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**TECHNICAL PUBLICATION**

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# **Sugar soils: A guide to characterising Australian sugarcane soils**



By  
**SM Eldridge**

# **Sugar soils: A guide to characterising Australian sugarcane soils**

**SM Eldridge**

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# Foreword

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In a friendly send-up of matters rural, 'Sir Arthur Fallowfield' of the Goon Show used to preface every exposition on matters of importance with the statement "Now Oy thinks the answer loys in the soil ...". As often is the case with humour, however, there was rather more substance to the comment than may have always been apparent, especially to the urban listener. The sustainable production of food, fibre and even some renewable energy resources through agriculture relies absolutely on the thin veneer of arable soils that cover a quite small proportion of the Earth's continental surface.

Yet at this time, around the world, agriculture is under challenge. The globalisation of markets requires ever-greater efficiencies to maintain profitability in the face of intensifying competition. At the same time, there are increasing demands for practices that maintain the productive capacity of the natural resource base and cause minimal harm to the wider environment. The challenge is no less apparent in the sugar industry, which needs to raise the productive capacity of local farmlands in light of the immense competitive pressures from low cost production countries like Brazil. At the same time, with production located adjacent to environmentally sensitive rainforests, coastal wetlands and reef, the industry must strive to minimise off-farm run-off of nutrients, sediments and chemicals.

The successful resolution of this conundrum requires the intervention of science and technology in ways that will ameliorate, not compound, the problems that accompanied the intensification of agriculture. Based on the lessons of the past, we now know that a crucial element of this process must be more sustainable management of agricultural soils in ways that progressively enhance, not 'mine' their productive capacity, and at the same time avoid adverse off-site environmental effects. Soils do much more than just 'hold the crop up' - they modulate the supply of water and nutrients to the crop and sustain a biologically complex community of micro-organisms that variously enhance or reduce the properties of

the soil itself, as well as plant health and function. Very importantly, different soils behave differently – and so they must be managed differently.

In the sugar industry, better knowledge of soils is needed: to fine-tune fertiliser applications to meet crop needs without losing too much to the environment; to manage irrigation to meet crop needs without losing too much water to the subsoil or through run-off; to apply amendments to overcome physical and chemical constraints to crop growth and tillage operations; to apply pesticides in ways that maximise their efficacy while minimising the risk they will move out of the soil; to manage the landscape and till the soils in ways that effectively manage run-off from heavy rainfall and minimise the risk of erosion; and to better target the management of a whole range of agronomic practices, like green cane trash blanketing, amelioration of sodicity and salinity, and spreading mill muds and biosolids.

The purpose of this book is to help those who are variously responsible for developing, promulgating or implementing advice on how to best manage sugar soils in an agronomic context. In particular, it emphasises the importance of detailed knowledge of soils and describes how to select a research site and characterise a soil. The book provides contemporary understanding of the main soils of the sugar industry, how to recognise them and their key properties, how they behave, and how they should be managed. CRC Sugar is proud to have been able to sponsor the development of the book. We trust that it will prove a valuable resource for those whose task it is to ensure a healthy and sustainable future for the soils of the sugar lands.



Chief Executive Officer  
CRC Sugar

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# Section 1. Introduction

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## 1.1 BACKGROUND

A CRC Sugar workshop in 1998 identified that there was a real need to improve the level of soil characterisation done at field research sites within the sugar industry (Bristow *et al.* 2000). This publication forms part of the response by CRC Sugar to that identified need.

The publication aims to provide some easy to follow guidelines and background information that will enable people who are not soil specialists to collect the necessary information to characterise the soil at a site. The guidelines commence at the very beginning of the trial site selection phase and continue through to the more detailed characterisations to acquire data to run simulation models. The guidelines can be used by researchers to either carry out a "do it yourself" job or as a reference to help inform another soil scientist or technician on what is required for the job. The information and photos in this publication are the culmination of two years of soil characterisation work by the author and colleagues for CRC Sugar in a range of locations extending from Tully to Bundaberg in Queensland.

