiments, allowing, stubble retention and gypsum incorporation have all shown that yield losses can be attributed to deterioration of surface structure and the effect this has on crop water use (Jarvis et al. 1986; Rowland 1985; Hamblin 1984; Tennant 1981). These results are summarised on Table 2. The average yield response from any single ameliorating treatment was 25%. On a larger range of soil types a number of gypsum experiments conducted since 1982 show that poor surface structure is limiting wheat production for a large area of the wheatbelt. The results for 38 crops grown on 17 sites in the eastern wheatbelt show an average yield increase of 0.4 t/ha from a surface application of gypsum (Howell, 1987). As these trials were not all designed as factorial experiments, it is probable that yield ceilings occurred through nutritional constraints in some cases.

Yield responses to loosening of traffic pans have been spectacular on soils of low waterholding capacity where restriction of rooting depth is the major cause of reduced growth and yield loss (Henderson 1985; Jarvis and Porritt 1985). On other soil types the responses to subsoiling (ripping) have been variable with as many negative as positive responses (Jarvis 1986). In some, subsoils of high or low pH have been disturbed, while in others subsoils of high salt content or low calcium saturation may have been brought to the surface, creating even worse surface conditions. These variable results from ‘reconnaissance’ trials should be viewed as a warning to the wholesale adoption of a single management practice across different soil types.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Authors</th>
<th>Ratio of yield improvement</th>
<th>No. of years averaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Direct drilling versus conventional cultivation</td>
<td>Jarvis et al 1986</td>
<td>1.35</td>
<td>10</td>
</tr>
<tr>
<td>a. continuous crop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. 1:1 rotation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Continuous, conventional crop versus 1:4 rotation</td>
<td>Rowland 1985</td>
<td>1.50</td>
<td>10</td>
</tr>
<tr>
<td>3. Stubble retention versus stubble burnt</td>
<td>Tennant et al 1987</td>
<td>1.10</td>
<td>2</td>
</tr>
<tr>
<td>a. at 2 t/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. at 4 t/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. at 8 t/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Fallow versus non-fallow</td>
<td>Tenant 1981</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. mechanical (12 months)</td>
<td></td>
<td>1.26</td>
<td>6</td>
</tr>
<tr>
<td>b. mechanical (10 months)</td>
<td></td>
<td>1.13</td>
<td>6</td>
</tr>
<tr>
<td>c. chemical (6 months)</td>
<td></td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>5. Gypsum versus none on degraded long-cultivated soil</td>
<td>Howell (unpublished)</td>
<td>1.45</td>
<td>3</td>
</tr>
</tbody>
</table>
3.4 Management Strategies for Structural Improvement

3.4.1 Surface soil

(1) Pasture

(a) Duration

An extended, well-managed pasture ley has long been considered the most effective means of improving soil structural stability (Clarke et al. 1967). Recent research policy statements by rural funding agencies and research organisations have endorsed the need for more research to improve pasture production, halt the phenomenon of “pasture decline” and diversify pasture legumes (Wheeler 1986; CSIRO 1985). The older research in Western Australia fully endorsed the need for long pastures. Stoneman (1973) found increases in > 2 mm water-stable aggregates (WSA) for up to 7 years after the initiation of a pasture phase at Merredin (Figure 1), although lesser responses were found on a coarser-textured soil at Wongan Hills. Aylmore and Sills (1982) found hard-setting decreased with years of pasture, using soils from some long-term rotation trials and a combined modulus-of-rupture (MOR) and sodium sensitivity test. Rowland (1985) used such results to argue that an extended pasture phase was necessary on fine-textured soils. Greenland, writing in 1971 before widespread adoption of conservation farming practices, and at the end of a period of higher-than-average rainfall with exceptionally good pasture productivity, concluded much the same. However, the case for long-extended pasture phases has diminished somewhat in the past fifteen years with the better documentation of increases in non-wetting associated with clover-based pastures and its associated acidification.
Figure 3. Changes in Structural Stability in the top 5 cm Merredin Loam

(b) The effect of stock

The effect of stock-trampling which inevitably accompanies the pasture phase has seldom been studied in Australia. Stoneman (1973) found some effect of winter grazing on WSA, but it was small.

Nonetheless stock trampling during wet winter conditions can have serious effects on subsequent surface pore structures and infiltration. Figure 2 shows the effects of sheep trampling on a degraded Merredin sandy clay loam after cultivation, with and without gypsum (Howell 1987). Improved soil stability with gypsum treatment resulted in higher macroporosity and higher infiltration rates measured at a slight tension (2.5 cm) on ungrazed quadrats. This improved stability however, had no effect on surface conditions after grazing at an average 3 DSE/ha during winter and spring, where macroporosity was reduced by 70%. The very low infiltration rates after grazing (10 mm/h) is lower than many rainfall intensities in the region and causes run-off and surface ponding. These data are striking, although too limited as yet to provide an adequate basis for the development of practical options for stock management. Stock management on fine-textured soils in winter requires more research, particularly of the alternatives available which may lessen the rapid deterioration of surface structure by puddling wet soil. The rapid build-up of a significant ‘litter’ layer of dead plant residues under a combined system of zero tillage, chemical azneliorants and dense-rooting pasture species may offer a useful strategy to combat the effects of stock trampling.
(2) Cropping

(a) Direct drilling

The detrimental effects of intensive cultivation methods on soil structure were reviewed for Australian conditions by Loveday (1980) and Hamblin (1987). Both concluded that direct drilling may retard or halt structural degradation relative to more intensive tillage methods but that absolute improvements have seldom been reported. However, it is now apparent that many of the current tillage trials in Australia have been laid out on soils which were already structurally degraded. Under such conditions absolute improvements are most likely to occur only after chemical amelioration, judicious rotation of crop species and careful management of crop residues. Despite that caveat the experiment on the Merredin soil series has provided some of the most convincing evidence for the potential for direct drilling to stabilise fragile soil surfaces. Hamblin (1984) studied the soil surface properties, infiltration behaviour and crop water balance in the 6th year of the experiment. The relevant components of the water balance and soil properties are given in Table 3. The differences in water available at seeding, total water use and infiltration rate were large. Some indication of structural improvement was apparent by the third year in the continuously cropped half of the trial (Hamblin 1982). The differential between the conventional and direct drill treatments has persisted into the tenth consecutive year (see Table 2), and has been monitored by Jarvis (1987) each year. WSA increased from 8% to 28% in the direct drill treatment over the 1981-86 period and remained at about 5% in the cultivated treatment.

Figure 7. Schematic cross-section of typical wheatbelt landscape.
### Table 3. Selected components of the measured water balance, and estimated soil evaporation, from seedling to harvest for a Merredin red-brown earth (Dr 2.33) continuously cropped for 6 years (Hamblin 1984)

<table>
<thead>
<tr>
<th></th>
<th>Conventionally cultivated (3 passes)</th>
<th>Direct-drilled with combine</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available water stored in soil at seeding (mm)</td>
<td>215</td>
<td>303</td>
<td>14</td>
</tr>
<tr>
<td>Ratio of evapotranspiration to pan evaporation (seeding to anthesis)</td>
<td>0.55</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>Ratio of soil evaporation to total evapotranspiration</td>
<td>0.38</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Depth to wetting front (cm) after opening rains</td>
<td>19.7</td>
<td>23.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Time to ponding (s)</td>
<td>735</td>
<td>930</td>
<td>90</td>
</tr>
<tr>
<td>Grain yield in the 6 year (kg ha(^{-1}))</td>
<td>583</td>
<td>1,003</td>
<td>136</td>
</tr>
</tbody>
</table>

LSD = Least significant difference P C 0.05.

(b) **Gypsum**

Problems associated with direct drilling frequently include a yield penalty resulting from slow seedling growth in early years of adoption (Cornish 1985). In the first year after pasture, structurally degraded fine-textured soils with hard-setting surfaces cannot be loosened by such superficial tillage methods. Soil surface amelioration by gypsum incorporation, followed by direct drilling with stubble retention, in rotation with grain and pasture legumes, should be seen as the type of integrated system which will best restore degraded fine-textured soils. Recent testing of the use of surface-applied gypsum at moderate rates (2.5 t/ha) shows that it has widespread application as a precursor to the adoption of conservation tillage farming and improve pasture production. Yield responses obtained so far suggest that the magnitude reflects the initial soil condition rather than soil type. Table 4 demonstrates this point. A higher proportional yield increase occurred when gypsum was applied to the conventionally cultivated soils than to the direct drilled soils, although absolute yields were higher with direct drilling, both with and without gypsum. At 15 of the wheatbelt sites referred to (Howell, 1987) physical and chemical measurements have demonstrated improved porosity and infiltration rates exemplified by those shown in Figure 3 for a hard-setting, grey sandy loam at Lake King. The hard-setting nature has also been reduced in these soils.
Table 4. Wheat grain yields from a set of tillage experiments with and without gypsum: central and eastern wheatbelt, Western Australia (Howell, unpublished)

<table>
<thead>
<tr>
<th>Location</th>
<th>Tillage type</th>
<th>Grain yield (t/ha)</th>
<th>% Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No gypsum</td>
<td>Gypsum at 2.5 t/ha</td>
</tr>
<tr>
<td>Merredin</td>
<td>DD</td>
<td>0.9</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.62</td>
<td>0.79</td>
</tr>
<tr>
<td>Merredin</td>
<td>DD</td>
<td>0.75</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.63</td>
<td>0.75</td>
</tr>
<tr>
<td>Kalannie</td>
<td>DD</td>
<td>0.95</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.86</td>
<td>1.05</td>
</tr>
<tr>
<td>Lake King</td>
<td>DD</td>
<td>0.89</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.66</td>
<td>0.91</td>
</tr>
<tr>
<td>Katanning</td>
<td>DD</td>
<td>2.44</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.30</td>
<td>2.28</td>
</tr>
</tbody>
</table>

n.s. = Not significant (at P 0.05).

DD = Direct drilled, with combine seeder.

C = Conventional (3 pass) cultivation-seeding.

Nevertheless, we consider that routine or repeated applications of gypsum are not viable in the Western Australian wheatbelt soils because current gypsum use is dictated by transport costs and is thus limited to local supply. Such cheap gypsum is a limited and non-renewable resource. In the soils studied so far gypsum is acting by alteration of the electrolyte concentration of the soil solution, not through reducing the exchangeable sodium percentage (Howell, Dellar and Jeffery unpubl.). Once the gypsum leaches below the surface 10 cm the soils are again susceptible to degradation. This may occur within three years following a 5.0 t/ha application. Gypsum resources must therefore be used sparingly, as an initial ameliorant stabilised by subsequent minimum tillage, stubble retention and grazing management regimes.
Figure 5. Changes in porosity and infiltration rate with gypsum application Lake King. (Howell, unpublished)
3.4.2 Stubble retention

Stubbles have a significant role to play in protection of soil surfaces from water as well as wind. The disadvantages of stubbles (increased crop nitrogen requirement, inadequate weed control, increased disease risk and phytotoxic products) all increase as rainfall increases, while the advantages (erosion control, mulching effects, leaf-disease suppression, summer feed value) tend to increase in the more arid environments where their protective effects on soil surfaces are equally needed. The low quantities of stubble produced in drier areas is the main limitation to their effective use. However, the main contribution of stubbles to the water balance of fragile fine-textured soils in these environments has been shown to be through improving infiltration, not through any mulch effect reducing evaporation losses. Tennant et al. (1987) found low quantities of stubble (1-2 t/ha equivalent to 50-70% surface cover) were as effective as 4 and 8 t/ha in increasing infiltration rate (IR) and crop water use over that measured on stubble-burnt soil. Similarly Howell and Porritt (1987 pers. conun.) found that there was no increase in IR above 50% stubble cover on soils already stabilised with gypsum, whereas the adjacent degraded soil had a much lower IR which increased until 100% surface cover was developed (Figure 4).

Figure 6. Infiltration related to percent ground cover (Howell and Porritt unpublished)
3.4.3 Subsoils

Apart from the highly successful deep-ripping of traffic pans on earthy sands which has been demonstrated in recent years, little improvement in the hydraulic or mechanical properties of Western Australian subsoils has been achieved in broad-scale agriculture. Engineering works have been attempted by the use of a variety of contour and interceptor banks, cut into the top of less permeable B horizons. These have had some modest effect upon excess overland flow and interflow (McFarlane et al. 1985). Some reduction in waterlogging has been ascribed to such banks placed at intervals of 60-120 m apart in shallow to medium yellow duplex soils. Subsoil drainage with slotted pipe has been attempted in some locations with physical success but at prohibitive cost.

Even the deep-ripping of earthy sands is not without problems. Ripped soils are initially very loose and may contain clods. Redevelopment of the traffic pan may occur within 3-4 years on multiple-cropped soils (Jarvis 1985).

(3) The plant factor

Vegetation provides a potentially low cost, large scale ameliorant to soil structure problems. For longer term improvement and preservation of soil structure we may need to pay far more attention to the selection of closely adapted and efficient plant types than has been considered necessary in the past. Many of the concepts and principles for such enhanced plant adaptation are already well in place. Tree planting for stock-shelter, wind breaks, amenity value and faunal refuge is already sponsored through several national organisations. The capacity of deep-rooted species which can develop good leaf canopies to extract more subsoil water has been demonstrated as a means of controlling groundwater salinity, and is being accepted. Plant breeding programmes aimed at producing cultivars adapted to hostile soil environments (acidity, Salt, waterlogging) are already in operation. O’Toole and Bland (1988) have reviewed the current world progress on selection of crop root characteristics for water extraction, deep rooting, nutrient uptake and high strength penetration. Sufficient success has already occurred world-wide for this to be a very worthwhile aim of plant research in Western Australia; to identify species and cultivars capable of growing deeper into poorly structured subsoils and thereby re-establishing the necessary biopores for gas, water and cereal-root movement. Other plant aspects which have, in our view, received insufficient research attention with respect to conservation of agricultural soils are:

- the search for deep-rooted perennial pasture and shrub species and
- agroforestry, such as the successful “alley-cropping” form developed at IITA, Nigeria.

The current agricultural systems in Western Australia have developed from a reliance on less than a dozen species, one of which has only recently achieved crop status through domestication. As economic and environmental pressures increase, the benefits of this latest introduction (Lupinus angustifolius) have continued to increase. There is a real need for further research on these lines.
3.4 Conclusion

3.4.1 Summary of Perceived Research Needs

1A. Considerable research on the processes of, and ameliorative techniques for, soil structural modification has been carried out on some soil types in Western Australia, particularly on some Red duplex soils such as red brown earths (Dr 2.23, Dr 2.13 to Dr 2.33) and on the sandy earths and sands (Uc 1.21, Uc 1.41). Little work has been done in comparison, on the podzolic, duplex soils and gravelly soils (Dy 3, Dy 4, Dy 5 groups). In general there has been far less work on the chemistry and hydrology of subsoils than of surface soils. These areas require further work.

1B. Integrated land-use and soil surveys need continued support to provide the necessary data bases for extension purposes.

2. Management of improved soil structure in rotational and mixed cropping farms requires a systems approach based on management of the farm according to soil types. There is a clear role for increased use of advisory and logistic modelling approaches to this need.

3. Vegetational interactions with soil structures are neglected areas of research considering their potential benefits to long-term structural improvement. Plant aspects related to deep rooting ability, specific chemical tolerances and persistence under grazing pressure are seen as important attributes in maintaining or stabilizing soil-ped structures developed from root growth.

3.5 References


4. Management of Water and Salt in the Agricultural Areas of Western Australia

Abstract

Western Australian soils often have infertile sandy topsoils and even less fertile sandy or clayey subsoils. Their low productivity makes them susceptible to degradation from water and salt. Rainfall patterns restrict plant growth during parts of the year, leaving soil surfaces unprotected and increasing recharge.

There are several unique features of Western Australia’s geologic history, landform and soil which makes research from other parts of the world of limited relevance. It is therefore essential that solutions developed elsewhere be tested adequately under local conditions before being recommended. Given the low productivity from Western Australian soils, any solutions to soil degradation must be low cost and extensive.

Water erosion in Western Australia is caused by intense summer storms throughout the State, and by prolonged winter rains in the higher rainfall areas. Much of the soil loss is insidious as gullying is uncommon and sheet and rill erosion are masked by subsequent cultivation. Methods of controlling water erosion are relatively well known but are often not adopted by landholders. There is a need to better quantify soil erodibility and the effects of water erosion on crop yields to aid extension.

Flooding is widespread throughout the State and is often spectacular. Methods of mitigating the problem have long been tried by landholders but their effectiveness has been poorly evaluated and the works are rarely appropriately designed. Without evaluation or design, money will continue to be wasted on inefficient structures.

Waterlogging is being increasingly recognized as a major form of soil degradation in Western Australia but its extent and importance is poorly quantified. Waterlogging interacts in an adverse way with salinity, plant nutrition, disease, water erosion, flooding, soil structure and landslips. The processes that lead to waterlogging in different soil types need better quantification. Other areas that require research are drainage design for clay flats, plant breeding and agronomy.

Soil salinity is caused by a clearing induced perturbation in the landscape hydrology. The cause has been well documented and methods of prevention, rehabilitation and reclamation are available. The most pressing need is for a rapid survey method of identifying hydrologically sensitive areas of the landscape which can then be appropriately treated.

Economic production can be obtained from salt affected soils but there are difficulties in establishing the most beneficial plants.
Water repellent soils cause considerable production losses throughout the State. While the causes of non-wetting are known and treatments have been identified, the current need is to adapt the treatment methods to broadscale agriculture.

Climatic change in Western Australia is predicted to have significant effects on agriculture. In the southern areas of the State temperatures will increase, winter rainfall will decrease and summer rainfall will increase in quantity and intensity. These changes have the potential to further degrade the land resource. Strategies must be implemented which will minimize the deleterious effects of climatic change.

4.1 Introduction

The amount and timing of rainfall are the principal determinants of crop and pasture yields in dryland agricultural areas of Western Australia. They are also the principal determinants of hydrologic forms of soil degradation; water erosion, waterlogging, flooding and salinity. Rainfall also greatly affects other forms of soil degradation (e.g. wind erosion is affected by plant cover and soil moisture, soil structure is affected by raindrop impact and soil moisture). The challenge facing dryland farmers in Western Australian is to maximise water use by plants while minimising soil degradation.

Many of the agricultural soils in Western Australia are formed on truncated parts of the laterite profile which developed during the Tertiary (Stephens 1946). The profile is characterized by being acidic, leached, poorly structured and containing large stores of salt. The leaching has resulted in the principal soil components being iron and aluminium sesquioxides, kaolinitic clay and quartz. The properties of these minerals result in soils with low physical and chemical fertility (Robson and Gilkes 1979). Topsoils are often sandy in nature and almost all soils are prone to hard setting. The lateritic soils (and some of the soils formed on freshly exposed rock) have some features which aid crop and pasture production (e.g. duplex soils maximise water storage), but they also have many features which predispose them to degradation by water and salt.

This paper outlines the extent of degradation attributable to water and salt, and reviews our knowledge of management systems to mitigate degradation. Gaps in our knowledge are identified and priority areas for future research indicated.

4.2 Extent of Degradation

While there may be no obvious benefits in quantifying the extent of land degradation, it is essential. The benefits of quantification are political, social and economic: political to inform the decision-makers of the extent of the problem; social to inform the community (which is largely urban) that there is a real problem which affects their living standards, and economic to ensure the rational allocation of funds to the most pressing problems. A knowledge of the spatial distribution of soil degradation and its change through time can also aid our understanding of soil degradation processes.
Quantifying the extent and economic impact of land degradation is difficult because of the very nature and distribution of the problems. Defining degradation is often difficult. For example, is soil considered to be saline when crops have slightly reduced yields due to salt or only when the soil is bare and salt-encrusted? Is a soil waterlogged when it is saturated for seven days or for three months? It is also common for forms of degradation to interact. For example, waterlogged soils shed rainfall and have low strengths, resulting in serious water erosion. Draining the soil profile (curing the waterlogging) may be the only way of preventing the water erosion.

Bearing in mind the difficulties of both definition and quantification, the following sections summarise our current knowledge of the extent of land degradation due to water and salt.

### 4.2.1 Water erosion

There have been few measurements of soil loss due to water erosion in the agricultural areas of Western Australia. Measurements of rills and gullies after major storms have been made by McFarlane (1984), McFarlane and Ryder (1987) and Bligh (1987). No measurements of sheet erosion (which affects larger areas than do rills and gullies) have been made due to the difficulty in measuring small changes in soil elevation. Measuring sediment concentrations in runoff is expensive. A pilot survey is currently estimating soil losses in nine areas of Western Australia using the isotope, caesium-137 (Richie and McHenry 1975). This method enables soil losses over the past 30 years to be estimated.

While there have been few measurements of soil loss, there have been two surveys of soil conservation needs. The first survey was carried out in the Midlands and Great Southern region in 1958/59 (Marsh 1971). Almost half of the cleared land needed contour working and about 20% needed banks. Half of the natural drainage lines were already eroded.

A second, more comprehensive, survey in 1975 estimated that 66% of the extensive cropping areas of Western Australia required some form of treatment or works to mitigate land degradation (DEHCD 1978). Of the area requiring attention, 72% was affected by water erosion and a further 14% was affected by both wind and water erosion. The construction cost for works alone was estimated to be $48 million with over $5 million required each year for maintenance.

Since the 1975 survey, water erosion will have become more widespread due to an increase in the area cropped each year, particularly in the higher rainfall areas. However the increased use of minimum tillage and the decreased use of fallow will have decreased the problem in the lower rainfall areas. Carder and Humphry (1983) estimated water erosion costs farmers in the less than 600 mm rainfall zone about $10 million each year.
4.2.2 Flooding

There are two types of flooding in agricultural areas. Flood peaks damage crops, fences, roads, railways and buildings. Flood waters can also spread out over low lying areas creating problems such as reduced access to paddocks and the waterlogging of crops and pastures.

There have been few estimates of damage caused by flooding in agricultural areas. However flooding due to summer thunderstorms and cyclonic rains, and to intense winter depressions, is common throughout the agricultural areas.

In February 1978, thunderstorms in the eastern wheatbelt washed away fences, damaged road and railway embankments and flooded parts of Southern Cross and Narembeen (Kratchler 1980). Clearing during the 1960’s was thought to have exacerbated the flooding as previous, worse storms did not have such severe results. Flood protection levees in the Belka Valley, built after flooding in 1963, were washed away by the 1978 flood. The 1978 flood, which produced an estimated flow of 55 m$^3$/sec through the Merredin townsite, was exceeded in February 1979 by a flood with an estimated flow of 105 m$^3$/sec.

Several millions of dollars worth of stock and fencing were lost and over two million dollars damage was done to roads after flooding in the Greatern Southern in January 1982 (Belstead et al. 1984). Several towns were flooded and there was extensive damage to railway embankments.

4.2.3 Water logging

Carder and Humphry (1983) estimated that waterlogging costs farmers in the less than 600 nun rainfall zone about $9 million each year on average. Negus (1983a) estimated that waterlogging during 1974 cost farmers in the Narrogin Shire about $4,300 each while in the Kondinin Shire the cost was over $23,000 each. The wet winter reduced the area sown to wheat in the Narrogin Shire by 27% and reduced the average wheat yield in the Kondindin Shire by 25%. These estimates are likely to be conservative. Salerian and McFarlane (1987a) have shown that average wheat yields in the Narrogin Shire decrease whenever the annual rainfall exceeds 485 mm rainfall, which can be expected to be exceeded every second year on average. Waterlogging will still occur during years with less than 485 nun rainfall but average yields will not decline. A Wheat Industry Research Committee project is developing a method of estimating the physical extent and economic importance of waterlogging in the Great Southern. Methods being assessed include monitoring water levels in representative parts of the landscape, examining crop statistics and the use of remote sensing (airborne and satellite).

4.2.4 Soil salinity

Surveys of the area of previously productive land made unproductive by soil salinity began in 1955 (Table 1). These surveys relied on the farmer’s memory of previous land
conditions and therefore, with time and changes of ownership, the reliability of the surveys has decreased.

**Table 1. Area of previously productive land affected by soil salinity**

<table>
<thead>
<tr>
<th>Year</th>
<th>Area affected (ha)</th>
<th>% of cleared land</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>73,500</td>
<td>0.50</td>
<td>Burvill (1956)</td>
</tr>
<tr>
<td>1962</td>
<td>123,600</td>
<td>0.68</td>
<td>Lightfoot et al. (1964)</td>
</tr>
<tr>
<td>1974</td>
<td>167,300</td>
<td>1.17</td>
<td>Malcolm and Stoneman (1976)</td>
</tr>
<tr>
<td>1979</td>
<td>263,700</td>
<td>1.75</td>
<td>Henschke (1981)</td>
</tr>
</tbody>
</table>

The rate of increase for the entire survey period 1955 to 1979 was 5.5% per annum but for 1974 to 1979 was 9.5%. Using the 1979 base figure, the area of salt-affected land in 1987 is estimated to be between 404,000 and 545,000 ha (or 2.7 to 3.6% of cleared land). If this simple method of extrapolation is continued to the year 2000 then the area affected would be between 800,000 and 1,750,000 ha (or 5.3 to 11.6% of cleared land).

These estimated rates of the spread of salinity may be conservative. Nulsen (1981a) examined the change in salt-affected area on three, 2,080 ha areas in the Wongan-Ballidu Shire between 1958 and 1976. Of the 6,240 ha examined, the salt-affected area increased from 618 ha in 1958 to 1,623 ha in 1976. Recently Henschke (pers. comm.) has detailed the area of saline land on a 139km² catchment east of Perenjori. Between 1980 and 1986 the area of saltland increased from 33 ha to 249 ha.

Using the lower estimate of salt-affected area for 1987, the cost of salinity to the State will be about $160 million lost in land capital (increasing at $8.8 million per year); $12 million lost in on-farm water supplies and an annual production loss of $40 million. These estimates do not include the off-site costs such as loss of potable water resources and increased depreciation of commercial and domestic equipment and appliances. There are also very important flora and fauna losses caused by land and stream salinity.

**4.2.5 Water repellent soils**

Water repellent soils are defined by Houghton and Charman (1986) as “soils which resist wetting when dry”. Surveying the extent of water repellency is difficult due to it being a condition of dry soils and also because it occurs in only a proportion of a given soil type.

The limited information available on the extent of water repellent soils in Western Australia has been reviewed by McGhie (1980a). Sandy soils are the most prone to developing water repellency. McGhie estimated that some 50% of the soils of the Swan Coastal Plain are affected by water repellency. Summers (1987) considered that one million hectares of the south coast sandplain has reduced production due to water
repellency and Blake (pers. comm.) estimated that about 30% of the soils of the West Midlands sandplain exhibit water repellency.

In the wheatbelt, sands, morrel soils and slopes below lateritic residuals supporting mallett (Eucalyptus astringens) exhibit water repellency to some degree. McGhie (1980a) considered the Booraan soil association to contain a high proportion of water repellent soils. This association occupied 20% of a 210,000 ha area surveyed by Bettenay and Hingston (1964). Burvill (1939) classified 20% of a 260,000 survey area around Salmon Gums to be morrel soils which Teakle (1940) described as not readily wettable.

Summers (1987) estimated that the production loss due to water repellency on the south coast sandplain was of the order of $15 per ha. If this figure (which will be conservative for the Swan Coastal Plain) is applied to all the water repellent soils in the agricultural areas then the annual production loss is about $45 million.

### 4.3 Water Erosion

For water erosion to occur, detached soil and runoff are required. The susceptibility of a soil to detachment and to producing runoff is termed its “erodibility”. The prediction and management of water erosion requires an understanding of how management practices affect soil erodibility.

Soil can be detached by raindrop impact, runoff, tillage and stock. Raindrops have a terminal velocity of up to 9 m/s and will result in soil detachment and sealing of the soil surface unless it is protected by vegetation (Hudson 1981). Vegetation also slows runoff and increases the time available for infiltration. Concentrated runoff can result in soil detachment as evidenced by scouring in rills and streambank erosion in watercourses. The importance of tillage in affecting water erosion can be seen when rilling occurs to the depth of cultivation only. Erosion during summer storms is most evident on fallowed paddocks. Marsh (1982) found that sheep detached between 0.3 and 1.0 tonnes of soil per week per head and this soil was available for removal by both water and wind.

Recently it has been recognised that soil is vulnerable to erosion in areas where seepage waters approach the soil surface (Zaslavski and Sinai 1981). In Western Australia, rills and gullies can be initiated at knick points in the landscape (e.g. at bank and drain channels, gully sides) where seepage forces produced by interf low in duplex soils approach the soil surface (McFarlane and Ryder 1987). The problem of rill initiation at drainage channels was one reason for the development of “reverse bank” seepage interceptor drains (Negus 1983b).

There are two, main runoff mechanisms recognized in agricultural areas of Western Australia, rainfall excess and saturation excess. In rainfall excess, the rainfall rate exceeds the infiltration rate of the soil and, when surface storages are exceeded, runoff occurs. This is most likely in areas where rainfall intensities are high. Soils in which rainfall excess is important are surface sealing soils, water repellent soils, soils with
inherently low infiltration capacities (e.g. clay soils, rock outcrops) and surface compacted soils (e.g. stock and vehicle tracks). In studies in the U.S.A., Wischmeier and Smith (1958) found that the rainfall factor which explained most of the variability in soil losses from runoff plots was a combination of rainfall energy and intensity. Their measure of rainfall erosivity has been mapped in Western Australia by McFarlane et al. (1986). Rainfall erosivity is dominant in winter in the western and southern agricultural areas and in summer in the eastern areas.

In saturation excess, the soil surface or profile is saturated and even low intensity rainfall runs off. Soils in which saturation excess is important are duplex soils, flooded or waterlogged clay soils (often in valley bottoms) and groundwater discharge zones (sandplain seeps, hillside seeps and valley salinity areas). Saturated soils have low strengths and are particularly susceptible to detachment by raindrops and runoff.

Marsh (1982) found that the removal of small amounts of topsoil from Western Australian soils resulted in decreased yields in subsequent wheat crops. The reduction in yields could be directly attributed to the removal of organic nitrogen from the soil profile. Yields were most affected when soil was removed from pastures, as organic nitrogen becomes concentrated in the top few millimetres of the soil profile in uncultivated soils. A relationship between soil loss and decrease in crop yield has been determined from these data by Salerian and McFarlane (1987b). The loss of organic matter from the top 2 mm of an uncultivated soil will cause an estimated 5% loss in the yield of a subsequent wheat crop. In some soils, yields will also be affected by a reduction in rooting depth and by a loss in arable area due to gullies.

Design criteria have been developed for most of the commonly used soil conservation structures (Bligh 1986). Salerian and McFarlane (1987b) developed a method of estimating the cost effectiveness of banks used to mitigate water erosion. The method showed that the land lost to production was the most important cost, and methods which limit land loss (e.g. broad based banks which can be cropped over) should be considered, even if this raises the initial cost of bank construction. The method also showed that more information is required on the amount of soil lost under different management systems and on the effect of this loss on short-term and long-term productivity.

A cross-section across a partly dissected landscape is shown in Figure 1 to relate current water management knowledge to different soils. Upland areas often have a gentle undulating topography and contain sandy and gravelly soils. While small areas of lateritic uplands occur throughout the agricultural area, extensive sandplains occur in south coastal areas and in the northern and eastern wheatbelts (Northcote et al., 1967). Steep breakaways often occur at the edges of upland areas and usually contain thin, water-repellent topsoils over clay. Further downslope, soil profiles often become duplex in form (i.e. have a coarse textured topsoil overlying a fine textured subsoil) and land slopes become more gentle. Often granite outcrops occur on these hillslopes and soils immediately below the outcrops are coarse textured. Further downslope, landforms become very flat and the soils are finer in texture. Broad clay flats, often with large areas
of primary salinity, are features of the wheatbelt east of the “Meckering Line” (Mulcahy 1967).

Water erosion can be a problem on the coarse textured, upland soils when intense summer storms occur on bare (overgrazed or allowed) soils. The greatest areas of upland soils are in the eastern and northern wheatbelt, where rainfall erosivities are dominant in summer. The runoff mechanism on the sands is poorly understood but is thought to be due to the small amount of clay in the soils dispersing to form a surface seal which limits infiltration. Water repellent sandplain soils also shed water. Current management of runoff on these soils involves the construction of absorption banks designed to retain the runoff from a storm with a particular return period and spaced to prevent inter-bank rilling (Davies and McFarlane 1986). It is possible that the retention of a vegetative cover on sandplain soils will improve infiltration in these soils, thereby reducing the need for the banks. More research is required on runoff mechanisms. McGhie (1979) has shown that lupins and clovers can increase water repellence, and soils can be made more wettable by cereal cropping, by deep ploughing to bring heavier textured soils to the surface and by cultivating in the rain. Wetting agents have also been developed (McGhie and Tipping 1983). Recent research has shown that level banks have the potential to increase recharge to saline aquifers (McFarlane et al., 1987b), and therefore level and absorption banks should be used only as a last resort. Water spreading techniques (Quilty 1986) are currently being evaluated as a means of safely disposing of runoff in areas where waterways are unstable. More efforts are also needed to improve the stability of waterways (e.g. fencing and the planting of selected grasses).

McGhie (1980) has shown that gullies in the Upper Great Southern can usually be retraced to runoff from steep, water repellent soils on lateritic breakaways (Figure 1). Following clearing, water repellency was reduced, presumably because sheet erosion removed some of the upper, more water repellent layers. However the erosion exposed heavy textured subsoils which continued to shed water. At present the only methods of controlling runoff on these soils are to retain a bush cover on the hills (which increases interception losses and slows runoff) and store runoff in large absorption banks around the hills. Generally the slopes are too steep to maintain stable waterways. In areas where salinity is a problem, pipes through the banks may be required to drain away the stored water to lessen recharge. The pipes drain the banks between storms and result in a more efficient storage.

On the truncated laterite area further downslope from the breakaways (Figure 1), water erosion is common due to runoff from saturated duplex soils, from water repellent sandy soils and from surface sealing soils. To prevent runoff on saturated duplex soils, the soil profile needs to be drained. Infiltration can be improved on water repellent soils by rotations, ripping and wetting agents as outlined above. Grade banks and waterways can be used in this part of the landscape to break up long slope lengths and to carry runoff away at non-erosive velocities. To limit runoff in surface sealing soils, minimum
<table>
<thead>
<tr>
<th>ZONE</th>
<th>LATERITIC UPLANDS AND SANDPLAIN</th>
<th>SOIL MANAGEMENT FOR SUSTAINABLE AGRICULTURE</th>
<th>SOIL MANAGEMENT FOR SUSTAINABLE AGRICULTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAJOR SOIL TYPE</td>
<td>GRAVELLY SANDY LOAM</td>
<td>THIN DUPLEX SOILS</td>
<td>DUPLEX (SANDY LOAM OVER SANDY CLAY)</td>
</tr>
<tr>
<td>MINOR SOIL TYPES</td>
<td>DEEP SANDS</td>
<td></td>
<td>SANDS (SPILLWAYS, GRADATIONAL SOILS)</td>
</tr>
<tr>
<td>HYDROLOGIC PROPERTIES</td>
<td>LOW SOIL WATER RETENTION</td>
<td>REPELLENT WHEN WATER REPELLENT</td>
<td>WATER REPELLENT, LOW SOIL WATER STORAGE CAPACITY</td>
</tr>
<tr>
<td>PROBLEMS</td>
<td>RUNOFF WHEN WATER REPELLENT OR SURFACE CRUSTING A PROBLEM</td>
<td>LOW TO MODERATE SALT STORAGES</td>
<td>SOME WATER REPELLENT, SURFACE CRUSTING</td>
</tr>
<tr>
<td>SOLUTIONS</td>
<td>GROW HIGH WATER USING CROPS AND TREES SOME BANDS REQUIRED ON</td>
<td>ABSORPTION BANKS</td>
<td>GRADE BANKS AND WATERWAYS SEEPAGE INTERCEPTORS</td>
</tr>
<tr>
<td></td>
<td>SANDPLAINS TO REDUCE RUNOFF</td>
<td></td>
<td>HIGH WATER USING CROPS MINIMUM TILLAGE, CONTROLLED STOCKING</td>
</tr>
</tbody>
</table>

**Diagram:**
- Matrices flow recharge
- Grade banks & waterways
- Recharge zone
- Seepage interceptors
- Hillside seep
- Interflow in duplex soils
- V drains
- V drains
- Levees & open drains
- Colerite dyke
- Saline
- Groundwaters
tillage is recommended. Reducing the amount of cultivation improves soil structure and increases infiltration capacities (Bligh 1984). It also decreases the time that soils are bare and cultivated, and therefore susceptible to erosion. Contour working increases surface storages and improves infiltration. However trials carried out over several years have failed to show improved wheat yields as a result of contour working.

Water erosion in the flat valley parts of the landscape (Figure 1) is usually confined to gullied watercourses and surrounding areas. Sheet erosion can be a problem during major flood events, although in summer storms the clay soils are often hard set and not easily detached (unless the areas have been heavily grazed).

4.4 Flooding

The runoff processes important for water erosion in agricultural areas are also important for flooding. Intense summer storms cause damage to crops, fences, roads and buildings somewhere in the wheatbelt each year. In winter, flood runoff takes place after less intense storms fall on wet soils with reduced infiltration capacities. Clearing and cultivation have been shown to decrease the infiltration capacities of soils (Abbott et al. 1979) which will tend to increase flooding.

Flavell (1983) has developed methods of estimating runoff peaks in agricultural areas while Davies and McFarlane (1986) have developed methods of estimating runoff volumes. Level and absorption banks are often used to increase the initial loss from storms to mitigate flooding. When used for flood control, the banks are spaced such that their capacity is sufficient to contain a storm with a particular probability of occurrence. In valleys, single and double levee bank systems are sometimes used to confine and direct flood waters. Only rarely (e.g. Belka Valley) are the systems properly designed.

Soil Conservation Districts often identify flood control in large catchments as a role for their group, as it necessitates co-operation between landholders. Davies et al., (1987) used a runoff routing program to estimate the effect of structures on floods. In a 187km² catchment near Wyalkatchem it was found that one of six tributaries contributed most to the peak flow. Absorption banks on this tributary could reduce flood peaks by 34% but would cost $100,000. Spending a similar amount on the construction of dams in the tributary would reduce the peak flow by only 7%. It was estimated that about $200,000 was needed to reduce flood peaks by more than 50%.

In a study of the effect of levee banks on flood peaks in an 800 km² catchment near Beacon, Davies et al., (1987) found that the reduction in flood plain storage following the construction of the levees would result in a 10% increase in peak flows at the end of the levees. However the increase would rapidly dissipate downstream of the levees. The effect of channel improvements and surface drains on flood peaks in a 380 km² catchment at West Nugadong was also simulated. While the increase in flood peaks was relatively small, the inadequacy of drains across a roadway in the catchment could result in a significant increase in the area affected by the flood waters.
The use of a computer model to simulate the effects of structures on flood peaks and volumes is useful to evaluate the effects of differing types and configurations of structures. However various assumptions are made during the modelling and the accuracy of the predictions needs to be checked against measured flow data wherever possible. It is therefore essential to continue monitoring the few catchments in the agricultural areas that have been instrumented.

4.5 Waterlogging

In Western Australia, a distinction is often made between three waterlogging situations;

(i) Soils with a restrictive layer within the soil profile. These are often duplex soils with low permeability subsoils. Saturation of the plant root zone begins above the restrictive layer and builds upwards in the profile. In extreme events even the soil surface becomes saturated and waterlogging is visible. This type of waterlogging can occur anywhere in the landscape.

(ii) Soils with low infiltration capacities and poor external drainage. Saturation may begin at the soil surface, limiting oxygen entry to the root zone. This type of waterlogging is common on heavy textured soils in flat valleys, which may also be susceptible to flooding.

(iii) Groundwater discharge areas. Here the perennial groundwater system comes close to the soil surface.

Theoretically waterlogging can be considered to be primary (existing before agricultural development) or secondary (resulting from agricultural development). Examples of secondary waterlogging are:

(i) Duplex soils in which vertical drainage through the subsoil has decreased because preferred pathways have closed after clearing and cultivation.

(ii) Heavy textured soils with decreased infiltration capacities due to poor soil structure (e.g. caused by overcultivation or cultivation at too high a water content).

(iii) Increased recharge after clearing resulting in raised groundwater levels.

(iv) Excessive irrigation relative to soil drainage.

Duplex soils are particularly susceptible to waterlogging as their sandy topsoils aid infiltration and limit evaporation while their clayey subsoils hinder drainage. Hillel and Talpaz (1977) showed that sand over clay soils have high water storage efficiencies which makes them good soils in areas with limited rainfall but they are susceptible to waterlogging in wet areas. The water which perches on the clay subsoil flows downhill in sloping areas, accumulating where flow lines converge (e.g. on concave hillslopes) and where soil profiles become thinner or flatter (McFarlane 1985). This flow of water is
called interf low or throughf low and can be cut off by interceptor drains which intersect the clay subsoil (Negus 1983b).

The following features of waterlogging in duplex soils and the performance of interceptor drains are poorly understood.

(i) The depth of the clay subsoil in duplex soils is often very uneven, appearing undulose in some drainage channels. The pedogenesis of the duplex soils, which could explain this distribution, is poorly understood. Possible pedogeneses include the eluviation of the fine soil fraction from the topsoil; deposition of the coarser textured topsoil over the finer textured subsoil; selective removal of the fine fraction from the topsoil by dissolution or winnowing, and enhanced chemical weathering of silicate minerals in the subsoil.

(ii) The distribution of perching in the duplex soils is often spatially very variable. The ability of the subsoil to perch water is apparently variable, possibly due to the presence (or absence) of preferred pathways (e.g. root channels). Changes in perching ability after clearing have been postulated but not measured.

(iii) The distance over which interceptor drains are effective is variable, sometimes extending over larger distances than can be explained by point measurements of soil hydraulic conductivity. Flow systems appear to form in the duplex soils which mimic surface flow systems in form. These systems are constant through time and are probably related to the soil’s pedogenesis.