## 1.2 SOIL CHARACTERISATION

### What is it?

The term soil characterisation is one that is used fairly loosely and often ill defined. It is generally related to those soil properties that have a greater degree of permanency about them and not to those that are prone to substantial fluctuations over time.

For this publication, soil characterisation is defined as the assessment and description of those more persistent soil properties that allow the soil to be classified and improve our understanding of how it behaves under sugarcane cropping and how it can be managed better. Assessment of lateral variation in soil properties across a site is also considered a necessary component of soil characterisation.

Later sections of this publication have been expanded to include the necessary soil input data for simulation modelling applications using common modelling programs such as APSIM.

As part of this characterisation process, soils should be classified according to the Australian Soil Classification (Isbell 1996). When research results are to be published in an international journal, soils will also need to be classified according to either Soil Taxonomy (Soil Survey Staff 1998) or the World Reference Base (FAO-ISRIC-ISSS 1998).

Measures of soil biology, apart from the coarser indirect measure of organic carbon, were not included in these guidelines because meaningful soil biological tests that accurately describe biological functions of soils are still being developed, and because of the difficulty of obtaining a result that is meaningful from one sampling visit to a site. This is because common soil biology measures such as earthworm numbers or microbial biomass vary greatly with soil conditions such as soil moisture and temperature which can vary from day to day depending on the weather. Soil biology is obviously a vital component of the soil, but it is difficult to evaluate from one sampling. Organic carbon is a useful surrogate, but even this can be confounded by the presence of large amounts of inert charcoal in the soil. Measures of the more dynamic fractions of organic carbon are worth considering.

### Why it is important ?

The following are a few reasons why soil characterisation is important.

#### **Extrapolation of experimental results to growers in the surrounding areas**

If the soil type at a research site is known, the locations in the surrounding area where the results are most applicable can be determined by examining soil maps for areas with the same soil type. Also, with this knowledge, research sites can be selected to ensure that they are located on a common soil type.

Generally this assertion in regard to extrapolating results is the case. However, the extent to which the extrapolation holds true is in part dependent on there being a good correlation between the properties important for soil classification and the underlying soil properties that were critical to the result. In some cases the results will relate to one or several soil properties which are represented in a number of soil classification groupings (soil structure shape, P sorption, organic C levels, soil pH etc). This correlation issue is in relation to the standard classification systems (e.g. Australian Soil Classification), as well as the soil map unit groupings (e.g. local series groupings and complex map units containing several soil types). An appropriate level of characterisation of soil morphology, chemistry and basic physics at a research site will at least allow the soil map resources to be used intelligently for appropriate extrapolation.

#### **Provides confidence that trial crop responses are largely due to the different treatments**

Adequate soil characterisation does this by ensuring the site is located on an area with an acceptably uniform soil distribution. If key soil properties are variable across a site, there is then the possibility that crop responses may be partly due to this and not the treatment differences alone, thus bringing the whole experiment under question.

#### **Allows the selection of better research trial sites**

Sites can be selected in areas with soil types that are representative or typical of the soils on which cane is grown within a region. Soils with less spatial variation in key soil properties can also be selected. Proper site selection procedures that include an assessment of available soil information at the beginning can help ensure this.

#### **Relate results to other studies in other regions on the basis of soil type**

By knowing the soil classification name for the soil at a site, results from the study at that site can then be compared with studies done on a similar soil type in other locations in Australia.

#### **Better interpretation of experiment results**

A thorough soil characterisation provides valuable knowledge about how the soil functions in terms of drainage, water and nutrient storage, root penetration etc. This knowledge provides insights on soil function and how this may be contributing to or impacting on crop responses to different treatments. This allows for a more informed interpretation of the experiment results and allows appropriate extrapolation to other soil types as well.

#### **Value adding to research results**

The additional characterisation of soil properties required as inputs for crop production models such as APSIM, provides the opportunity for the use of simulation models to make projections about the research results under different scenarios and over longer periods of time.