(iv) Once wet, small amounts of rain can result in large increases in perched watertables. This phenomenon may be due to the capillary fringe above the watertable interacting with the ground surface (Gillham 1984).

Waterlogging on clay flats is often more difficult to mitigate than that on sloping, duplex sites. On the flats it is important to locate the origin of the excess water causing the problem. If it is local water such as in-situ rainfall not infiltrating in-situ, methods of improving internal drainage (e.g. using gypsum or minimum tillage to improve soil structure) or increasing external drainage (e.g. surface drains) are needed. There are a number of different types of surface drains available, but there are few local criteria available (McFarlane et al., 1985). Mole drainage has been found to be ineffective in many Western Australian soils, and tube drains often fail due to iron deposits and bridging. If the problem is surface runoff, interflow or deep groundwater flow, methods of intercepting these flows are required. Often it is difficult to identify the source of the excess waters, particularly when they flow below the ground surface.

Salerian and McFarlane (1987a) developed a method of financially evaluating drains used to reduce waterlogging. Using typical values from the Great Southern, interceptor drains were found to be cost-effective if a waterlogging year coincides with a cropping year within a few years of the drains being installed. The cost-effectiveness of interceptor drains decreases if bulldozers are used to construct the drains rather than...
graders. Using bulldozers costs more, but more importantly, more land is lost from cropping.

It has become increasingly apparent that waterlogging is pivotal to a number of forms of soil degradation. The susceptibility of waterlogged soils to water erosion has already been mentioned. Winter floods commonly occur after rain has saturated soil profiles. Cultivating and stocking waterlogged soils can destroy soil structure in heavy textured soils. Landslips in the higher rainfall areas result from low strength soils following saturation.

There are a number of interactions between waterlogging and salinity. Recharge is thought to be enhanced when perching occurs in duplex soils, producing saturated flow down preferred pathways (Johnston 1986). Waterlogging can also decrease water use by crops and pastures, resulting in increased deep drainage. This can occur on clay flats subject to waterlogging and flooding (McFarlane et al., 1987a) as well as on hillslopes. Iijas (1969) showed that sands with a higher initial water content had a faster rate of capillary rise from a watertable. Waterlogging of valley flats results in both a higher water content in spring and a lower plant cover, both of which encourage capillary rise (Malcolm 1961, Bettenay et al., 1964).

Perhaps the most important interaction between waterlogging and salinity is the decrease in the ability of plants to exclude sodium chloride from their roots under waterlogging conditions (Barrett-Lennard 1986a,b). This feature appears to be present in halophytes (Rozema et al., 1981) as well as in glycophytes (Munns et al., 1983). The presence of even small amounts of salt will affect many plants if the soil profile becomes waterlogged. This interaction explains why controlling waterlogging (e.g. by interceptor drains) can improve crop yields in mildly saline areas (Barrett-Lennard 1986b).

Plants tolerant of waterlogging (e.g. rice) generally contain air passages (called aerenchyma) in their root systems (Jackson and Drew 1984). These passages enable the diffusion of oxygen to the root tip. Without an adequate supply of oxygen, root tips die within one to two days (Barrett-Lennard pers. comm.). At tillering there are no aerenchyma in the seminal roots of cereals, but aerenchyma can form in crown roots after the onset of waterlogging. Aerenchyma have been recorded in sea barley grass (Wordeum marinum) growing under non-waterlogging conditions. As barley (Hordeum vulgare) is relatively salt tolerant but not waterlogging tolerant, there is a possibility of transferring the genes for aerenchyma formation from the barley grass to barley. If successful, this will greatly increase the productivity of saline areas.
4.6 Dryland Salinity

4.6.1 Causes

The basic cause of increased land and stream salinization in Western Australia was defined by Wood (1924). He proposed that the replacement of native vegetation with agricultural species led to increased recharge which mobilised stored salts and increased groundwater levels. When the groundwater levels approached the soil surface, significant quantities of salt were transported into the root zone by capillarity.

Wood's hypothesis has been examined in considerable detail during the last 60 years and found to be sound (Teakle 1937b, Smith 1962, Peck 1978). To test the hypothesis it is necessary to establish that:

(i) There is a store of salt in the soil profile.
(ii) There is increased percolation of water through the soil after clearing.
(iii) The percolating water mobilises the stored salt.
(iv) The percolating water causes watertables to rise.
(v) When the watertable rises to within about 2 m of the soil surface there is an accumulation of salt in the root zone.
(vi) Increased salt concentration in the root zone are detrimental to plant growth.

Salt origin and storage

Only small sections of the agricultural areas of Western Australia have been under the sea during the past 50 million years. The granitic rocks of the Yilgarn Block, from which most of the agricultural soils are derived, contain very little sodium and chloride. Therefore their weathering products are not saline. However the rain falling on the soils contains considerable concentrations of dissolved salts. Rain falling on the west coast contains 13 to 27 mg/L sodium chloride. This results in an annual salt deposition of between 40 and 240 kg/ha/annum. The annual salt deposition at Merredin is about 20 kg/ha and at Narrogin about 65 kg/ha (Teakle 1937a, Hingston 1958, Hingston and Gailitis 1976).

During the Tertiary the native vegetation used most of the water and left the salt in storage. The majority of the salt is stored in the pallid zone clays of the laterite profile. In the Darling Range total salt storages are in the range 50 to 100 kg/m² in 20 to 40 m depth of regolith (Dimmock et al., 1974). In the central wheathelt, storages up to 200 kg/m² are common (Malcolm et al., 1978). Very high storages of 400 to 600 kg/m² occur in some areas along the south coast (Nulsen unpubl. data) which were subject to marine incursion during the Eocene.
Change in water percolation after clearing

Various studies have measured, or estimated, the quantity of water percolating beyond the root zone after clearing. When the forested areas of the Darling Range are cleared, an extra 23 to 65 mm of water escapes beyond the root zone (Peck and Hurle 1973). At Gibson, George (1978) estimated the additional recharge to be 20 to 30 mm and a similar figure was found for a catchment north-east of Newdegate (Nulsen et al., 1986).

Salt mobilization

If the extra water percolating beyond the root zone mobilizes stored salts, then the quantity of salt moving out of a catchment should be greater than the quantity arriving in rainfall.

For a fully cleared catchment (at Gibson) the ratio of the quantity of salt moving out of the catchment to the quantity arriving in rainfall (salt flow:salt fall) was 26 (George 1978); for a 70% cleared catchment (at Williams) the ratio was 21; for a 50% cleared catchment (Hotham River) the ratio was 7.7 while in a fully forested catchment it was 1.6 (Peck and Hurle 1973).

Watertables rises after clearing

Watertables begin to rise soon after clearing. At Bakers Hill, Williamson and Bettenay (1979) observed that the watertables began to rise within one year of clearing and rose at a rate of 0.6 m/year. Peck (1983) reported that for fully cleared sub-catchments in the Collie River catchment, the potentiometric heads increased significantly compared with the forested control catchments. The relative rates of increase were 1.4 m/year in a zone of 1,150 mm/year rainfall and 0.7 m/year in a zone of 800 mm/year rainfall. The rise in a partly cleared catchment was 0.3 m/year.

Shallow watertables and surface salinity

The rise of liquids by capillarity is a well-documented physical phenomenon. The height of capillary rise is dictated by the pore size distribution in the soil profile. The rate at which water is transported by capillary action is proportional to the mean pore radius. In Western Australia, when the saline watertable is within 1 to 2 m of the soil surface, capillary transport is effective in causing salt accumulations within the root zone (Teakle and Burvill 1938, Nulsen 1981b).

Salinity and plant growth

Increased soil salinity has two main effects on plant growth: a toxic effect due to excess ions (principally sodium and chloride in Western Australia) and an osmotic effect which makes it more difficult for the plant to extract water from the soil. Hoffman and Shannon (1986) have reviewed the effects of soil salinity on plant performance. It is important to realise that salinity affects yield at much lower values than visual symptoms indicate.
Although the basic causes of soil salinization in Western Australia have been qualitatively understood since the 1920’s, quantification of the process components was lacking until the mid 1970’s. Since that time several investigations have quantified various components on different catchments throughout the State (Peck et al., 1980, Nulsen and Henschke 1981, Loh et al., 1984, Williamson 1986). These investigations have given insight into the nature and dimension of the recharge process and have defined the aquifer characteristics in terms of degree of confinement, saturated thickness and hydraulic characteristics. The improved understanding has led to the development of groundwater models which enable predictions to be made of the effects of catchment treatments of salinization (Hookey pers. comm.).

A conclusion commonly reached from the various investigations is that all catchments have differing characteristics. For example dolerite dykes have little effect on the location of saline seeps in the sandplain catchments of the eastern wheatbelt (R.J. George pers. comm.) whereas they have a substantial role in hillside seeps in the Great Southern (Engel et al., 1987a).

4.6.2 Treatments

Given the large number of catchments in the agricultural areas with different hydrologic regimes that require treatment, an essential part of the treatment process is the identification of the hydrologically sensitive areas. Traditional hydrological methods can be used but they are expensive and time consuming. Recent advances in the use of geophysics and remote sensing offer an alternative rapid and cost-effective method of surveying catchments. For example Engel et al., (1987b) have used electromagnetic induction techniques to identify and map areas thought to have different forms of recharge (matrix and preferred pathway). Landsat is being evaluated as a means of rapidly mapping saline areas throughout the agricultural areas. These methods require further evaluation.

The basic concepts of treating salt-affected catchments have been outlined by Nulsen (1986). The concept of catchment management to control land salinization involves the control of surface waters, the reduction of recharge and obtaining production from salt-affected areas.

The control of surface and shallow subsurface waters have been detailed previously in this paper. Recharge can be reduced by the judicious use of trees (Greenwood et al. 1985) or, on a broad scale, by changing cropping strategies (Sedgley et al. 1981, Nulsen and Baxter 1982). Trees can also be used to increase discharge and therefore lower groundwater levels on the margin of salt-affected areas (Engel pers. comm., Hookey et al., 1987). Engineering solutions such as tube drainage and aquifer pumping can be effective and economic in some situations (George 1985, George and Nulsen 1985).

Economic production can be obtained from salt-affected land using halophytic shrubs and grasses. Malcolm (1986) has reviewed the experimental data available in Western
Australia. Re reported that some *Atriplex* species were capable of producing enough forage to support 24 dry sheep equivalents (DSE)/ha for two months in late autumn. Although good production can be obtained from halophytic plants, there are often problems in establishing them. The species with the best long term production, *Atriplex amnicola*, is difficult to establish from seed. Selection of different genotypes, development of seeding techniques and better definition of site characteristics are required to improve the establishment of halophytes.

### 4.7 Water Repellent Soils

Water repellency in soils was first described by Schreiner and Shorey (1910) who found that some soils in California could not be wetted and therefore were not suitable for agriculture. In Western Australia the first reference to water repellent soils was by Teakle and Southern (1937) who noted them in the course of a soil survey of a potential market gardening area north of Perth. Water repellency is now recognized as a major cause of poor crop and pasture establishment in many areas of Western Australia. Water repellency is also a significant contributor to various forms of land degradation in the State. Water erosion is enhanced by the runoff generated from water repellent areas; water repellent soils with poor plant cover are prone to water and wind erosion, runoff from water repellent areas can contribute to waterlogging down slope and water ponded below water repellent areas can increase recharge to groundwater and thus exacerbate land salinisation.

#### 4.7.1 Causes

Current knowledge on the causes of water repellency has been reviewed by McGhie (1980a) and DeBano (1981).

Water repellency is essentially caused by a hydrophobic, organic coating on the soil particles. The severity of water repellency is dependent on several factors. The nature of the organic material and the soil texture are the most important factors although fire intensity and soil water content are also important.

There is no relationship between the quantity of organic matter in soils and water repellency. Normally it is desirable to add organic matter to soils to improve soil structure which enhances aeration and infiltration. However, when some types of organic matter are added to coarse textured soils, water repellency is induced. In many sandy soils, this presents severe management problems.

The characterization and identification of naturally occurring water repellent substances has been studied with varying degrees of complexity. The results of these investigations will not be discussed here.

In Western Australia the occurrence and severity of water repellency is plant species dependent. The litter from *E. astringens* induces severe non wetting even in fine textured soils. Similarly organic residues from subterranean clover (*Trifolium*...
*subterraneum*) increase water repellency whereas the organic material from wheat (*Triticum aestivum*) increases soil wettability. McGhie (1980a) found that most dicotyledons and particularly the pasture legumes increased water repellence. Monotyledons generally increased wettability, although perennial veldt grass (*Ehrhata calvcina*), a monocotyledon, induced severe water repellence.

### 4.7.2 Treatments

The aim of most treatment strategies is to induce wettability sufficient to successfully establish plants. Seeds sown into water repellent soils do not get the opportunity to imbibe water to initiate germination. The problem is compounded in coarse textured soils where seed-soil contact is poor. Often in water repellent soils, water will pond in minor depressions and infiltrate. Germination is subsequently patchy.

Treatment of water repellent soils with polar solvents has proven effective at increasing wettability. However the cost of the solvent prohibits its use as a total area spray. Recent work (Crabtree pers. comm.) has shown that spraying solvent in very narrow strips above the seed placement is effective in obtaining plant establishment and is economic.

Other treatment methods, such as the incorporation of cereal derived organic matter, narrow bed formation and cultivation to expose wettable non-surface soils have met with limited success.

It is apparent that water repellent soils severely affect agricultural production and land management in Western Australia. Their importance has not been adequately recognized and research into effective management of them has been limited.

### 4.8 Climatic Change

Everyone is well aware of the impact that different seasonal conditions have on agricultural production. These seasonal variations can be considered as short term changes in climate. However, there is irrefutable evidence that climates change in the longer term and, although there is some dispute about the exact nature of any future climatic change, there is a consensus that the climate will change.

In planning for sustainable agriculture, it is essential that the consequence of future climatic change be considered. The likely consequences of climatic change are particularly pertinent to the management of water and salt in the agricultural areas of Western Australia.

Australia has been subject to large climatic changes in the recent past. For example at Atherton in Queensland some 12,000 years ago, rainfall was only 25% of its present value while between 8,000 and 4,000 years ago it was 175% of its present value (Bowler et al., 1976). These climatic changes occurred when man’s impact on the environment was minimal. Man’s activity since industrialization in the 19th century has the potential to significantly affect climate. It was estimated by Keeling (1978) that the
The concentration of CO$_2$ in the atmosphere in 1860 was 280 parts per million (ppm). Measurements taken at Mauna Loa, Bass Strait and the South Pole have shown that mean CO$_2$ levels have risen from 325 ppm in 1955 to 337 ppm in 1980 and are rising at 1 ppm per year. Thus atmospheric CO$_2$ concentration is predicted to be 680 ppm sometime between 2,030 and 2,080 (Tucker 1981).

The climatic impact of increased atmospheric CO$_2$ concentration can only be estimated from models of global climatic processes. While there is some agreement that these models adequately depict gross global changes, their applicability to specific regions, such as south western Australia, is doubtful. The predicted effect of a doubling of atmospheric CO$_2$ in this State is that mean annual air temperatures will rise by 4°C in the south and 2°C in the north; winter rainfall in the south will decrease by 20% and summer rainfall will increase in quantity and intensity; tropical cyclones are expected to extend 200 to 400 km further south (Pittock and Salinger 1982, Pittock 1983, Emanuel 1987).

The consequences of this predicted climatic change on agricultural production and on the management of water and salt will be significant. Increased CO$_2$ per se is predicted, from experimental data, to increase photosynthetic assimilation rates and thus increase productivity (Kimball 1983). However, most of these experiments were done by temporarily imposing a high CO$_2$ regime on crops grown in the current atmosphere. Recent evidence (Cowan pers. comm.) suggests that plants grown from seed under high CO$_2$ conditions adapt to those conditions by reducing their stomatal index. Consequently they may not have higher assimilation rates with higher CO$_2$ concentrations. A shorter, drier and warmer growing season would be expected to greatly decrease the yield of current crop species used in Western Australia.

The increased intensity of summer rainfall, combined with less vegetative cover, may well result in increased water erosion, increased summer flooding and increased aquifer recharge during summer. The increased summer recharge may be offset by a decrease in winter recharge. The impact of water repellent soils on plant growth will be greater because of reduced wetting during winter and increased runoff during summer.

The above scenario is depressing. It illustrates that there will be severe implications for agriculture and land management in Western Australia when the climate changes. Since the change is now expected as evidenced by the atmospheric CO$_2$ figures, there is an urgent need to examine the likely consequences of change and plan to minimize the disbenefits and maximize the benefits.

4.9 Priority Areas for Research

In all the areas reviewed in this paper there is a need for more information on the physical extent and economic importance of the problem. Caesium-137 shows promise for assessing the extent of erosion during the past 30 years, while remote sensing shows promise for assessing waterlogging and salinity. Priority areas for each individual form of degradation are summarized below:
4.9.1 Water erosion

(i) Understanding and quantifying the erodibility (especially runoff mechanisms) of Western Australian soils.

(ii) Quantifying the effect of plant cover (types and amounts) on runoff and soil loss.

(iii) Better quantification of the effect of soil loss on productivity.

(iv) Water erosion and flood control methods in areas where waterways cannot yet be safely maintained.

4.9.2 Floodina

(i) The design and placement of structures in catchments to mitigate flood peaks.

(ii) The design of structures to drain away waters ponded on clay flats.

4.9.3 Waterlogging

(i) Understanding and quantifying waterlogging processes in Western Australian soils.

(ii) The effect of waterlogging (intensity and duration) on crop and pasture productivity.

(iii) Plant breeding for waterlogging tolerance.

(iv) Better quantification and understanding of the interactions between waterlogging and salinity, nutrition and disease.

4.9.4 Salinity

(i) Definition of regional landscapes within which catchments have similar hydrologic regimes.

(ii) Development of remote methods for identifying hydrologically sensitive areas in catchments.

(iii) Quantification of the water use characteristics of trees, shrubs, crops and pastures with respect to their impact on recharge reduction and discharge enhancement.

(iv) Development of techniques to guarantee the establishment of halophytic shrubs and pastures.
4.9.5 Water repellent soils

(i) Delineate the extent of water repellent soils which cause production losses and associated land degradation.

(ii) Determine effective economic methods of ensuring plant establishment on water repellent soils.

4.9.6 Climatic change

(i) Assess the consequences of climatic change on agricultural production and management of soil and water resources.

(ii) Develop strategies to optimize the consequences of climatic change.

4.10 References


Burvill, G.H. (1939). The soils of the Salmon Gums district, Western Australia. (Draft report held in the Western Australian Department of Agriculture).


Engel, R., McFarlane, D.J. and Street, G.J. (1987b). Using geophysics to define recharge and discharge areas associated with secondary salinity in south-western Australia. Symposium on Groundwater Recharge, Mandurah, Western Australia.


Hingston, F.J. (1958). The major ions in Western Australian rainwaters. CSIRO Division of Soils Report 1/58.


5. The Farmer Perception of Soil Management - the Development of New Land Farms

What I would like to do in this talk is to begin with two background points which I believe are important when farm development is being considered, then move on to my own particular experiences relative to soil management and its problems. I will conclude the paper with two recommendations which will be preceded by a consideration of three other pertinent factors.

The first background point addresses the question - “When does new land become old land?”. I suggest the concept of ‘new’ and ‘old’ land be dropped; for two reasons: firstly most of Western Australian land is extremely old - the soil on my farm is probably derived from rock which may be 3,000 million years old; has never been under the sea, and has not been affected by glacial or tectonic activity. The second reason is that the age of the land is the major contributing factor towards Western Australian soils having the following characteristics: extremely fragile, highly deficient in nutrients, contains large quantities of salt in the profile and is highly abrasive on cultivation points or discs. For these reasons I believe the best way to describe the land in relation to clearing is to refer to it as being cleared for five years or less; twenty years or more, or if necessary in between.

The other relevant background point is that during the last 20/30 years land release and development for agriculture in Western Australia has been dramatic. Commencing in the 1960s the State Government had a policy of releasing one million acres (400,000 ha) of Crown Land annually for agriculture; much of which was very lightly timbered making the initial clearing operation very easy. During the early period some of this C.P. land was not keenly sought after, although in later years intense competition was prevalent. Much research was devoted to discovering nutrient deficiencies, illustrating effective techniques and developing satisfactory machinery for the task. Successful applicants also had access to a wider range of finance - e.g. C.D.B. Probably all these factors have contributed to the fact that in my area only approximately 5% of allocated farm land remains uncleared. The overall result is that generally speaking three generations of development has been compressed into one. This is a significant change to pre-war agriculture in Western Australia: the first generation began clearing - existing with only meagre improvements; the second generation continued or completed the clearing - concentrating mainly on the provision of adequate improvements, with the third generation expanding or consolidating, frittering the asset away or coping with emerging problems.

Although initially very different I believe land cleared for agriculture in Western Australia soon develops essentially the same problems relative to soil management as land which has been cleared much longer. Some special features of land cleared five years or less in my district are: most clearing was done ‘on the square’ which meant that early cultivations and root raking were carried out in ‘lands’ or strips during late summer or autumn to avoid bogging at seeding time; root diseases and weeds were virtually
unknown; high fertilizer rates, especially phosphorus were essential and clover establishment was very easy - literally 'just throw it in the air'. Problems associated with soil management which have become evident during the last 15/20 years include: wind erosion - especially in particular areas or spots; salt encroachment due to secondary salinity; compaction where sandy top soils are more than 30 cm deep; surface sealing due to non-wetting sands or hard setting clays; weed infestation - some deliberately introduced e.g. rye grass, and plant diseases - particularly cereal root diseases. On my own farm which has been continually cropped to cereals and soil tested for the last four years, three significant changes have occurred: phosphorus and organic carbon levels have risen dramatically, even though phosphorus application rates have been low, while soil pH has declined. These changes would appear to emphasize the need for continual soil monitoring especially when farm practices are altered.

An overview of land development for agriculture with its associated soil-management problems; as I consider this paper to be, must also be conscious of three other pertinent factors - the first two of which involve the community at large. There is a rising level of interest in different aspects of conservation in Australia: this was quite apparent at the recent Federal elections. Also, from some sections of government, industry and landusers there has been a positive response to this rising level of interest. The third significant factor is related directly to the soil. I believe there is a need to be acutely aware of the fact that the Department of Agriculture has estimated that 70% of the land cleared for agriculture in Western Australia must be regarded as unstable. The land ethic of previous times based on development and increasing production in the short term, I believe has caused this instability, and therefore is no longer appropriate. A long term ethic, based on matching land use to land capability, which maintains or improves soil fertility is what is needed. However such an ethic would have to be accepted by the general community and land users as well.

Before stating my two recommendations for this conference I would like to make my position clear: I am not advocating a reduction in the level of funds for soil research, because if new attitudes to the soil are developed and accepted by the wider community, increased funding would be necessary and I believe could be anticipated. My recommendations therefore are:

1. research aimed solely at what to do to the soil is not enough;

2. some research needs to be devoted to ascertaining how best~ to have a more suitable land ethic incorporated into the rising level of environmental interest which is evident in the community as a whole.
6. Wind Erosion and Soil Fertility

Summary

Wind erosion is a major form of land degradation in Western Australia. Estimates vary in time as to the actual extent of land affected by wind erosion: they do not vary greatly as to the extent of land susceptible to wind erosion. Most, if not all, of the agricultural area of Western Australia is recognized as being prone to wind erosion.

This paper reviews the current state of knowledge on wind erosion processes, the soil, landscape and climatic factors of the Western Australian environment that affect wind erosion, the effect of wind erosion on soil fertility and productivity, and the available information on farming practices required to prevent or control wind erosion.

Continued research into wind erosion processes is considered as unlikely to rapidly advance knowledge of erosion prevention methods. Survey information is badly needed on the distribution and properties of soils in the agricultural area. With the exception of a survey of the Merredin area, no large scale soil survey data exist for the agricultural area of the State. Similarly there is a dearth of general climatic data, particularly wind erosivity data. Both needs are recognized as long term, low return ventures which are nevertheless essential for the use of land according to its capability. Erosion - productivity research is needed to identify the short and long term costs of wind erosion. The requirements of farming practices to prevent wind erosion in cereal:lupin rotations are shown to be well established, but similar knowledge for other crops and, in particular, pastures is inadequate or non-existent. The application of current wind erosion knowledge and technology to develop stable farming systems, especially for areas prone to such erosion, is identified as the major research priority.

6.1 Introduction

Wind erosion can have serious effects on the productivity of soils, and if allowed to continue, will transform fertile soils into sandy deserts. Substantial portions of Central Asia, the Middle East and North Africa are stark testimony of this potentiality. Wind is capable of this transformation through its ability to lift and remove the fertile portions of surface soil, thereby reducing both the fertility and the depth of the original soil.

Wind erosion occurs when equilibrium conditions between soil, vegetation and climate are disturbed. It is accelerated by processes that deplete vegetative cover and cause the breakdown of soil structure, and impeded by practices that retain cover and improve structure. Land use practices and the vagaries of weather thus combine to affect the occurrence and severity of wind erosion.

In the South-West Land Division of Western Australia, approximately 16 M hectares of land are used for grazing and extensive cropping (Carder, 1978). Much of this land has
been developed in only the past 30 years, and the extension of farming into the newer eastern and drier areas has not been conducive to their long term stability and productivity (Robertson, 1983). Indeed, even on the longer established agricultural land some farming practices have been shown to induce land degradation.

Given the appropriate climatic and soil conditions wind erosion can affect virtually all of the agricultural land in the South West Land Division of Western Australia (Carder and Humphrey, 1983). These authors indicated that nearly one quarter of the agricultural land required immediate treatment to combat wind erosion and that a further 40% required additional measures to prevent both wind and water erosion. Another report (Robertson unpubl.) showed that in 1986 0.5 M ha of land was actually affected by wind erosion and a further 10 H ha was susceptible.

Even though wind erosion is known to be widespread in Western Australia (Marsh, 1985), there is little documented evidence of its occurrence, severity and cost. Opportunistic surveys of wind erosion in the Jerramungup area (Carter and Houghton, 1981 and Goddard et al1982) showed that even in the year of its occurrence the cost of wind erosion damage can be substantial. This information showed that wind erosion affected approximately 44,000 ha and 64,000 ha in 1980 and 1981 respectively, and cost estimates of the immediate damage amounted to an average of about $18,000 per farm. Overall the total loss to the district was $1.5 million. Subsequent surveys on the long term effects of this erosion on productivity have not been done.

To design suitable methods for wind erosion control, knowledge is needed of the conditions that influence its occurrence and their relative significance. This paper reviews the knowledge of wind erosion processes and their effects on soil, in the context of the Western Australian agricultural area, and identifies research areas and approaches that may be effective in developing measures to prevent wind erosion in the future.

6.2 Wind Erosion Processes

The physics of wind flow and its interaction with surface soil particles to produce erosion have been well understood for upwards of thirty to forty years (e.g. Brunt 1944, Bagnold 1936, Chepil and Milne 1941, Chepil 1959, 1961).

As wind passes over land, or any surface, frictional forces operating close to that surface cause the velocity near it to rapidly decrease. In fact, for a very small distance, k, above the surface the velocity of wind is in fact zero (Brunt, 1944). The actual height above the ground at which wind speed is zero depends upon the roughness of the surface or its cover, and their resistance to wind and soil particle flow (i.e. the flexibility of vegetation or the abrasion resistance of soil clods or other inflexible objects). This height is called the aerodynamic surface (Chepil and Woodruff, 1963). Large, wind resistant clods, rocks, grass, stubble, shrubs and trees covering a soil surface all progressively raise the height above the ground at which the wind velocity is effectively zero (Geiger 1957, Chepil and Woodruff 1963).
The velocity of wind decreases exponentially from that of the bulk air mass as the point of measurement approaches the ground surface. On a bare, smooth surface of the most erodible size soil particles erosion is initiated by a wind velocity at 1 cm height of 0.15 m/s (0.5 kph) (Chepil and Woodruff 1963). This translates with height to a velocity of 4.5 m/s (16 kph) at 0.3 m and 8 m/s (29 kph) at 2.0 m.

Once wind erosion commences, the soil particles lifted into the air effectively reduce the wind velocity close to the ground (Bagnold 1943). This does not cause the erosion to slow and stop, however, because the energy of particles carried by the wind is expended in dislodging others as they return to the surface. The velocity at which a soil-carrying-wind is just capable of sustaining erosion is called the impact threshold velocity and is related to the equivalent diameter and relative density of the particles dislodged and carried by the wind (Chepil and Woodruff, 1963).

On bare soil surfaces, the nature and state of the surface soil affect its susceptibility to wind erosion. With soils that are not resistant to the wind, the rougher the surface the lower the velocity required to initiate erosion (Chepil and Woodruff 1963). On the other hand, where roughness elements are resistant to the wind, the rate of increase in wind speed with height (or the surface drag) is lesser, being dissipated on these elements, and the required velocity to initiate erosion is dramatically increased.

Once wind erosion begins the soil being moved undergoes a sorting process. This sorting relates approximately to the diameter of the soil particles, which, in turn, determine the mechanism by which they are moved and the distance they are moved. Wind erosion initiation begins with the movement of particles that are of sufficient size and density to be lifted and carried only a short distance. They effectively hop, and on impact dislodge other particles of soil. This hopping mechanism is called saltation and it moves particles in the size range of 0.1-0.5 mm (Bagnold 1941, Willetts 1983). These are essentially fine sand particles. Particles dislodged or abraded by the impact of saltating particles are of both smaller and larger size. The smaller particles of 0.1 mm (mostly 0.05 mm i.e. silt and aggregated clay particles) are light enough to be easily carried by the wind (Greeley and Iverson 1985) once they are lifted into the airflow. In fact they can rise several kilometres in height and be carried indefinitely (Gillette et al. 1973). This mechanism is called suspension and is recognized by the presence of dust in the air. The effect of impacting saltating particles on larger particles (> Q~ mm - i.e. coarse sand) causes them to roll along the surface, and this is called surface creep.

Thus, it is the different mobility of the various soil particles sizes that causes them to be sorted by wind. This sorting produces different depositional products. Creep produces lag sands, saltation dunes, and suspension deposits of dust or loess.

The amount of soil material moved by each mechanism depends, of course, on the soil and wind conditions. In general, saltation will move between 50-75 per cent by weight, surface creep, 5-25 per cent and suspension 3-40 per cent of all soil moved (Chepil and Woodruff 1963). Of these, suspension loss is the most significant. Its removal from the erosion site varies in distance from a few to thousands of kibometres (Gillett et al. 1973).
More importantly, particles of this size represent the surface active component of the soil which stores plant nutrients and, in combination with larger particles, increases the water holding capacity of the soil. Such a loss thus leaves behind a less fertile, more drought-prone and thus inherently more wind erosion prone soil.

6.3 Factors Affecting Wind Erosion

Of the factors affecting wind erosion some are influenced by land use, others are not. The environmental factors of climate, soil type and topography predetermine the susceptibility of a landscape to erosion, and can, at best, be only understood and appreciated. It is the condition of the land surface which determines whether or not wind erosion actually occurs, and this is totally influenced by the way in which the land is used. Ideally, such use should be tailored by a knowledge of the environment and the susceptibility of the soil to wind erosion.

6.4 Soil factors

The factors which influence the size and stability of soil aggregates directly affect its susceptibility to erode. These are the texture, structure stability, organic matter content, soil micro-organisms, salts and colloids. Of these man’s use of the soil affects the structure, organic matter content, soil micro-organisms, water content and, less directly, the salt content. For most soils their wind erosion susceptibility is increased by those actions of man which reduce soil clod/aggregate size, organic matter content and water content (i.e. ploughing, cultivating and grazing). However, for some soils with colloids that are not highly expansive, improved structure and organic matter may make them more susceptible to wind erosion. High salt contents have the same effect, through electrolyte induced flocculation, which explains the wind erosion common on fine textured saline flats.

By far the major factor affecting the wind erosion susceptibility of soil is its texture. This cannot be influenced, and it also directly affects capacity to hold moisture. The coarser textured soils are generally an order of magnitude more susceptible to erosion than other more uniformly graded or fine textured soils (Chepil and Woodruff 1963) (Table 1). (Note the surface texture of most Western Australian soils is sand or loamy sand.) Coarse textured soils also hold less water and drain and dry more rapidly than finer textured soils, making them more frequently susceptible to wind action.

Increasing water content, through its cohesive effect on soil particles, reduces wind erosion susceptibility (Chepil and Woodruff 1963). In fact, relatively little water is required to prevent wind erosion. Chepil (1956) showed surface soils with 15 atmosphere (or permanent wilting point) moisture content failed to erode.
Table 1. Texture, structure and wind erodibility of dry soils(1)

<table>
<thead>
<tr>
<th>Texture</th>
<th>Structure (%)</th>
<th>Soil eroded (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(% water stable aggregates)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(&gt; 0.8 mm = &lt; 0.02 mm diam.)</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>6.5</td>
<td>123</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>6.8</td>
<td>73</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>13.0</td>
<td>13</td>
</tr>
<tr>
<td>Silty clay</td>
<td>14.7</td>
<td>8</td>
</tr>
<tr>
<td>Clay</td>
<td>12.7</td>
<td>16</td>
</tr>
<tr>
<td>Clay loam</td>
<td>18.5</td>
<td>4</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>19.6</td>
<td>3</td>
</tr>
<tr>
<td>Silty loam</td>
<td>20.8</td>
<td>5</td>
</tr>
</tbody>
</table>

(1) Data from Chepil and Woodruff (1963)

6.5 Landscape factors

Soils of the Western Australian landscape have been surveyed in a very uneven fashion. Most surveys have been conducted along the coastal strip between Esperance and Geraldton, and have generally not extended any further inland than 100 km. In consequence, detailed knowledge of soils in the agricultural area is generally unavailable. However, it is clear, in general, that the landscape and soils in Western Australia are highly susceptible to wind erosion. The landscape is flat and there is a predominance of soils with sandy-textured surfaces. Furthermore most have a high proportion of particles in the highly erodible 0.1 to 0.5 mm size range, with small proportions of silt and clay particles (0.02-0.05 mm) which are the least wind erodible.

Despite the assessment of the generally high wind erodibility of Western Australian soils, it has become obvious from recent large scale surveys on the South Coast (e.g. Huller and Moore (unpubl.), Muller et al., (unpubl.)) that there are wide local differences in the susceptibility to wind erosion of soils which, on the surface, have the same sandy texture. On the Esperance sandplain these differences arise from profile differences in clay content, gravel layers and organic matter content. For example, substantial differences in the agricultural capability/productivity have been found to be dependent on the depth of sand over clay and/or gravel, in favour of those with shallower depths to clay and gravel (Muller and Moore unpubl. data). This assessment rebates to the water holding capacities of the soils which vary directly with the depth to clay or gravel layers. Waterholding capacity affects the bulk and persistence of crops or pastures that soils are able to sustain and hence the length of time during the year when the vegetative cover is adequate to prevent wind erosion. Also affected is the amount of organic matter in the soil, which is a supplement to clay for storing plant nutrients and holding moisture.
The variability in the profiles of such soils probably represents the result of earlier wind erosion events (Chepil and Woodruff 1963) and highlights the need for detailed soil survey data. Such data enable the landuser to identify the deeper, sandier ‘hot spots’ and employ farming practices consistent with their capability. This will generally mean fencing them off. If left without special management, they will endanger surrounding crops and less susceptible soils.

6.6 Climatic factors

Extended periods of low precipitation, high temperature and high wind velocity often contribute to the severity of wind erosion (Chepil and Woodruff, 1963). Such conditions occur annually in Western Australia between the months of November and May. However, wind erosion becomes progressively more severe as the sequence of dry years continues (Chepil and Woodruff 1963).

Analyses in the United States of wind velocity at 10 m, indexed for evaporative conditions (i.e. soil dryness) and expressed as 3-year running averages have produced an intensity-frequency relationship of the major climatic conditions that influence wind erosion (Chepil et al., 1962) (Figure 1). This analysis identified those years in which erosion was most severe and thus demonstrated a successful method of characterizing the climatic factors involved in wind erosion.
In Western Australia, climatic data of wind velocity and direction, rainfall, temperature and evaporative conditions is very sparse. In recognition of this fact and of differing regional occurrences of wind erosion, the Western Australian Department of Agriculture set up weather stations at Newdegate, Badgingarra, Merredin and Jerramungup to collect climatic data and characterize regional differences in wind erosivity. An idea of the length of the data collection period necessary to provide a satisfactory analysis is illustrated in the United States data (3 year running averages over 30 years). The Western Australian stations so far have a life of only 5 years or less, and analyses of these data have only just begun. These will be completed in the near future and will provide a guide as to the detail of data collection necessary and the length of record required to adequately characterize each site.

Such weather stations can only provide a knowledge of the severity and seasonality of erosive winds at their various localities in the agricultural area of Western Australia. They will not be able to predict actual wind erosion events in advance because the timing of specific climatic conditions cannot be predicted.

Figure 8. Frequency analysis of erosive wind conditions from data (1920-1960) at Branch Agricultural Experiment Station, Kansas. The most severe wind erosion events in Kansas occurred in the 1930’s and 1950’s. (From Chepib and Woodruff, 1963).
6.7 Consequences of Erosion

6.7.1 Soil fertility

General concern that substantial wind erosion events have deleterious effects on soil fertility has led several Western Australian workers to opportunistically try to assess nutrient loss from soils after wind erosion events. The barge wind erosion caused by cyclone Alby in 1978 produced a number of such data sets. However, the lack of rigour of too few replications and the inability to precisely sample the same site before and after the storm has made clear-cut conclusions from these studies impossible to draw (Bowden unpubl. data). As well, detailed soil descriptions were lacking, making even hypotheses of expected results difficult to formulate (i.e. detailed descriptions of profile distributions of particle size and nutrients would provide insight as to the likely consequences of selective or general soil removal from the surface). Despite these inadequacies the data do provide prima facie evidence of substantial loss of nutrients, as would be expected.

Of course much of the significance of soil movement during wind erosion depends on the net movement of nutrients out of any particular site. Western Australian soils, particularly the sandy, highly wind erodible soils, are inherently low in the plant macronutrients N, P and K and micronutrients Cu, Mo, Zn, Co, Mn, and applications of these are generally necessary for reasonable pasture and crop production. Many studies have been undertaken to ascertain the fate and effectiveness of nutrient applications to these soils. Evidence exists that on all but the coarser, less clayey sands, most applied phosphorus remains in the surface layers and only small amounts move down the profile to layers of greater adsorptive power. This movement is generally slow, however, and is peculiar to the more soluble superphosphate form (Bobland 1985, 1987 et al., 1987 Yeates unpubl.). Potassium is a highly mobile nutrient and its profile distribution tends to be uniform (and low) unless recently applied or held by surface organic matter (Yeates unpubbl.). The micronutrients Mo, Mn, Cu, Zn and Co are generally immobile in soils, even sandy soils of low clay content (Riley et al. unpubl., Brennan and Riley unpubl.).

The role of nitrogen and its distribution in sandy soils is less well understood and few data are available on it. Marsh (unpubl.) has shown substantial concentration of nitrogen in the surface layers of a pasture soil.

In general, agricultural practice produces, even on very sandy soils, nutrient profiles with accumulations at the surface which rapidly decrease with depth. Wind erosion on sandy soils is thus likely to result in substantial net losses of nutrients as surface soil is moved and its fines transported as suspended material well away from the erosion site. Consequent substantial declines in productivity should result.
6.7.2 Productivity

Little evidence is available that relates productivity decline directly with wind erosion. This is as much a result of the difficulty of experimentally unravelling the complex interaction of factors affecting plant production in the field, as it is of the amount of research effort expended on this subject in Australia. One effort made some years ago by Marsh involved areas of soil swept with a road broom to simulate erosion. This work revealed that the removal of the surface 8 mm of soil from a pasture paddock induced a reduction in yield of up to 25% in a wheat crop grown on the site the following year (Marsh and Carter, 1983). However lack of reproducibility in the results prevented the placing of adequate confidence in the findings. Nevertheless, anecdotal evidence and observations certainly point to productivity decline both at the removal ~ deposition sites of wind erosion (Carter pers. comm.). The better results directly from sand blasting and less directly from the deposition of coarser, infertile material.

6.8 Farming Systems

6.8.1 Crop cover standards

The retention of some form of vegetative cover over the summer months is essential for the control or prevention of wind erosion in Western Australia. Recent work (Carter 1984) has shown that erect, anchored wheat stubble is about twice as effective as prostrate wheat stubble in preventing wind erosion. Furthermore comparatively little stubble is required for effective control - 400 kg/ha of anchored stubble (Figure 9).
Figure 9. Wind erosion (measured by sand flux) for various quantities of standing stubble. Wind erosion effectively ceases at standing stubble quantities around 200 kg/ha. Note that this quantity translates to near 400 kg/ha for paddock conditions. Only stalks were used in the experimental treatments - all leaf and chaff material was removed.

Lupin stubble, on the other hand, is coarser and sparser than wheat stubble and, compared to wheat stubble, approximately twice the weight of stubble/unit area is needed to effect the same control (Carter et al unpubl.). The importance of the height of stubble cover has been investigated and shown to have relatively little effect on reducing wind erosion compared to the amount of stubble/unit area (Carter 1984). Stubble cut as short as 10 cm is as effective as longer stubble in reducing wind speed close to the ground (Figure 10).
Figure 10. Profile of wind speed above the ground in stubbles cut to 40 cm and 10 cm heights. Note the insignificant difference in speed close to the surface.