### **1.3 SOIL PROFILE – DEFINITIONS**

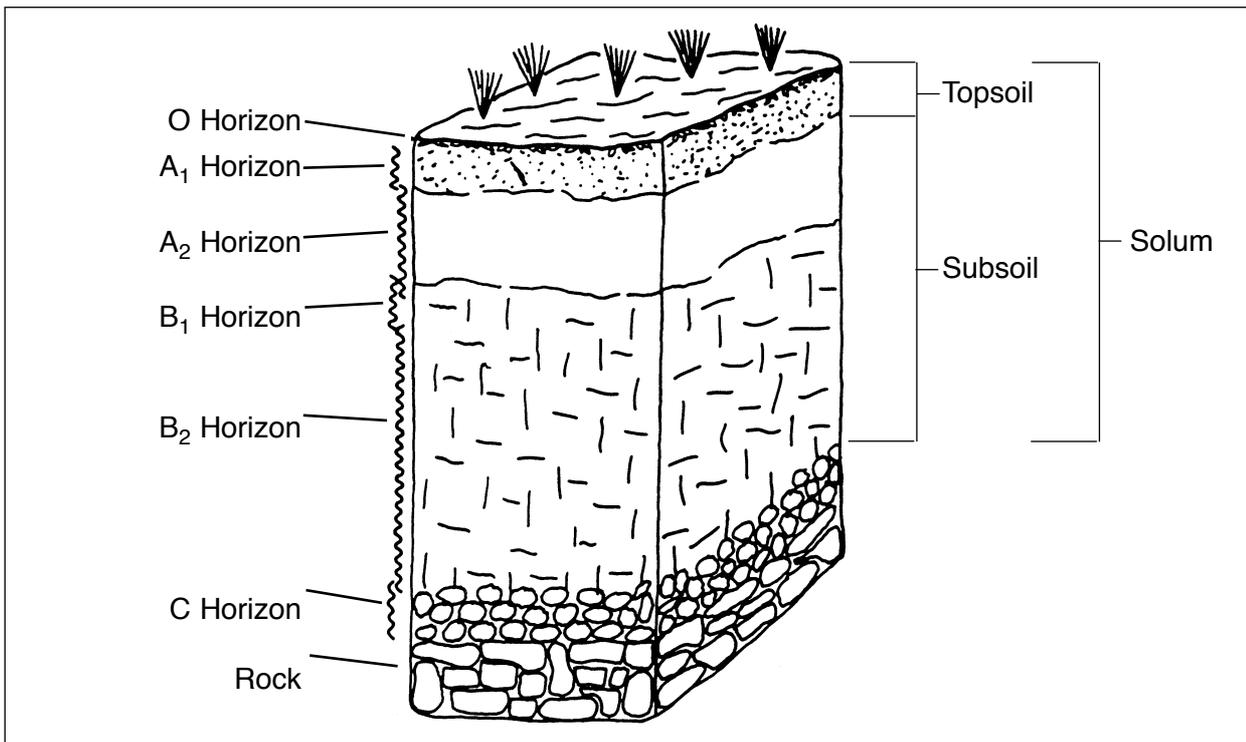
It is important to first define what a soil profile is, as this is what we are attempting to characterise.

#### **Soil profile**

A soil profile is "a vertical section of a soil from the soil surface through all of its horizons down to the parent material or unconsolidated substrate material...." (McDonald and Isbell 1990, p.103). If bedrock is very deep, as is the case in most alluvial settings, the depth of investigation of the soil profile is usually restricted to around 1.5m for practical reasons. The influence of soil properties on plant growth normally becomes much less significant at depths below 1.5 m as well. Photos 4.1 to 4.22 show 22 different soil profiles from sugarcane fields from Tully to Bundaberg in Queensland.