These findings, under Western Australian conditions, are in broad agreement with United States work (Chepib and Woodruff, 1963; Siddoway et al., 1965) i.e. the more erect, finer and denser the residue, the smaller the amount of erosion. As may be expected, therefore, other Western Australian work on summer pasture cover preceding a crop shows that for roughly equivalent amounts of dry matter/unit area, a grass based pasture is 10 times more effective in reducing wind erosion than a clover based pasture (Carter 1984) (Figure 11).
Figure 11. Wind erosion (measured as sand flux) at various wind speeds for clover-based and grass-based pastures.
6.8.2 Fallow grazing management

Grazing animals reduce the amount of vegetative cover and trample the soil surface. Under the dry summer conditions experienced in Western Australia such trampling pulverizes and loosens soil, and greatly increases its susceptibility to wind erosion. Marsh (1982) estimated that one sheep can loosen approximately 330 kg/ha/week of surface soil on sandy booms and clay barns and 660 kg/ha/week on loamy sands and sands. The careful management of even reasonable fallow stocking rates thus represents an essential factor in the control of wind erosion in the fallow period between crops. This may be achieved by selling stock in early summer and thereby reducing stocking rates in the late summer-autumn period (a sometimes profitable alternative, Bathgate pers. comm.), or by moving stock to less wind erosion prone paddocks.

6.8.3 Tillage practices

Like the action of grazing sheep, tillage generally increases the risk of wind erosion. Ploughing or cultivating loosens soil and enhances the supply of particles for wind transport (Carter 1984). As well, it roughens the surface and decreases the wind velocity required to initiate wind erosion (Chepil and Woodruff 1963). Cultivation at speed and too dry a soil moisture content, particularly on structureless soils, further increases the pulverisation of soil and the supply of particles available for wind transport (Chepil and Woodruff 1963, Carter 1984).

The widespread adoption of herbicides for weed control has greatly reduced the need for cultivation in preparing crop seedbeds and thus the prospects of wind erosion at this crucial stage of crop husbandry. The adoption of direct drilling in the Jerramungup area, for example, has greatly reduced the incidence of wind erosion in the district (Crabtree, pers. comm.).

6.8.4 Stable cropping systems

The development of stable, profitable cropping (or grazing) systems is an important objective for any person seriously concerned with long term, sustainable agriculture. These may sometimes arise through efforts to improve productivity rather than to prevent erosion.

An example of such a farming system occurred in the early 1980’s with the development of the lupin:wheat rotation system on the yellow sandplain of the northern wheathelt. This system comprises a cropping rotation in which lupins are direct drilled into standing wheat stubble. The wheat stubble is retained and bupins direct drilled into it to prevent both wind erosion in the summer-autumn period and sandblasting of the young bupin crop. The introduction of lupins permits the use of grass-selective herbicides to eliminate brome grass, a serious weed problem in long wheat rotations. The lupins also provide a disease break for wheat crops and use water and nutrients from deeper soil depths, whilst adding nitrogen. These attributes of lupins have brought about an increase in the yield of wheat crops, a reduction in accessions to the watertable, more efficient use of
applied nutrients and a reduction in the need to apply nitrogenous fertilizer (Nelson, 1985). Furthermore, bupin stubble provides improved summer grazing. Overall, this cropping system is more ecologically stable, wind erosion has been virtually eliminated from the cropping enterprise and cropping and grazing profitability increased. This has resulted in an increase in the area under crop (now 2/3 of the Geraldton Advisory District) and the movement of the annual feed shortage period for stock from late summer-autumn to winter (Nelson, pers. comm.).

On the south coast, on the other hand, a stable farming system has not yet been developed. Grazing pastures still occupy about 70 per cent of the farmed area, and despite the fact that perennial grass and legume pasture species are available, summer feed shortages remain in pasture/crop rotations. In addition, the grasses are a host to soil borne diseases for cereal crops. Between these factors, wind erosion remains one of a number of serious land degradation problems in the area (Hamblin 1987).

6.9 Economics of Wind Erosion

Economic analyses of farming strategies to prevent wind erosion need to take into account the costs and benefits of either employing or not employing preventative practices. The few analyses so far done have largely examined farming practices and management systems without knowing the productivity consequences of erosion (Bathgate, pers. comm.). For example, analyses at Albany and Esperance have explored the benefits of strategies known to avoid or minimize wind erosion. These have shown that the strategy of selling stock early to avoid the critical feed shortage at summer’s end results in higher market prices and greater profitability. It also avoids overgrazing sparse pastures and the risk of wind erosion in the late summer period.

Economic analyses for both wind and water erosion must remain incomplete while on-site and off-site production functions are unavailable. This deficiency has long been recognized (Marsh 1981, 1983). However, it must be remembered that it only represents an impediment to farmers adopting erosion preventative practices when productivity benefits are not apparent from better farm management systems. The bupin:wheat cropping rotation on the northern sandplain and the stock marketing strategies on the south coast are examples of the probability that more often than not profitability accompanies better farm management.

6.10 Conclusions

1. Knowledge of wind erosion processes has not substantially changed in the past 20 odd years, nor has the insight it provides as to the wind erosion susceptibility of soils and the likely productivity consequences of such erosion.

2. Knowledge is lacking for the agricultural areas of Western Australia of the distribution and properties of soils that influence their capability for agricultural use and their susceptibility to various forms of degradation. Better definition of the
soil resource is needed. This can only improve the standard of land use practices and help prevent further degradation.

3. Knowledge is backing of the climate, particularly wind erosivity information, for most of the agricultural area of Western Australia. Better climatic data are needed to aid the assessment of the capabilities of agricultural lands. The provision of weather stations and analyses of their data is a long term, costly exercise with no immediate link to improved productivity. For this reason the undertaking of such a task is more appropriately done by a government agency.

4. The consequences of wind erosion (and other forms of degradation) on the productive capacity of soils is not well understood. This needs research attention, but it must be recognized that at best such knowledge is a negative incentive for the development and adoption of improved soil management practices.

5. The requirements of cropping practices to prevent wind erosion are reasonably well established for cereals and lupins. Similar requirements for other crops, cropping rotations, pastures and pasture:crop rotations need to be researched.

6. The development and economic evaluation of erosion preventative farming systems, particularly those involving grazing and crops other than wheat and lupins is the major research need deriving from this review. The development of such systems is possible with the current level of wind erosion knowledge and technology. Research effort in this area should first focus on regions or soils known from past experience to be particularly prone to wind erosion.

6.11 References


7. Soil Acidification, Carbon, Nitrogen Cycling and Agricultural Practices

7.1 Introduction

Acidification is a natural phenomenon in soils which often is exacerbated by agricultural practices, including pasture improvement, use of nitrogen fertilizers and removal of plant and animal products. Because of the potentially detrimental effect of acidity or low soil pH on the chemical environment of soils and the activity of key biological processes it is important to understand the rate at which soils acidify in different agricultural systems. A detailed understanding of the processes which contribute to acidification also enables strategies to be devised to reduce rates of future acidification.

This paper examines the current information on the extent of both surface and subsoil acidification in Western Australian soils and evaluated the role of biogeochemical cycles and product removal in this acidification. Procedures for assessing lime requirements are discussed and possible strategies to minimize future acidification outlined.

7.2 Soil Acidification

Soil acidification results in a decrease in pH, the adsorption of \( H^+ \) and desorption of exchangeable cations from soil cation exchange sites. This leads to a lowering of the base saturation (percentage of exchange sites occupied by exchangeable cations e.g. \( Ca^{2+}, Mg^{2+}, K^{+} \) and \( Na^- \)) and an increase in the exchange acidity (percentage of cation exchange capacity occupied by \( R^- \) and forms of aluminium). This acidification results in, for example:

1. leaching losses of cations such as calcium, magnesium and potassium;
2. mobilization of aluminium and manganese;
3. reduction in the availability of molybdenum;
4. changes in biological activity, including mineralization of organic nitrogen, oxidation of ammonium N to nitrate (nitrification), nodulation and nitrogen fixation in legumes.

The rate of decline in pH is dependent on the capacity of soils to buffer the change in, \( H^- \) ion activity. Thus, the sensitivity of a soil to acidification is inversely related to its buffering capacity. Soils of sandy texture and those low in organic matter typically have the lowest buffering capacity.
Porter (unpublished data) has estimated that approximately 7 million hectares of land in Western Australia have sandy surface soils. Clearly there is a large potential for soil acidification in Western Australian agricultural systems.

### 7.3 Evidence of topsoil acidification

Few studies have systematically evaluated acidification in Western Australian soils. The extent of acid topsoils can be gauged from soil tests data obtained from CSBP and Farmers Ltd (Figure 1). Approximately 10% of the total samples submitted for analysis in 1985/86 had pH values in water less than 5.4. Most of these acid soils were located in the coastal regions in the south-west of the State or in the north-eastern Shires. However, many of these soils may have been acid before cultivation. Perhaps more significant is the high proportion (32%) of soil samples that fell in the pH range 5.4 to 6.0 in water. These soils, many of which are located in the 350 to 500 mm rainfall belt, could be considered at risk in the future.

![Figure 12. Percentage of soil samples (0-10 cm) with pH (water) < 5.4. Data source, CSBP and Farmers Ltd.](image)
Local surveys of pH in soils by staff in the Western Australian Department of Agriculture verify the figures obtained by CSBP and the farmers. Glencross and Clarke (1984) showed soils of pH (CaCl₂) ≤ 4.5 (equivalent of pH 5.3 in water) to be widespread in the Albany and Plantagenet shires of the bower Great Southern. In contrast, Davies and Porter (unpublished data) found only 5% of soil samples taken from the top 10 cm of cultivated soils in the central wheatbelt had pH (CaCl₂) ≤ 4.5 and 22% < 5.0.

Several attempts have been made to compare pH in ‘cleared’ and adjacent bushland to gauge the effect of pastoral development and cultivation on soil acidification. Glencross and Clarke (1984) report that soil pH in cleared paddocks compared to virgin area declined overall by 0.16, 0.32 and 0.24 of a pH unit in the Kojonup, Frankland and Manypeaks areas respectively. Typically, the decline in pH was positively correlated with the numbers of years the land was cleared. A similar survey by Davies and Porter (unpublished) in areas around York, Quairading and Beverbey, chiefly on coarse textured soils, showed the mean drop in pH was 0.3 of a pH unit, while the largest decline was 1.8 pH units. Most of the topsoils sampled by Davies and Porter were below pH 5.5 in water.

Although these comparative studies of soil pH implicate agricultural practices with soil acidification, they do not provide reliable estimates of the rate at which soils acidify under given agricultural practice. This detail is best obtained from carefully managed long-term trials. Data on soil pH (in water) provided by Rowlands (Figure 2) shows that pH declined from 6.1 to 5.4 after 8-10 years of continuous pasture in a trial conducted at Newdegate (Figure 2). No further depression in pH was noted between 10 and 15 years. Soil pH declined more slowly in continuously cropped treatments which did not receive nitrogen, but pH values also reached pH 5.4 in water after 15 years. The initial rapid decline in pH in soils under pasture is also evident in the study of acidification conducted by Barrow (1964). In this study pH declined from pH 5.1 (CaCl₂) to pH 4.3 (CaCl₂) in a span of 20 years. Soil pH declined further after 20 years albeit at a slower rate.
Soil acidification is not restricted to soils under pasture. Trials conducted by CSBP at 14 locations in the wheatbelt showed that the mean annual decrease in soil pH was 0.020 for urea and ammonium nitrate (Agran(R)), 0.028 for sieramonium phosphate and 0.052 for ammonium sulphate - ammonium phosphate mixtures (Agras(R)) where 20 kgN/ha/year was applied to cereals. In another study with continuous cropping the application of ammonium sulphate at 76 kgN/ha/year for eight years decreased soil pH by approximately 1 pH unit when compared to a treatment which received no nitrogen. Urea applied at the same rate over the same time interval decreased pH by between 0.2 to 0.6 of a pH unit depending on soil type. However, there was little difference in soil pH after 12 years in plots receiving either urea or (NH₄)₂SO₄ when pH values in water approached pH 4.8, 5.0 and 5.4 at Merredin, Wongan Hills and Beverley respectively (Mason, 1980). The differences in the rate of acidification obtained between sources are clearly demonstrated in Figure 3.
Figure 14. Effect of nitrogen fertilizer on soil pH. Adapted from Mason, (1980).

(R) Registered trademark

7.4 Processes contributing to surface soil acidification

Acidity may be added or removed from an ecosystem in the form of H~ ions or H~ ions may be produced or consumed in reactions within the ecosystem. In Australian agricultural systems direct inputs of H~ through acids in rainfall are minor (Hingston and Gailitis, 1976). However, there are many processes within the agricultural systems which indirectly affect the size of the H~ pool.

These processes are components of the major biogeochemical cycles operating in soils, including the carbon, nitrogen and sulphur cycles (Helyar and Porter, 1987). Acidity also arises when plants absorb an excess of cations over anions.
7.5 Carbon cycle

The carbon cycle primarily contributes to acidity through the accumulation and export of bicarbonates. These are derived from carbonic acid which itself is in equilibrium with carbon dioxide contained in soil air. Displacement of bicarbonates to depth by percolating water causes surface acidification.

7.6 Nitrogen cycle

Figure 4 illustrates which nitrogen transformations contribute or consume H~ ions during the cycling of nitrogen. Nitrification or oxidation of ammonium to nitrate is a major contributor of acidity (2 moles of H~ for every mole of nitrate produced). This process is indigenous to most soils. However, soils rarely reduce nitrate to ammonium but can reduce nitrate to nitrogen gas and nitrous oxide (denitrification) when waterlogging restricts the availability of oxygen. Denitrification consumes one H~ per mole of nitrate reduced.

The uptake of nitrate by plants also results in the consumption of H~ ions (one mole H~ for every mole of nitrate accumulated) while the uptake of one mole of ammonium contributes one mole of H~.

Using Figure 4 as a guide it can be seen that no acidification or net input of hydrogen ions occurs when legume-fixed nitrogen, urea or anhydrous ammonia are applied to soil provided that none of this nitrogen is oxidized to nitrate. On the other hand, the application of ammonium sulphate, ammonium chloride or ammonium sulphate/ammonium phosphate mixtures (Agras) causes acidification when nitrogen is taken up by plants irrespective of its conversion to nitrate. The acidity produced during nitrification is neutralized during the uptake of nitrate by plants or when nitrate is denitrified, provided that (1) the nitrogen is derived from organic sources, urea or anhydrous ammonia; (2) the uptake or denitrification of nitrate occurs in the topsoil. Displacement of nitrate from the topsoil by percolating water (leaching) removes the potential for this consumption of H~ ions and acidification results.

Nitrification of N sources such as ammonium sulphate adds an additional H+ ion even when nitrate is fully consumed at the zone of nitrification because H~ ions are not being consumed during the formation of the ammonium ion (Figure 4). This result in part accounts for the faster rate of acidification of soil amended with ammonium sulphate compared to urea (Figure 14).

How important is each of these acidifying processes? It is possible to estimate the contribution of each to acidification provided that the fluxes, for example, of carbon and nitrogen can be quantified for relevant transformations and detailed information is available on produce removal. Unfortunately insufficient data is currently available on carbon and nitrogen cycling in Western Australian agricultural systems to permit such an assessment. However, Hebyar and Porter (1987) were able to identify the major sources of acidity in permanent pastures in the Tablelands of New South Wales,
ecosystems not dissimilar to those present in the south-west coastal regions. In these, acidification was mainly caused by nitrate bosses (40-51%), organic matter accumulation (34-43%) and organic anion exports in products and waste products (12-15%). Other sources of acid and alkaline effects including the accumulation of ammonium and nitrate-N, addition and export of bicarbonate ions accounted for less than 4 per cent of the total acidification.

It is doubtful whether the acidifying effects associated with organic matter accumulation can be counteracted without use of lime or alternate liming agents. However, there is obviously much scope to minimize acidification through the improved management of nitrogen resources. This improved management vii). also have a direct benefit on crop production by improving the N status of crops. Possible management strategies are outlined later in the paper.

Figure 15. The nitrogen cycle and ecosystem H⁺ pool. (Helyar and Porter, 1987).
7.7 Subsoil acidification

There is currently no Western Australian data showing subsoil acidification. However, a number of studies have been conducted in New South Wales which provide evidence that subsoils can acidify rapidly and to a very low pH. In the Southern Tablelands of New South Wales, under permanent pasture, the soil profile had been found to have acidified to a depth of at least 60 cm (Figure 5). In another study on a long term wheat/lupin rotation experiment, the subsoub at 10 to 20 cm was found to have acidified at the extremely rapid rate of 1.1 units in 6 years (Helyar, pers. comm.).

Figure 16. The relationship between pH (1:5 water) and soil depth under permanent pastures. Profiles A and B are virgin soils, C and D are soils from 26 year old subterranean clover pastures and E and F, 55 year old pastures. Adapted from Bromfield et al., (1983).

In the Southern Tablelands study (Figure 5) the subsoil acidified to a pH similar to that found in the profiles of some of the naturally acid and least productive soils in Australia. One example of these very acid soils is the ‘wodgil’ soils of the Western Australian eastern wheatbelt. Subsoil acidity in those soils has been shown to limit the production of wheat to as little as 30% of the yield potential which could be achieved if the profile was not acid (Table 1). The main mechanism by which plant growth is affected by...
subsoil acidity is probably the reduction in root growth and consequent reduced ability of the plant to extract nutrients and, more importantly, water from the subsoil.

Table 1. The effect of neutralizing the acidity in an extremely acid, eastern wheatbelt yellow sandplain soil ('wodgil' soil).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Very poor wodgil soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total dry matter (t/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lime</td>
<td>1.47</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0.36</td>
<td>1.99</td>
</tr>
<tr>
<td>Plus lime</td>
<td>4.03</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0.77</td>
<td>6.13</td>
</tr>
<tr>
<td>Grain yield (t/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lime</td>
<td>0.64</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0.68</td>
</tr>
<tr>
<td>Plus lime</td>
<td>1.76</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. More productive wodgil soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total dry matter (t/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lime</td>
<td>2.14</td>
<td>1.43</td>
<td>2.94</td>
<td>0.20</td>
<td>2.47</td>
</tr>
<tr>
<td>Plus lime</td>
<td>3.21</td>
<td>2.24</td>
<td>4.39</td>
<td>0.28</td>
<td>4.92</td>
</tr>
<tr>
<td>Grain yield (t/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lime</td>
<td>0.89</td>
<td>0.50</td>
<td>1.22</td>
<td>0.55</td>
<td>0.95</td>
</tr>
<tr>
<td>Plus lime</td>
<td>1.50</td>
<td>0.87</td>
<td>1.81</td>
<td>0.70</td>
<td>1.62</td>
</tr>
</tbody>
</table>

N.A. = Not available

Exactly how subsoils become more acid in time is unknown. The nitrogen cycle effects which are so important in the acidification of topsoils are probably much less significant in their effects on the subsoil. One possible source of subsoil acidification is related to the acidification which results from nutrient uptake. Plants tend to take up more positively charged nutrients than negatively charged nutrients from the soil. In order to maintain electrical neutrality in their tissues (i.e. make the number of positive charges equal the number of negative charges), the plant excretes acidity (positively charged hydrogen ions) into the soil. This results in the plant tissues being alkaline and
the soil surrounding the roots being more acid than it was before the roots started growing into the soil. The acidification which results from product removal (Table 2) stems from this nutrient uptake effect. However, even if no produce is removed, this nutrient uptake effect has implications for soil acidification. At the end of the growing season the above ground plant material contains the accumulated alkalinity which has resulted from the season’s nutrient uptake and nutrient movement into the plant tops. The amounts of alkalinity accumulated in legume, grass and cereal plant material are similar to those shown in Table 2.

Table 2. Product removal and soil acidity (Davidson, 1987)

<table>
<thead>
<tr>
<th>Product</th>
<th>Lime required to neutralize acidity resulting from removal of product (Kg CaCO₃ per tonne product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lucerne and clover hay</td>
<td>55-65</td>
</tr>
<tr>
<td>grass hay</td>
<td>35</td>
</tr>
<tr>
<td>cereal hay</td>
<td>22</td>
</tr>
<tr>
<td>cereal grain</td>
<td>3</td>
</tr>
</tbody>
</table>

To examine the possible consequence of this mechanism on subsoil acidification, take the case of a 1:1 cereal:legume system. Assuming that 5 t/ha of cereal (containing alkalinity equivalent to 100 kg lime/ha) and that 5 t/ha of legume (300 kg lime/ha) is grown in alternating years (an average plant material alkalinity of 200 kg lime/ha/year). A sandy subsoil, low in organic matter, is likely to have a buffer capacity of the order of 0.5 t lime/ha/pE.10 cm unit. Assuming that, the subsoil pH can drop a further 0.5 units before plant growth is affected, then the time required for that subsoil to reach a problem pH depends upon what proportion of the acidity added to the total profile (20 kg lime/ha/year) is excreted into each layer. Table 3 shows the potential acidification from this system, assuming different proportions of the total acidity is excreted into the subsoil layer. As little as 5% of the total acidification from this hypothetical rotation can acidify a subsoil significantly within 25 years.
Table 3. Calculated potential acidification from a cereal/legume rotation (5 t total dry matter produced of each) assuming a range of proportions of acidity excreted into a given subsoil layer. The acidification is expressed as the number of years for the pH of the subsoil layer to change by 0.5 unit.

<table>
<thead>
<tr>
<th>Percentage (*) of acidity excreted into subsoil layer</th>
<th>Years for pH to drop by 0.5 unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
</tr>
<tr>
<td>1</td>
<td>125</td>
</tr>
</tbody>
</table>

* Assuming 200 kg lime/ha/year equivalent accumulated into plant tops, and a soil pH buffer capacity of 0.5 t lime/ha.10 cm/pH unit, and a layer depth of 10 cm.

7.8 Critical levels of acidity

There is no published information on the level of surface acidity which affects the yield of Western Australian wheat varieties. Large responses to lime have been observed in permanent clover pastures growing on soils of pH (Ca\text{d}_2) < 4.2 in high rainfall areas, although rarely have the responses been observed when lime was applied to the surface of undisturbed pastures Yeates et al., (1984). Other spasmodic responses of subterranean clover to lime have been noted in the Great Southern region (Glencross and Clarke, 1984) mostly when soil pH (Ca\text{C}_2) was less than 4.5 but also at higher pH levels at some sites. Growth responses to lime were attributed in part to the stimulation of mineralization of nitrogen and sulphur. Barrow (1964) was unable to show any significant improvement in clover growth when lime was applied to soils with pHs (Ca\text{C}_2) C 4.2. However, grass growth and thus pasture growth was increased after lime applications, probably because of the higher rate of mineralization of nitrogen.

Pot studies have shown that the response of subterranean clover to lime in disturbed pastures is primarily due to effects of lime on Rhizobium nodulation. Below pH (Ca\text{d}_2) 4.2 Rhizobium nodulation is greatly inhibited and nitrogen fixation and growth of subterranean clover is much reduced (Figure 6; Yeates et al., 1984; Bromfield et al, 1983; Coventry g~.,, ~ 1985). This effect is not observed in undisturbed pastures chiefly because a layer of organic matter in the top 2 to 3 cm of soil maintains soil pH (CaCl_2) at 4.2 or higher, eventhough underlying soil is often less than pH 4.0 (Ca\text{d}_2). Cultivation disturbs this organic rich layer therby removing a favourable zone for nodulation if the bulk pH of the surface cultivated soil is below 4.2 in CaCl_2 (Figure 6). Critical minimum soil pHs in Ca\text{C}_2 for other Rhizobium species include 3.5 to 4.0 for \textasciitilde. lupini (infests lupin and serradella), 4.2 to 4.7 for \textasciitilde. leguminosarium (infsects field peas) and 5.2 to 5.7 for meliloti (infests medics), (Howieson and Ewing, 1984).
Figure 17. Effect of lime on nodulation of subterranean clover. Soil was collected from established permanent pasture. Yeates, (unpublished data).

7.9 Lime as Part of our agricultural system

Given that our soils are acidifying, and that there is some level of soil acidity at which the productivity of any agricultural system is limited, it can be concluded that lime will almost certainly have to become an intrinsic part of our farming system in the future. The questions which arise for a farmer are “How long before I will have to start liming my soils?” and “What will be the long term costs of lime?”

If the liming decision is to be based entirely on economic criteria, the answers to both these questions rely on information about the relationship between the level of soil acidity and the productivity of the agricultural system, and upon the rate of soil acidification. There is clearly no economic return in liming a soil with a pH of 6.0 if the productivity of the system is only affected when the pH drops below 4.2. Equally, with a critical pH of 4.2, there is a much greater chance of getting a significant return from liming a soil of pH 4.5 if the rate of acidification is 0.1 pH units per year (3 years to reach 4.2) than if the soil is acidifying at 0.01 pH units per year (30 years to reach 4.2). The amount of lime which is required to maintain that soil pH is the amount of lime which will exactly neutralize the acidity which is added each year.
There are only a few estimates of the rate of acid audification in Western Australian agricultural systems. The data of Barrow (1964) and Rowland (unpublished) cited earlier in this paper provide the basis for two estimates.

1. Barrow 1964

Barrow’s worst scenario was that the pH of the Coolup sands dropped by 0.8 units in 20 years (.04 pH units/year). An estimate of the buffer capacity of the soil can be obtained from a study by Barrow (1964) of the effect of lime (1 ton of 70% neutralizing value/acre, equivalent to 1.73 t CaCO₃/ha) on the productivity of four Coolup sands. He observed a 0.8 unit change in pH after 5 months. This can be interpreted as a buffer capacity of 2.16 t CaCO₃/ha.10 cm/pH unit. The long term lime requirement of this system can therefore be estimated as 86 kg CaCO₃/ha/year.

2. Rowland, unpublished

The pH of the soil of a long term rotation trial at Newdegate changed by variable amounts from year to year and in different rotations. Taking the worst case, the pH of the continuous pasture plots dropped from 6.1 to 5.6 between 1969 and 1973. This is an acidification rate of 0.125 pH units per year. Laboratory analyses of the soil from this site revealed that the buffering capacity is 0.5 t CaCO₃/ha/.10 cm/pH unit. thus the ‘worst case’ acidification rate can be calculated as 65 kg CaCO₃/ha/year.

It is impossible to say how representative these rates are of other environments or other agricultural systems. In both cases only the acidity of the topsoil has been measured, and so any acidification of subsoil must increase the estimates of acidification rates. Figure 7 shows how the cost of 1 tonne of lime at the farm gate varies over the south west of Western Australia. This can be assumed to be the amount that a medium or high rainfall farmer will have to find every 10 or so years to neutralize an acidification rate of 100 kg CaCO₃/ha/year. Low rainfall farmers can expect 0.1 t CaCO₃/ha to last longer.
7.10 Strategies to minimize soil acidification

The leaching of nitrates was earlier identified as a major contributor to soil acidification in permanent pastures. This situation is likely also to apply to legume ley systems. Acid promoting fertilizers are additional sources of acidity in cereal cropping systems. Thus the manner in which nitrogen resources are managed will influence the rate of acidification in agricultural soils.

An obvious objective should be to minimize the rate of leaching of nitrates. This is probably easiest achieved in continuous cereal systems. Here the farmer has the choice of fertilizer form, rate and time of application of nitrogen. Ideally nitrogen should be applied at rates and times which satisfy the nitrogen demand of the crop. Applications of nitrogen after sowing of cereals are less likely to result in the leaching of nitrates than applications made at sowing or particularly prior to sowing. Theoretically use should be made of nitrogen sources such as urea which have a low acidification potential (Table 4). However, recent research has shown that urea is nitrified more rapidly than
(NH₄)₂SO₄ in coarse-textured poorly pH-buffered soils (McInnes and Fillery unpublished data). Thus there may be higher risk of nitrate leaching when urea is used in place of ammonium sulphate. This phenomenon could, in the long term, narrow the differences in acidification rates between urea and ammonium sulphate as is apparent in data presented in Figure 14.

Table 4. Lime equivalents (kg CaCO₃ ha⁻¹) required to neutralize acidity produced with the use of N sources in leaching and non-leaching environments.

<table>
<thead>
<tr>
<th>Application rate KgN/ha</th>
<th>Ammonium sulphate</th>
<th>Diammonium phosphate</th>
<th>Legume-fixed N, urea and Agran</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All NO₃ leached</td>
<td>No NO₃ leached</td>
<td>All NO₃ leached</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>140</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>280</td>
<td>140</td>
<td>210</td>
</tr>
<tr>
<td>100</td>
<td>720</td>
<td>360</td>
<td>520</td>
</tr>
</tbody>
</table>

Fewer options are available to minimize soil acidification under permanent pastures, especially those in Mediterranean climates characterized by prolonged dry periods over summer and autumn. In these environments nitrate accumulates in the absence of pasture growth and is subject to leaching with the abrupt onset of late autumn-early winter rains (Figure 8). Grazing animals also concentrate nitrogen in urea which is returned to the soil at rates well in excess of pasture plant’s ability to utilize that nitrogen. This excess nitrogen is invariably subjected to leaching during periods of rainfall, (Field et al. 1985; Ryden et al., 1984). Davidson (1987) has suggested that soil acidification in permanent pastures could be minimized by sowing quick-growing deep-rooted annuals in late autumn to tap nitrate which is leached below the rooting depth of pasture species. However, this strategy will probably not be acceptable in areas where conservation of rainfall is crucial to the productivity of the legume crop.

The build-up of large concentrations of nitrate in soil could possibly be avoided in pasture-ley systems by depleting mineralizable nitrogen with appropriately timed cropping phases. Two strategies could be adopted. Pastures could be cultivated when (1) soil nitrogen has accumulated sufficiently to support a single wheat crop (2) when the potential for loss of nitrate by leaching exceeds predetermined limits. Figure 9 illustrates the effect of from 1 to 7 years of pasture on the mineralization of soil N following cultivation.
Sufficient N (90 kg N ha\(^{-1}\)) was mineralized after two years of pasture to support a wheat yield of 2 tonnes/ha. Approximately 140 and 200 kg N/ha were mineralized when 3 and 7 year old pastures were cultivated, respectively. Loss of the excess nitrogen (50 kg N/ha\(^{-1}\)) by leaching following the cultivation of the 3 year old pasture could have contributed the equivalent of 180 kg CaCO\(_3\)/ha to the acidification of the soil in addition to acidity caused by leaching of nitrate at the onset of the preceding winter.
The implementation of any management strategy will be dependent on the adequacy of information on rate of fixation of nitrogen by legumes, the retention of nitrogen in soil in grain legumes opposed to grazed pasture legume systems, the mineralization potential of soil as influenced by cropping history, potential for beaching of nitrate and the crop demand for nitrogen. Little of this information is currently available for Western Australian agricultural systems.

Figure 20. Changes in total soil nitrogen following years of pasture and years of wheat at Wongan Hills. (Rowland et al., 1980).

Other practices which could help lower the potential for acidification include:

1. the retention of stubbles in continuously cropped soils to immobilize mineral N in the autumn and early winter;

2. use of grasses or cereals as hays in preference to clovers (Table 2) to minimize the removal of cations; and

3. the use of pasture legumes in preference to grain legumes particularly if it can be demonstrated that important quantities of cations are removed in grain in the case of lupin or pea crops.
7.11 Research needs

There is a dearth of information on the past rates of acidification in Western Australian soils. Such information is needed to enable an immediate assessment of the effect of past agricultural practices on the rates of acidification. Comparisons of pH in soil profiles beneath cleared and adjacent virgin land will likely yield the most comprehensive information in the short term. However, detailed pedological studies should accompany these measurements to establish whether paired soils were similar before land clearing.

At the same time a limited number of long-term trials should be established, or existing long-term trials modified, to facilitate measurements of future changes in surface and subsoil acidity in relation to the major biogeochemical cycles and export of cations (product removal). It is envisaged that these trials would provide the necessary data to test current hypotheses on:

(1) projected acidification rates for major agricultural systems;
(2) the contribution of processes to soil acidification;
(3) the impact of changes in agricultural practices on soil acidification.

Research is also urgently needed on subsoil acidification to:

(1) establish its significance in Western Australian soils and agricultural systems;
(2) to elucidate the mechanisms causing subsoil acidification; and
(3) to evaluate potential means of ameliorating this acidification.

Current research appears to be identifying the relationships between acidity and productivity of permanent and disturbed subterranean clover pastures. However, little is known about these relationships for wheat outside of the naturally acid wodgil soils. Such information is needed to enable economic assessments of liming practices.

7.12 Literature cited


8. Effects of Agricultural Practices on the Soil

8.1 Introduction

The living components of soil, excluding plant roots, are extremely heterogeneous and often interrelated. This paper describes the major components and summarizes research on the effects of agricultural practices on those organisms relevant to south-Western Australia, highlighting areas poorly studied or little known. Finally, case is put for a more integrated and directed approach to research.

8.2 What is Soil Biology?

Soils contain a diverse range of micro-organisms and invertebrates from bacteria (1-2 μm) to earthworms (30 cm) (Table 1). General introductions to soil biology are presented by Campbell (1985), Lynch (1983) and Russell (1973). The diversity of forms of organisms in soil reflects the complexity of soil as a habitat. Thus, the heterogeneity of microsites within soil can result in both aerobic and anaerobic micro-organisms being active near one another. Organisms are most abundant in the surface layers of soil.

The activities of organisms that occur within soil vary with climatic conditions and with variability in physical and chemical characteristics of the soil (Dommergues et al. 1978). It is therefore not surprising that agricultural practices will influence micro-organisms and invertebrates in many ways. Only 4-10% of the total population in soil is usually active at any one time; a major limitation to microbial activity is carbon supply. Most micro-organisms obtain their carbon and energy from dead organic matter (plant or microbial) which they decompose, or from substances released from living plant roots. Indeed, the rhizosphere (the volume of soil influenced by roots) usually represents the zone of soil with the greatest microbial activity (Campbell 1985).

Soil organisms can affect plant growth either directly or indirectly (Table 2). In both cases the effects may be either beneficial or detrimental, depending on the organism and environmental conditions.

Beneficial organisms directly affecting growth of plants in south-Western Australia include symbiotic root nodule bacteria (rhizobia) which fix atmospheric nitrogen in association with legumes (Vincent, 1982) and vesicular arbuscular (VA) mycorrhizal fungi associated with roots of nearly all agricultural plant species (Abbott and Robson 1982). Mycorrhizal fungi can enhance phosphate uptake by plants. Organisms which adversely affect plant growth through direct associations with plants include plant pathogens and pests (fungi, bacteria, nematodes and some insect larvae) (Table 2). Such organisms are of obvious economic importance in south-Western Australia. Benefits from symbiotic organisms (related to level of effectiveness of symbiotic nitrogen fixation or phosphate uptake) are equally important but not as visible as is the damage caused by pathogens and pests.
Table 1. Comparative sizes of some soil organisms

<table>
<thead>
<tr>
<th>Length or diameter (mm)</th>
<th>Organism</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2$</td>
<td>Earthworms</td>
</tr>
<tr>
<td></td>
<td>Fly and Moth larvae</td>
</tr>
<tr>
<td></td>
<td>Beetles and their larvae</td>
</tr>
<tr>
<td>$1^0$</td>
<td>Centipedes</td>
</tr>
<tr>
<td></td>
<td>Termites</td>
</tr>
<tr>
<td></td>
<td>Ants</td>
</tr>
<tr>
<td>1</td>
<td>Symphylids</td>
</tr>
<tr>
<td></td>
<td>Mites</td>
</tr>
<tr>
<td></td>
<td>Nematodes</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>Rotifers and water bears</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>Fungi</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>Bacteria</td>
</tr>
</tbody>
</table>

In contrast to the groups of organisms which directly affect plant growth, those which are indirectly important are less well studied and often overlooked. Examples include organisms beneficial for plant growth because of their essential role in mineralizing organic matter (i.e. affecting the chemical environment (see reviews by Jenkinson and Ladd 1981, Sparling 1985)) and their role in maintaining soil structure (i.e. affecting the physical environment) (see reviews by Jansson and Persson 1982, Lynch 1984, Lynch and Bragg 1985). Organisms having indirect detrimental effects on plant growth include those associated with the development of water-repellant soils, denitrification and the production of phytotoxic compounds (Table 2). The same organisms may enhance or reduce plant growth, depending on the nutrient levels in the organic material being degraded. This will be explained below.

Plant residues are the major source of energy and carbon for heterotrophic microorganisms and some invertebrates (Lynch 1983). The organisms which degrade this material include a large number of different species with different physical and chemical...
optima for their growth. The degradation of organic matter results from a chain of
activities by a succession of micro-organisms (Harper and Lynch 1985). Certain micro-
organisms produce enzymes capable of degrading particular molecules. Their activities
will release smaller molecules which may be further degraded by either themselves or
other micro-organisms. A combined effort by different organisms, often interacting with
one another is required for this process. Waste products such as ammonia, released by
the micro-organisms, provide inorganic nutrients for plants. Thus the process of
mineralization of organic matter (conversion to inorganic forms) results in the release of
nutrients (particularly nitrogen, phosphorus and sulphur) otherwise unavailable for
plants.

Table 2. Direct and indirect effects of soil organisms on plant growth

<table>
<thead>
<tr>
<th>Direct effects</th>
<th>Indirect effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beneficial</strong></td>
<td><strong>Beneficial</strong></td>
</tr>
<tr>
<td>(i) symbiotic nitrogen fixation (rhizobia)</td>
<td></td>
</tr>
<tr>
<td>(ii) phosphate uptake (VA mycorrhizal fungi)</td>
<td></td>
</tr>
<tr>
<td><strong>Detrimental</strong></td>
<td><strong>Detrimental</strong></td>
</tr>
<tr>
<td>(i) plant disease</td>
<td></td>
</tr>
<tr>
<td>(ii) root or shoot boss due to insect feeding</td>
<td></td>
</tr>
<tr>
<td><strong>Beneficial</strong></td>
<td><strong>Beneficial</strong></td>
</tr>
<tr>
<td>(i) mineralization</td>
<td></td>
</tr>
<tr>
<td>(ii) non-symbiotic nitrogen fixation</td>
<td></td>
</tr>
<tr>
<td>(iii) soil aggregate formation and stability</td>
<td></td>
</tr>
<tr>
<td>(iv) inorganic nutrient transformation</td>
<td></td>
</tr>
<tr>
<td>(v) biological control</td>
<td></td>
</tr>
<tr>
<td>(vi) soil aeration, infiltration</td>
<td></td>
</tr>
<tr>
<td>(vii) pesticide degradation</td>
<td></td>
</tr>
<tr>
<td><strong>Detrimental</strong></td>
<td><strong>Detrimental</strong></td>
</tr>
<tr>
<td>(i) inorganic nutrient transformation (e.g. denitrification)</td>
<td></td>
</tr>
<tr>
<td>(ii) production of water repellent substances</td>
<td></td>
</tr>
<tr>
<td>(iii) production of plant toxins</td>
<td></td>
</tr>
<tr>
<td>(iv) competition with plants for nutrients</td>
<td></td>
</tr>
</tbody>
</table>

The combined organic matter (humus) in soil results from microbial activity and usually
accounts for the greatest fraction of soil carbon, but this has a half-life of 1,000 years
and as such as virtually unavailable for further degradation by micro-organisms (Lynch
1983). Fresh plant residues are degraded most readily. Dead microbial cells are also a
source of organic matter which is easily degraded. Once compounds such as sugars
and amino acids are degraded, the remaining molecules within plants are available only
to an increasingly limited group of micro-organisms which produce the enzymes
necessary to oxidize them (e.g. cellulase necessary for breaking glucose linkages in
cellulose). Some molecules remain virtually unavailable to microbial breakdown due either to their poor access (e.g. bound by phenolic compounds) or to the absence of enzymes for degradation.

During the degradation of organic matter, micro-organisms incorporate a proportion of the mineral nutrients released into their own cell structures. This immobilization of nutrients makes them unavailable for plants until the organisms themselves die and are mineralized by other micro-organisms. Thus the release of nutrients (e.g. inorganic nitrogen) into soil for plant growth is the excess of mineralization after immobilization has taken place (Jansson and Persson 1982). The quantities of nutrients released depends upon their proportion, relative to carbon, in the dead organic matter. For example, the proportion of nitrogen in cereal straw relative to carbon may be lower than that required by the micro-organism for its growth. Therefore nitrogen may be absorbed from the soil by the micro-organisms to make up the difference, leading to competition with plants for nitrogen (Leeper 1964). Organic residues from legumes usually have a higher proportion of nitrogen to carbon than is needed by the micro-organisms, resulting in excess inorganic nitrogen being released into soil during mineralization. The various roles of micro-organisms in nitrogen cycling in soil are summarized in Table 3.

Certain micro-organisms produce compounds (e.g. polysaccharides) in soil during the mineralization of organic matter which can help form and maintain soil aggregates (Lynch and Bragg 1985). However, under some circumstances compounds produced may be hydrophobic and lead to non-wetting soil characteristics (Roberts and Carbon 1972). The structure of soil can also be rebated to the activity of soil invertebrates which either physically modify the soil by burrowing (e.g. by termites, earthworms) and influence the rate of incorporation and breakdown of organic matter (e.g. by earthworms) (Edwards and Lofty 1972; Lee 1985; Seastedt 1984).

### Table 3. Microbial transformations of nitrogen in soil

<table>
<thead>
<tr>
<th>Transformation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralization:</td>
<td>Nitrogen in plant residues or dead microbial cells is converted from organic to inorganic form. (NH(_3)/NH(_4^+)).</td>
</tr>
<tr>
<td>Immobilization:</td>
<td>Nitrogen is incorporated into micro-organisms as they grow [either directly from organic matter or from soil inorganic nitrogen].</td>
</tr>
<tr>
<td>Nitrification:</td>
<td>NH(_4^+) \rightarrow NO(_2^-) \rightarrow NO(_3^-) (inorganic nitrogen transformation).</td>
</tr>
<tr>
<td>Denitrification:</td>
<td>Inorganic nitrogen converted to gas (e.g. N(_2), N(_2)O).</td>
</tr>
<tr>
<td>Nitrogen fixation:</td>
<td>Atmospheric nitrogen is converted to ammonia.</td>
</tr>
</tbody>
</table>

Some soil micro-organisms that are not directly associated with plants have metabolic processes that alter the form of inorganic nutrients (e.g. nitrification, denitrification, non-symbiotic nitrogen fixation (Table 3)). Others are responsible for degrading pesticides added to soil (Torstensson 1980).

The activities of an organism within soil are rarely independent of those of other organisms (Clarkholm 1985). Organisms may benefit one another (e.g. provide
nutrients) or be directly antagonistic (e.g. act as an agent of biological control of a pathogen). Certain organisms are the food of some invertebrates (e.g. fungi for Collembola and earthworms). Another example of interactions between organisms can occur during the mineralization of organic plant residues. Micro-organisms within the gut of earthworms may be responsible for some of the beneficial effects of earthworms on mineralization and soil structure (Edwards and Lofty, 1972).

Unfortunately, it is not easy to study individually the activities of many soil organisms in their natural environment. Frequently, activities of the population as a whole, or a component of it, are all that can be measured (e.g. total microbial respiration, denitrification). Methods for measuring the abundance of many soil organisms and identifying them are laborious or inaccurate (see Jenkinson and Ladd 1981, Nannipieri 1984, Waid 1984). For some organisms, direct methods of quantification are feasible (e.g. handsorting earthworms). Usually, direct methods of observing and quantifying micro-organisms are of limited value, partly because it is often not possible to determine whether cells are dead or alive. Indirect methods for assessing microbial populations, such as pure culture plating, Most Probable Number estimations and measures of microbial biomass by the fumigation method all have their limitations. Often it is desirable to use more than one method. The value of a particular method will depend upon the organism being studied.

8.2 Effects of Agricultural Practices on Soil Biology

There is little doubt that the physical, chemical, and biological changes in soil resulting from changes in agricultural practices alter the soil as a habitat for micro-organisms and invertebrates. As a general principle, the effects of a practice on a particular group of soil organisms will depend upon the tolerance of those organisms to the new conditions. Not all organisms will be affected by a particular practice in a particular soil in the same way (Figure 1, Table 4). Pathways illustrating possible effects of agricultural practices on microbial or invertebrate activity may be direct or indirect (via effects on other organisms). Usually more than one pathway will be operating simultaneously, possibly with opposing results. The consequence of changes in microbial or invertebrate activity may be direct or indirect (via effects on other organisms). Usually more than one pathway will be operating simultaneously, possibly with opposing results. The consequence of changes in microbial or invertebrate activity may be additional changes in the physical and/or chemical properties of soil which can affect plant growth (Figure 21).
Figure 21. Pathways for effects of agricultural practices on microbial/invertebrate activity and plant growth.

Alternatively, plant growth may be directly affected by the activity of the soil organisms induced by changing the agricultural practice (Figure 1). All of the changes in microbial activity will lead necessarily to changes in plant growth. In other instances, the net affect of beneficial and detrimental effects may be no change in plant growth. There are many reports showing effects of agricultural practices on soil organisms (see reviews by Lynch 1984, Curry 1986, Domsch 1986, Douglas 1987, Rees 1987 and Rovira 1987). In order to integrate current knowledge and assess its relevance and deficiencies, it is essential to determine (i) which organisms are important in a particular soil, (ii) what measures of their presence in soil is relevant to their effects on plant growth, and (iii) what information is needed to predict the impact of an agricultural practice on plant growth mediated by soil organisms.
Table 4. Examples of possible pathways to explain increases (↑) or decreases (↓) in activities of soil organisms and plant growth

<table>
<thead>
<tr>
<th>Pathway (refer to Fig. 1)</th>
<th>Agricultural practice</th>
<th>Direct effect</th>
<th>Indirect effect(s)</th>
<th>Effect on plant growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Addition of NH₄⁺ based fertilizer</td>
<td>Decrease in soil pH (CHEMICAL)</td>
<td>Biological control agent</td>
<td>↑ pathogen ↓</td>
</tr>
<tr>
<td>2</td>
<td>Lime application</td>
<td>Increase soil pH (CHEMICAL)</td>
<td>↑ Rhizobial growth</td>
<td>↑</td>
</tr>
<tr>
<td>2</td>
<td>Incorporation of legume residues</td>
<td>Increase organic C (CHEMICAL)</td>
<td>↑ Net mineralization of N</td>
<td>↑</td>
</tr>
<tr>
<td>3</td>
<td>Change rotation</td>
<td>Absence of host for a pathogen (BIOLOGICAL)</td>
<td>↑ Pathogen</td>
<td>↑</td>
</tr>
<tr>
<td>3</td>
<td>Change rotation</td>
<td>Absence of host for VA mycorrhizal fungi (BIOLOGICAL)</td>
<td>↓ Mycorrhiza development</td>
<td>↓ (Following season)</td>
</tr>
<tr>
<td>4</td>
<td>Cultivation</td>
<td>Increase soil compaction (PHYSICAL)</td>
<td>↓ Invertebrates</td>
<td>↓</td>
</tr>
<tr>
<td>6</td>
<td>Fungicide application</td>
<td>(CHEMICAL)</td>
<td>↓ Pathogen</td>
<td>↑</td>
</tr>
</tbody>
</table>

8.3 Research in South-Western Australia

All groups of soil organisms in Western Australia soils have not been equally studied in relation to the impact of agricultural practices on their abundance and activity. Furthermore, recommendations to farmers are made on extensive knowledge and experience that is not always well documented. Most research has concentrated on organisms which directly affect plant growth (Table 2), particularly major plant pathogens. Research on the effects of agricultural practices on organisms which indirectly affect plant growth has been largely ignored. Nutrient cycling in relation to agricultural practice has been studied without giving emphasis to the micro-organisms and invertebrates involved.
8.4 Organisms Directly Affecting Plant Growth

a) Plant pathogens and pests

The effects of agricultural practices on wheat yield reductions due to *Rhizoctonia* and the take-all fungus have been extensively studied. Damage to wheat roots by *Rhizoctonia* is reduced by cultivation (Jarvis and Brennan 1986, MacNish 1985, Rovira 1987) but the mechanisms involved are not properly understood. Opposite effects of tilbage on take-all of wheat have been demonstrated in Western Australia and South Australia (Rovira 1987). The effects of tilbage on the number of propagules and their ability to infect wheat seedlings has been extensively studied (Cotterill, b and Sivasithaznparain 1988). However, the relationship between propagule number and disease development in field soils is not well understood. The form of nitrogen fertilizer affects the development of Take-all (MacNish 1980, MacNish and Speijers 1982) and this may be rebated to an effect of soil pH on the growth of the fungus. Prediction of the effects of agricultural practices on take-all may be possible once the factors affecting saprophytic growth (only recently demonstrated Grose et al. 1984, Glenn and Parker 1988) of the pathogen in soil are better understood (Glenn et al. 1987a,b).

The effect of agricultural practices on lupin diseases has been studied in line with the rapid increase in areas sown to this legume in recent years (Sweetingham 1986, Wilson 1985). The extent of *P. leiochaeta* root rot of lupins is rebated to the number of spores of the fungus present in soil (Sweetingham 1986).

There has been relatively little study of the effects of agricultural practices on pathogen activity associated with pasture plants. Certain foliar diseases of plants may depend on the survival of the pathogen on dead plant material between seasons. Tillage practice can affect propagule number by changing the rate of breakdown of the organic matter. In Western Australia, ~tillage has been shown to affect scald in barley (Janakiram and Boyd 1980) and *Septoria* in wheat (Brown and Rosielle 1980). There have been no data published on the responses to insect pests to changed agricultural practice excluding insecticides.

b) Symbiotic micro-organisms

There is a general understanding of the ecology of rhizobia in agricultural soils of south-Western Australia (see reviews by Parker et al. 1977, Parker and Chatel 1982). However, relatively little direct study of the effect of changing an agricultural practice on the survival of rhizobia has been reported. In Victoria, lime addition to pasture increased the number of *~. trifoli* in soil, even in the absence of subterranean clover, and subsequent nodulation was also affected (Coventry et al. 1985).
The effects of agricultural practices on the VA mycorrhizal symbiosis in south-Western Australia are under study (Abbott and Robson 1985, 1987). In greenhouse experiments, the development of mycorrhizas can be increased or decreased with addition of lime and phosphate or by changes in host species or host density (Abbott and Robson 1985). In field soils elsewhere, fallowing (Clarke and Mosse 1981), non-mycorrhizal crops (Powell 1981) and erosion (Hall 1980) all reduced the extent of mycorrhizal development.

8.5 Organisms Indirectly Affecting Plant Growth

a) Micro-organisms

Micro-organisms which indirectly affect plant growth have received almost no study within Western Australia. Research elsewhere clearly demonstrates that they change in abundance and activity with agricultural practice (for tillage effects see Lynch 1984). In the long term, stubble retention will increase soil organic matter (Powelson et al., 1987). The incorporation of this material will increase or decrease plant growth depending on its rate of degradation, time of degradation in relation to crop growth and on the type of metabolic products released into soil. The latter will depend on the composition of the organic matter and on the species of micro-organisms. Changes in total organic matter in soil can be difficult to measure if the amount added relative to the organic matter already present is small (Undersander and Reiger 1985). Rapid response by the soil microbial biomass to changes in soil organic matter content could be used to predict trends in organic matter accumulation before their detection by chemical analysis (Powlson et al., 1987). Plant and microbial residues represent a major pool of nitrogen in soil and an understanding of their conversion into inorganic forms available to plants could help refine predictions for fertilizer recommendations. Studies aimed at understanding the role of the micro-organisms in nitrogen mineralization and immobilization should complement those already being conducted to predict the effects of agricultural practices on nitrogen cycling in south-Western Australia.

Most studies of the effects of herbicides and insecticides on soil micro-organisms show few adverse effects, providing these pesticides are applied at recommended levels (Rodriguez-Kabana and Curl 1980, Trappe et al., 1984).

b) Soil invertebrates

There are no published data for south-Western Australian agricultural soils on the effects of the interval between crops or the sequence of crops on soil fauna. However, the number of groups of soil animals declines with regular cultivation (Abbott and Parker 1980a). In particular, pasture is more favourable than cultivated soil for earthworms and other large soil animals including termites, ants and beetles (Abbott et al. 1979, Abbott and Parker 1980b). It is not known whether physical damage by ploughing, or the decline in organic matter levels following regular cultivation is responsible. In laboratory experiments earthworm biomass increased with the quantity and quality of food supplied...
Research elsewhere shows that some soil invertebrates may be adversely affected by particular herbicide application (House et al., 1987).

8.6 Research Directions

Research should be aimed at predicting the effects of agricultural practices on organisms recognized as being important in particular soil types and climatic zones.

First it is necessary to identify those organisms likely to be important. This can be achieved using local knowledge and research conducted elsewhere, although further research may be necessary, particularly for organisms which have previously been neglected.

Second, the effects of agricultural practices on the physical, chemical and biological environment of soil in relation to plant growth need to be quantified in a representative range of soils and climates. Microbiologists, zoologists, soil chemists, soil physicists and agronomists need to collaborate in the collection of data from these sites. Collaboration is necessary to ensure that all relevant data are collected, and to ensure that these physical, chemical and biological data are integrated. This approach will provide the most appropriate data for the development of a model to predict the effects of changed agricultural practices on plant growth. There is a need to understand the various pathways for changes to the physical and chemical environment in soil. Are they direct effects or do they include physical and chemical alterations to the soil environment that are mediated by soil organisms? A collaborative approach to collecting data would also ensure a more efficient use of limited research funds.

Third, there is a major limitation to developing a model to predict how agricultural practices change the activities of soil organisms and how they subsequently influence plant growth. For the majority of organisms there is little understanding of the relationship between the number or activity of organisms at one time (e.g. early in the growing season) and their effect on plant growth at a later stage. A measure of the number of propagules of a micro-organisms at a particular time may (Pbeiochaeta setosa; Sweetingham 1986, Gaeurnannomyces graxninis; Cotterill and Sivasithamparam 1988) be useful for predicting subsequent damage to a host resulting from disease. Bioassays, (tests which measure the potential of a micro-organisms to infect plants) may be more useful for some types of micro-organisms (e.g. VA mycorrhizal fungi: Abbott and Robson 1987). Therefore research will need to be directed towards identifying which characteristics of particular organisms need to be measured. Massive data collection would be of little use in developing a model if much of it is irrelevant.

Predictions about the likely effects of agricultural practices on important micro-organisms or invertebrates will be made more easily if additional information on the tolerance of organisms to ranges of soil chemical, physical and plant factors is available. Research to
identify the limits of activity of organisms in relation to expected changes in the soil environment following particular agricultural practices will also be required.

In summary, research is required to identify neglected but potentially important organisms. Collaboration in data collection between scientists with different skills is essential. The aim of data collection is to develop a model to predict the effects of agricultural practices on soil organisms and to predict how this will change plant growth. Two major limitations for this model concern the back of understanding of (i) what to measure for many organisms and (ii) the range of conditions tolerated by many soil organisms. Finally, the challenge lies in using this information to choose management practices, which may include inoculation with selected organisms (Robson and Abbott 1986), so that maximum benefits are gained from beneficial soil organisms and damage resulting from detrimental organisms is minimized.
9. Acknowledgements

We thank Alan Robson, Michael Ewing and John Howieson for discussion and comments.

9.1 References


MacNish, G.C. and Speijers, J. (1982). The use of axnmonium fertilizers to reduce the severity of take-all (Gaeuniannomyces graminis var. tritici) on wheat in Western Australia. Annals of Applied Biology ~Q,Q,: 83-90.


10. The Farmer Perception of Soil Management - Soil and

10.1 The Purpose of the Workshop

Before getting into my talk fully, I believe we should again briefly set out the aims of this workshop.

The following concept can be seen as a somewhat radical approach compared to the types of seminars and conferences usually held.

Today farmers have the opportunity, for the first time, to put before scientists, research councils, research committees and Government Ministers their understanding of the deficiencies in soil research. It is also an opportunity to put forward some of the questions we want answered and to influence the direction of future research.

Secondly, while we concede that soil research is a vast area and that some isolated research projects may have been necessary, the time has come for full integration of research projects. Also, farmers must be seen as being capable of contributing to research programmes.

Thirdly, scientists have the opportunity of telling the industry the nature of the soil research currently taking place and the direction in which it is going, and what the expected results are.

This should enable the selected groups to make an assessment of the real needs of the farming community. They will then be able to prepare a submission for approval by the Grains Council. If approved the Grains Council will advertise world-wide for applicants to, under contract, do the initial project. I believe the initial work will take approximately three years; give some basic answers and map the direction that future work should take.

To fund the work the Grains Council will seek finance from the three Grains Research Councils and the three Western Australian state research committees, while at the same time maintaining a “watch dog” control on the project.

10.2 The Reasons We Need More Research

1. The agricultural production increase in Australia is only 0.05% per annum, whereas a 2.5% increase is achieved in other parts of the world.

2. The poor performance of new cereal varieties. If you book at individual cases, you will agree that overall new varieties do not produce more when released than the older ones produced when they were first released. There are always exceptions to the rule, but overall this statement is true.
Look at the south coastal areas where a new barley variety is currently required every two years. Surely it must be realized that the soil eco-system is changing so rapidly that breeders cannot keep up with the changes. These soil changes occur more rapidly in the higher rainfall areas, but are occurring all over the agricultural areas.

Dr Rodger Boyd of the University of Western Australia has said that the ability to breed tolerances into the plant is varied between varieties, but is very limited and scientists realize they can only go so far.

Some people are blaming the breeders for not producing the correct varieties, but I believe the fault lies in our lack of understanding of the degradation of our soils and the failure to integrate research.

Trials where old and new varieties are grown side by side have shown the new cereal varieties are clearly superior.

Surely these results must indicate that the fault is in the soil and the breeder is barely keeping up. In fact, the breeding programme is losing the battle.

3. Waterlogging, while being widely acknowledged as a problem, is poorly understood and is wrongly thought by many, perhaps by most, people to only exist in high rainfall areas.

Salinity has received a huge amount of publicity over recent years, but is, in fact, merely a symptom of waterbogging, although this fact is not understood by most people.

When we cleared out band the first imbalance created in the soil was an excess of water. Our winters contain periods of very wet weather, lasting in the high rainfall areas for perhaps two months. We cannot control the water in this period by the use of crops or pastures as is done in other parts of the world. Therefore, we require mechanical means of balancing the water in the soil during this time, and yet maintain a means of preserving water for the period of too little rain.

Soil cannot store water without the assistance of organic carbons, i.e. rotting plant material being transformed into the soil biologically. Western Australia has the harshest farming conditions in the dryest continent, yet we mostly talk of drainage and not conservation.

Water control and water balance in the soil must be the first priority in any integrated soil research programme. This is the most neglected area in soil research, despite extensive media coverage of the problems associated with waterbogging and salinity.

This research has not been seriously undertaken by our institutions so far. I believe there is no doubt that this situation exists because of the senseless
argument between the Department of Agriculture and Harry Whittington. For more than 30 years the argument has developed around how to control water, not whether it should be controlled. This argument has resulted in meaningful research being put back 15-20 years.

I refuse to be drawn into who is right and who is wrong, but evidence in the paddock shows that co-operation would have resulted in the industry being in a much better position today to understand our soils.

This workshop intends to get above such confrontations and instigate integration of soil research and have field successes by farmers included in research programmes.

If farmers are able to solve their present economic problems they will still be faced with disaster through poor productivity in the longer term. As soil research is a long and continuing exercise, producers must insist that full integration must proceed immediately without room for bias.

4. Chemical changes which take place in the soil cause solidification and crusting of soils, even causing some sands to seal off and hold water after a period of continual waterlogging. No attempt has been made to identify these changes and understand them with a view to reversing the process.

5. The soil structure has broken down over the years as a result of our agronomic practices. Our harsh treatment of the soil zoology by hot clearing fires, ploughing and perhaps too many workings of the seed bed have all played their part.

More recently, agronomic practices to minimize soil workings have helped. Deep ripping in some areas is giving increased production in the short term. However, no practices have been developed which would assist nature to restore soil balances which are necessary for good soil structure. I believe we must learn to work with nature if we are to obtain lasting results.

6. Soil testing should be standardized and testing equipment calibrated for Australian conditions.

Professor Alan Robson of the University of Western Australia has repeatedly called for these changes. We need better advice on fertilizer requirements and we need to know what changes are taking place, biologically and chemically.

Fertilizer trials undertaken at Badgingarra for wet, medium and dry years were carried out in recent years. The trial results gave no clear indication of requirements, in fact, it was anybody’s guess what rates should be used. The most profit for the actual dollar spent was achieved by not using fertilizer in all of the trial years.
However, there was one significant factor which affected production and that was moisture. When I mentioned this at a “farm update” held in my area, I was told that the trials were not about moisture.

As a result of all this work there was no answer to the fertilizer question and the moisture aspect which had not been picked up, was ignored. Why shouldn’t this accidental finding have encouraged someone to investigate the possibility of retaining moisture in the soil? It would have made sense as the production increase was significant.

10.3 Some woolly logic

Three scientists were travelling from London to Scotland for a conference in Edinburgh. Shortly after crossing the border they saw a black sheep.

“How interesting”, the astronomer remarked, “tall sheep in Scotland are black”.

“An unwarranted inferences”, the physicist replied. “We can only conclude that some sheep in Scotland are black”.

“All we can really be sure of”, the logician said, “is that at least one sheep in Scotland is black on at least one side”.

Too often we see something familiar and presume the rest or we are so obstinate we won’t see what is staring us in the face.

In wetter areas increasing run-off is causing major problems for individual farmers. What to do with the water and how to handle it is a matter not always easy to solve. Scientists have told us that water run-off from cleared land increases by 3% per year. This run-off is draining off nutriment and humus from the soil. Crops and pastures are slowly deteriorating as a result and moisture stress is evident at the end of the season.

7. Various methods of controlling water have been developed in the State, generally by farmers. These methods should be realistically studied without bias, to ascertain whether some management practices can reverse the degradation cycle of our soils. If we do not succeed in this, the future of agriculture within Australia is gradual decline. The problem is just too serious for the industry to ignore. There is enough evidence to show that some of the methods are succeeding even if the results do not fit into proven scientific equations.

8. Research into soil bacteria, while acknowledging imbalances in the soil, has concerned itself with producing specific bacteria and placing it in the soil.

Approximately six years ago a UWA project in the eastern wheatbelt was set up to study the differences in virgin bushland and cleared land. Sites were chosen
where there was virgin bush on one side of a fence and land which had been cleared for varying periods on the other side.

It was found that the virgin bushland contained 40 times as many earth animals as the cleared land. It was also found that the virgin bushland was 24 times more penetrable than the cleared band and in as little as five years.

What understanding is there of this changed soil structure and eco-system? Without this knowledge how can we create an environment for sustaining micro and macro soil zoology, essential for turning stubbles into humus?

9. Wind erosion is becoming an increasing problem throughout the State. While farmers and environmentalists are calling for answers to the problem, research committees are not funding submissions because they are repeats or variations to past efforts.

Only root matter will hold soil and this will only grow where the soil can sustain it. We need to take a good look at the basic reasons, the soil will no longer sustain good root matter, and learn to help nature reverse that process. Agriculture must learn to work with nature!

10. “Non wetting soils” are a spreading problem, now often mentioned, but not yet measured by a survey as was done for salinity.

These sands are usually coarser and the grains are said to form a “skin” which sheds the water. These areas are leached of nutrient and grow very few plants even with extra fertilizer. Efforts have been made to mix water holding materials in these sands to encourage growth.

However, the problem again stems from a deteriorating soil structure with the symptom showing first in the weaker areas and spreading as the soil structure weakens and leaches out. Often these areas begin as drainage lines for the surrounding country and sheep can be seen digging holes to lay in during hot days. Examination will show the sand is moist and cool below the first few inches of the surface in the early stages of degradation.

Farmers have gained some success by implementing a full conservation programme.

11. Diseases of cereals and pastures have increased rapidly over recent years. The problem has been almost devastating for individual farmers. Unfortunately we accept disease as inevitable and often look for chemical control as the answer.

Could it be that the poor health of our soils is a major contributing factor?

Mr Don Blesing, Chairman of the Federal Wheat Research Council, said in April 1987 to the Grains Council of Australia that submissions on soil research were
poor. There is a need for good soil research projects which would benefit all producers right across Australia. I believe that research based on the points I have made would fill that criteria.

10.4 Integration of Research

I first became aware that there was little integration of research soon after I was appointed to the State Barley Research Committee.

Arrangements were made by Dr Clive Francis of the Western Australian Department of Agriculture for the committee to meet the research officers in charge of projects funded by barley.

To the credit of Dr Francis, he ensured the scientists listened to the growers, but unfortunately they did not listen to each other.

The projects by Kevin Young at Esperance and John Hamblin at Geraldton are certainly attempts to produce a total package. However, they are working with one hand tied behind their backs through lack of answers to some of our basic soil problems.

At Merredin separate projects are being funded on acidity, boron toxicity, salinity and a waterbogging project has just been concluded at Mt Barker.

South Australian work has shown that salinity and boron are tied together. That is, where boron is found, there is also salinity present.

Salinity is a symptom of waterbogging and boron has shown up in recent years along with salinity in a number of areas in Western Australia.

Waterlogging causes soils to collapse and salt to be squeezed out. It seems logical that boron being soluble is squeezed out in the same way and is becoming a problem as the hardpan comes closer to the surface. Common sense would dictate that these projects should be integrated and not treated in isolation.

There are good people in research, but they are individually following narrow specialized areas without a fully integrated programme.

The rural industry can no longer afford the time-consuming isolated approach to soil degradation problems. Research must co-ordinate a fully integrated research programme into all biological, chemical and structural changes in the soil which are causing land degradation, loss of fertility, loss of production and salinization of water supplies for metropolitan and rural purposes.

I am not laying all the blame on scientists, but equally on producers. As producers we have not demanded more, but have been prepared to sit back and grizzle at being told what was good for us.
This workshop is an opportunity for scientists and farmers to have a fresh look at what is required and co-ordinate our efforts for the good of the industry. Scientists generally have not accepted that farmers can contribute.

One exception is Dr Rodger Boyd of the University of Western Australia who is as happy working with farmers as scientists. Dr Boyd admits to not being an agronomist, but did some agronomic work to get some answers for his breeding programme.

Experimental work at the University of Western Australia proved to him that waterlogging was our major problem and not salinity.

In the paddock situation using raised seed beds to get the roots out of the water and allow oxygen to be present in the soil increased production to an economic level.

This work shows we have two choices:

(i) breed tolerances into plants and this area is very limited; or

(ii) control waterlogging sufficiently to create a balance in the soil to allow for healthy growth.

In the machinery field it has been recognized that farmers play an important part by their innovation and skill. Many machines, gadgets and alterations have been invented by farmers and refined by engineers.

I am told that this is different to agricultural science, but I contend that it is only different because it has not been accepted that farmers can contribute.

10.5 What Chance Success?

Apart from success in many fields by scientists, farmers through necessity have had many successes in the areas I have mentioned and now list below:

(a) overcoming waterbogging and salinity;

(b) reducing acidity;

(c) overcoming hardpans and creating an environment for the propagation of a biological balance;

(d) retained fertilizer in the soil-soil tests to back this;

(e) been able to reduce fertilizer application;

(f) grown crops and pastures where they would not previously germinate;

(g) re-generated natural trees and scrub, previously dying.
These are some of the benefits farmers have demonstrated by using proven land management practices throughout the State.

How much more benefit could have been obtained if scientists had been involved in measuring the changes as they occurred?

Photographs on display are to give an indication of changes and can be backed by neighbours and soil tests. I am not supporting any one system, and wish to show that we are capable of success if we join forces.

I believe that District Soil Conservation Committees are capable of carrying out a lot of the ground work if given the opportunity. The concept of the committees is good in my opinion, but while it is early days yet, they are in danger of floundering. They need encouragement and must not be stifled by too tight guidelines.

A lot of concern is currently being shown for the pollution and degradation in the Peel Inlet and Avon River areas. I will not enter the dispute, but Beermullah Lake in the Gingin Shire has been cleared of poisonous algae. Also, at the Shire Office is data relating to the bake and surrounds which is said to be unique in the world.

In conclusion, I would like to thank all those people who have given such strong support for the concept of this workshop put forward by the Grains Council and assisted on the technical side by four scientists.
11. The Integration of Soils Research - a Queensland Viewpoint

11.1 Introduction

This paper, and the following one by Dr Robertson, change tack and complete the seminar by presenting overview papers on integration of soils research. Dr Robertson will present a local perspective. As a Queenslander, I will share my experiences from a very different point of view. Since our soils and climate contrast strongly with those in the cropping areas of south-west Western Australia, there are different problems in soil management and different opportunities for solution of those problems.

Our aims in this paper are:

• to define the integration process;
• to look at advantages and problems of integration;
• to provide some guidelines, based on our experience, on how to integrate (requirements and method);
• to share our experiences on the integration of soils research within the Queensland Department of Primary Industries (QDPI). Integration has involved both multidisciplinary projects and formation of more permanent mission-oriented (rather than discipline-oriented) work groups. I will use the formation of Soil Conservation Research Branch as an example of the second type of integration.

11.2 Definition of Integration

Integration is defined by the Macquarie Dictionary as ‘combination (of parts) into an integral whole’. As it applies to soils research, the parts would represent individual projects in the discipline areas of pedology, soil chemistry/fertility, soil physics/soil mechanics and soil biology. The definition of ‘whole’ is more important since integration of the disciplines requires a common goal. In our opinion, this is often not possible for the soil science disciplines alone.

This is overcome by re-defining ‘soils research’ in a broader sense as ‘soil management research’ or ‘soil conservation research’. This allows the adoption of goals such as that adopted by Soil Conservation Research Branch in QDPI, i.e. ‘to research and develop land management practices for sustainable and economic primary production’. However, the achievement of this goal obviously requires inputs from disciplines outside soil science, such as plant science and economics, to take into account interactions between climate, soil and animals or plants that occur in agricultural production systems.
Integration in the above context is well-illustrated in Figure 1, which defines the Research and Development function in terms of both location of research and approach to research.

![Figure 1. A conceptual model of research and development in an agricultural context.](image)

Process Research concentrates on explaining why something happens. To do this, the system studied must be well-defined and, therefore, process research studies components of production systems. Management Research studies more complex and ill-defined systems, and asks the question 'What is happening?'. For example, one may study the effect of surface retention of crop residues on fallow water storage. In Management Research, farming systems are usually compromised to meet a scientific requirement, e.g. statistical design; monoculture instead of a full cropping system; the same planting date for different treatments. Development Research looks at practical farming systems, often on a farmer's property. It asks the practical question of how to do something. The scientific facts are generally known. The unknowns are costs and practical considerations.
For the Research and Development function to be integrated, activities at all levels are required, often simultaneously. The natural progression is from process research in the laboratory to development research in the farmer’s field (up and to the right in Figure 1). However, review is required at various phases of the process, and this leads to definition of deficiencies in more basic knowledge and feedback of research priorities at lower levels (i.e. down and to the left in Figure 1). In the scientific sense, integration may occur by bringing different disciplines together to achieve a supra-ordinate goal or bringing individuals from the same discipline together (sometimes from different organizations), so that each individual can bring unique knowledge/research approaches to bear on a problem.

11.3 Advantages and Problems of Integration

The major advantage of integration is that, by working together in a structured way, a group can achieve more complex goals (and solve more complex problems) than individuals working separately. Thus, it is theoretically more effective and allows better use of (increasingly) scarce resources. However, translation of theory into practice requires a high level of planning by scientific managers to ensure appropriate timing of inputs, e.g. integration requires shared use of resources. If a piece of field equipment is unavailable because it is being used on another project, significant time wastage may occur. Non-integrated research, on the other hand, is limited to achievement of simpler goals. However, individual scientists have more control over achievement of those goals.

This last point illustrates the major problem associated with integration, in that it requires a high bevel of management input. Also, managers in integrated research units often require inputs from scientists outside their unit, and therefore beyond their control. For this reason, integrated research units exist only with the support of other units within an organization (and sometimes outside it). Lack of co-operation resulting from personality clashes and communication problems can result in the effective destruction of such units.

Some other problems which may arise are ownership of data, scientific ‘freedom’ and conflicts in priorities or competition for funds between groups. The problem of ownership of data may be partially overcome if planning for reporting is incorporated as part of initial project planning. Problems may still arise if timing of publication is not co-ordinated. For example, reporting by one scientist may be held up until a second scientist has time to make his planned input to the publication. Conflict for funds is overcome by developing a joint project whose objective is common to the different groups involved.

Despite these disadvantages, there are a number of very positive outcomes from integration. These are:

- Individual scientists within the integrated system have more meaningful, ‘ends-oriented’ goals. It is easier to define the ‘client’ or user of the research information,
and, therefore, to obtain feedback about the effectiveness and usefulness of
research. Clients for Research and Development vary from scientists within the
organization (for Process Research), through scientists outside the organization (in
the form of reports, models and training), to the farmer (the major client for
Development Research).

- Tasks can be better defined as the review and feedback process clarifies their place,
direction and importance within the research path.

- Co-location of work can occur, with obvious cost savings, e.g. different organizations
or different disciplines may be able to use the same field site. For example, we have
set up a number of regional sites to study soil water, crop growth, runoff and soil loss
under different fallow management systems. These sites are just as useful to study
seedling emergence or the effects of changed nutrition, disease incidence or insect
activity occurring as a consequence of the change in fallow management. Therefore,
a number of disciplines can conduct studies concurrently. Also organizations such as
CSIRO, which have particular strength in process research, could well conduct (say)
basic infiltration studies at such sites, with obvious advantages to both organizations.
This is a good example of integrating to use the comparative advantages of different
groups - CSIRO in process research and state agriculture departments in regional
field research. Another advantage of co-location is to ensure a data set which is
useful for a range of purposes, and for integration, e.g. runoff needed to interpret soil
water data.

- Improved communication and synergis between groups. For example, soil physicists
have often been considered to be theoretical and impractical. When there is
communication with other groups such as hydrobogists to solve common problems,
however, they are able to show the practical value of the soil physics discipline. The
value of the two groups (soil physicists and hydrobogists) working together is greater
than the sum of the individual groups - a good example of synergis.

11.4 How to Integrate?

There are several ways to integrate research. It can be done in a highly structured way
in which a large group is set aside to carry the main thrust of the work; in a formal, but
less heavily structured, way by the task force or project team approach; or by informally
co-ordinated arrangements which have considerably less likelihood of proceeding
successfully towards a common goal.

In the area of soil management research, QDPI have opted for the first of these by
developing a separate branch specializing in this area, but able to seek assistance
elsewhere in the Department where specialist expertise is already in place. We,
therefore, would like to share our experience on the formative years of Soil Conservation
Research Branch (a multi-disciplinary, task-oriented branch) in QDPI. This branch was
effectively formed in 1984, and we have both been involved with its development since
that time.
Some important requirements for such a branch are listed below:

(i) An aim defined in terms of a production system (final output). This aim must be broad enough for all branch members to identify with. For Soil Conservation Research Branch, as we have said, it is ‘To Research and Develop Land Management Practices for Sustainable and Economic Production’. This is an aim within which each discipline involved can find a scientific reason for its work.

(ii) (Preferably) some common scientific focus. In our case, it is the soil water balance, illustrated in Figure 2, and its relationship to soil properties and soil management in different climates. The main research functions involved in production systems use this focus towards the Branch Aim. For example:

- soil physicists are mainly concerned with infiltration, evaporation and deep drainage, and soil properties related to these;
- hydrobogists are concerned with saturated water movement in surface runoff and groundwater;
- agronomists are involved with soil water and crop water use.

Studies on water conservation soil erosion, salinity and structural deterioration have similar interests in the soil water balance.

Figure 2. A general representation of the soil water balance.
(iii) Well-defined research areas which can be linked back to the aim, with periodic review and appraisal of existing activities. To this end, our branch sponsored in 1986 a review of Research and Development needs for conservation production systems (Anon., 1986). Other branches in QDPI, industry representatives and farmers were involved in providing feedback. All of these have a strong interest in the development and practical application of our research findings, or are able to provide advice and comment on the direction of our work. Reviews like this provide a basis for the development of an integrated research programme, since those people involved in the review (both within and outside the branch) have a greater commitment to the new research programme arising from the review.

A similar review of Research Priorities for Vertisols (cracking clay soils) was also carried out by an ‘expert group’ with representatives from CSIRO and QDPI (Coughlan et al. 1986).

(iv) Strong management input to project planning. We have already discussed the importance of this, and indicated some of the management functions required.

(v) A range of disciplines (to cover the main technical areas of branch interest), as well as scientists with a range of research approaches. Approaches may range from the more specific process research to the more integrative development research.

Within Soil Conservation Research Branch, the main disciplines are soil science (concentrating on physics/mechanics), agronomy (concentrating on crop physiology), hydrology (emphasizing runoff prediction), and engineering (hydraulics, design of runoff control structures). Deficiencies within the branch at present are in soil biology, soil chemistry, engineering aspects of machinery development, economic evaluation of systems, and in extension expertise to manage traditional development-demonstration roles. While these fields of expertise are available elsewhere in our Department, it is sometimes difficult to compete with other priorities set by the managers of these people.

We have found the need for two types of integrating people. Both types need to be pragmatic and to be willing to make preliminary judgements on the basis of limited data. They are:

- the systems integrator or modeller, to enhance extrapolation of data across climate-soil type-cropping sequence situations. This person provides regular feedback to researchers on knowledge deficiencies.

- the applied integrator, who can work with farmers to ensure that land management practices recommended from research can be practicably
incorporated into the local farming system. However, to be effective, this activity needs focus and structure.

(vi) Ability of scientists to work in teams. Although we require a range of different types of people, we have found ability to work in teams to be an important selection criterion for staff, even for process researchers. Poor inter-personal relationships can soon destroy a team.

(vii) Comprehensive soil property and climatic data bases that are easily accessible.

(viii) A common method of handling data from regional experiments. This allows the interpretation of data both at the regional centre and by the systems integrator.

(ix) Good contact with other branches/organizations to ensure maximum cooperation with the integrative research unit. Activities such as staff interchange should be used.

11.5 References


12. Integration of Soils Research - Directions in Western Australia

Accountability, corporate planning, goal setting, multidisciplinary research teams, integration, application are all words enthusiastically embraced by the research bureaucracy in this latter part of the 1980s. While these concepts do have a place in agricultural research, it is worthwhile to briefly reflect on the nature of the research process and what we know about the attributes of successful research programmes.

Agricultural research is largely applied or developmental. It is innovation, the discovery of economically efficient ways of improving land management and crop and pasture production systems.

I am aware of little research on agricultural research and what makes it effective. Ruttan is one writer on the subject. While he focuses on the benefit/costs of research, he does indicate that research organizations are most efficient when they are young and vibrant. They, like us, become less innovative with maturity. Ruttan’s hypothesis is relevant to Western Australia and over the last thirty years we have seen many groups and individuals contribute strongly and then wane. Managing research requires strategies to prevent this senescence.

Most analysis of research innovation, albeit limited, has been based on private enterprise, particularly big business in the U.S.A. Peters and Austin (1985) provide a useful summary of this work and identify several features of successful research and technological development. The points they make include the following:

1. Innovation is highly unpredictable. Peters and Austin cite a study by John Jewkes of fifty eight major inventions of 20th century Europe and America. At beast 46 occurred in the “wrong place”, certainly not as a result of a planned research programme. Jewkes concluded that there was no industry group where invention occurred where and when it was supposed to.

   In another study Utterback overwhelmingly concluded that there is a tendency inherent in organizations for planning to do exactly the wrong thing in directing research. In 32 of 34 major market leading companies investment was reduced in development of new technologies in favour of propping up old technologies and the companies concerned subsequently lost market leadership. (Are we guilty of that with subterranean cbovers?).

2. Success in innovation is most likely if the researcher moves as quickly as possible to real tests of the result. Essential to success is getting a new idea to a lead user, someone who will test the innovation and experiment with the researcher. A Hewbet Packard executive is quoted by Peters and Austin as reflecting on the cause of most of their recent failures by stating ‘the number one mortal sin is excessive quantification of the imponderable’.
3. The most successful innovators are pragmatic, non dreamers who live by the dictum, ‘try it now’. A really new idea first has only one believer hence organizations wishing to be successful in research must give researchers the freedom to think differently and to try out their ideas quickly. A corollary to this is that failures must be expected and the possibility of failure should not be a disincentive to innovation.

4. Small teams can be many times more efficient than large teams. Indeed innovation is more likely to occur in radically decentralized organizations. In decentralizing research groups, that is getting them away from unnecessary regulation and organization, success is most likely if such groups are multidisciplinary and able to carry out the range of functions required.

5. Lead users are the best source of leading edge innovation. Most progress in innovation occurs when the research group is close to innovative users (Figure 1).

Figure 1. Site of mast innovation (after Peters and Austin., 1985)
What has the above to do with the future directions for soil research in Western Australia?

Before addressing this I would like to make, and perhaps provide support for, two hypotheses. Firstly soil degradation processes are limiting agricultural production in Western Australia. Previous papers have detailed some of the effects. Table 1 re-emphasises them.

Secondly, until recently soil research, with the exception of plant nutrition research has contributed little to agricultural systems in Western Australia and probably Australia. In Western Australia soil research has generally not been able to predict the development of yield limiting soil processes and until recently the majority of soil research has been laboratory based and seldom has it interacted with either leading farmers or scientists in other agricultural production areas. Agronomists in Western Australia may have been guilty of not discovering plant roots until the 1980s, but soil scientists can be justifiably criticized of attempting excessive quantification of the imponderable. Certainly the undoubted world wide reputations achieved by Western Australian institutions in soil physics has not been translated into improved soil management by farmers.

<table>
<thead>
<tr>
<th>Mean yield kg/ha (wheat unless noted)</th>
<th>Factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degraded plots</td>
<td>Unaffected or ameliorated plots</td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>1200</td>
<td>Structure</td>
</tr>
<tr>
<td>1,336</td>
<td>1,608</td>
<td>Wind erosion</td>
</tr>
<tr>
<td>1,085</td>
<td>1,670</td>
<td>Water erosion</td>
</tr>
<tr>
<td>1,330</td>
<td>2,730</td>
<td>Waterlogging</td>
</tr>
<tr>
<td>2,960</td>
<td>5,170</td>
<td>Acidity</td>
</tr>
<tr>
<td>1,020</td>
<td>1,740</td>
<td>Compaction</td>
</tr>
</tbody>
</table>

Back to future directions. There is little doubt that soils in Western Australia have been poorly categorised and described and the identification of their characteristics, behaviour and response to management practices is a prerequisite to further improvement in productivity. The soil resources on a farm will be increasingly used for the most suitable enterprise and different soil types must and will be used for different purposes under distinct management systems.
To achieve this farmers will need to understand their soil types and the appropriate management structure. Similarly agronomists, plant breeders and animal scientists will need also to be aware of the suitability of soils. This will need better definitions and interpretation than is available today.

The priority areas for research do not and should not be a list of processes that need solving, such as salinity, or structural decline, waterlogging or acidity, rather it should be to ensure that adequate soil research expertise is available to work with other scientists and innovative farmers in developing land use systems that are stable. The emphasis should be on identifying the soil characteristics and developing practices to avoid or overcome degradation processes.

While not wishing to be tempted into providing a plan for future directions there are some elements that are essential steps to take:

1. Understand the Soil and Land Resources in Western Australia and their distribution.

   In many areas the soils have not been described, mapped, let alone understood.

2. Provide soil expertise in all regions to facilitate definition of the interaction of soil characteristics with local farm management systems and the identification of actual and potential limiting processes or constraint.

3. Establish multidisciplinary groups charged with the responsibility of developing and implementing profitable management systems to overcome the specific problem.

4. Maintain close liaison between research groups and leading users.

5. Field test solutions and systems with leading users at the earliest possible stage.

It is very clear that the land resource in Western Australia is fragile and has been and is still being damaged by current land use systems. This damage is causing environmental effects as well as reducing the income of farmers and the Nation.

The solution to the problem is not necessarily to pour resources into soil research, but to ensure future research is planned on farming systems and that the soil is adequately understood and considered.
12. References