#### **Horizons**

The main soil horizons or layers can be distinguished by examining soil profiles in the field (Figure 1.1 and Table 1.1). They include the O horizon or decomposing organic matter (trash) on the surface, the A horizon or topsoil



**Figure 1.1.** A diagram of an idealised soil profile showing the location of soil horizons (Source: Murphy 1991).

layers, the B horizons or subsoil layers and below this either weathered parent material (C horizon) or other soil materials such as a different, older alluvial layer (D horizon). A horizons are typically dark in colour due to the accumulation of organic matter and they are the horizons where most of the plant nutrients are stored. Occasionally a pale, bleached A2 horizon is present below the topsoil (Photos 4.3 and 4.11) and this is often the result of water sitting in this layer due to an impermeable clay subsoil layer below. Alternatively A2 horizons can form from the leaching of iron, aluminium and clay coatings of sand grains in sandy soil profiles (e.g. dune soils). Below the topsoil layers are the subsoil layers (B1, B2, B3 horizons) and these are often distinguished by brighter colours and/or heavier textures (higher clay content). Hence they have a great influence on soil drainage and water storage for plants and can also supply some nutrients, though to a much lesser extent than the topsoil.

### Soil forming factors

Jenny (1941) developed the following "State Factor Equation" to explain how soil development is dependent on climate, organisms, relief, parent material and time:

$$S = f(\text{cl}, \text{o}, \text{r}, \text{p}, \text{t})$$

*Climate (cl)* is important as it influences moisture and temperature in the soil which in turn affect the chemical reactions and physical processes associated with weathering and soil development (illuviation, eluviation, leaching).

*Organisms (o)* include the activities of soil macrofauna such as earthworms, ants and other insects whose burrowing and feeding activities are important for breaking down and incorporating organic materials in the topsoil and sometimes redistributing soil materials within the profile. Such activity creates burrows that provide pathways for drainage within the soil profile. Microorganisms are important in the breakdown of organic matter and recycling of nutrients and are involved in chemical transformations that influence soil development.

*Relief (r)* is important as it can effect drainage, erosion and deposition of sediment as well as microclimate.

*Parent material (p)* has a great influence on the soil profile as it can influence the texture of the soil, clay mineralogy and chemistry. As it is the original material, it defines the range of possible soil characteristics that could develop by the interaction of the other four factors.

*Time (t)* is very important as it affects the extent

**Table 1.1** Notations for common soil horizons according to McDonald and Isbell (1990)

| Horizon notation | Horizon description   |
|------------------|---|
| Surface horizons |   |
| 0                | Organic materials in various stages of decomposition, on top of the surface of the mineral topsoil (A1) horizon.  |
| A1               | Topsoil layer – Zone of maximum biological activity; mineral soil horizon at or near the surface with some accumulation of humified organic matter; darker colour than underlying horizons.   |
| Ap               | An A1 horizon that has been disturbed and mixed with the underlying horizon by tillage practices and/or other disturbance by man to the point where it is no longer possible to infer with any reliability what the original A horizon depth and texture were. Many sugarcane soils have Ap horizons.   |
| A2               | Mineral topsoil horizon; paler colour than A1 horizon above; paler colour and or coarser texture than the B below.  |
| A2e              | As for A2, but with a conspicuously bleached (pale white) colour when dry.  |
| A3               | Transitional horizon between A and B horizons but properties are more like the overlying A1 or A2 horizons.   |
| Subsoil horizons |   |
| B1               | Transitional horizon between A horizon above and B2 horizon below, but properties are more like the underlying B2 horizon.  |
| B2               | Horizon of maximum soil development. Maximum clay content and/or, maximum iron, aluminium-humus content, and/or stronger colours than either the A horizon above or any of the horizons below, and/or different structure.  |
| B3               | Transitional layer between overlying B horizon and C or D horizon below but more like the B2 horizon above.   |
| C                | Partially weathered parent material – weak rock strength, lacks pedological development, shows signs of geological organisation –ghost rock structure, sedimentary layers.  |
| R                | Strong bedrock (as a continuous mass)   |
| D                | D horizons commonly underlie soil profiles in floodplain settings instead of a C or R horizon. In this setting they represent a previous flood deposit of a different soil material to the profile subsoil. A soil material below the B2 horizon (solum) which is unlike the soil above it in terms of its soil properties (e.g. gravel composition and content, texture, colour, structure etc) and cannot be given a reliable horizon name. |

of soil profile development by setting the time period over which the soil forming processes outlined below occur. The climate factor often needs to be considered in conjunction with time when comparing soil development between regions. A prime example of this is the common occurrence in temperate Australia of soil profiles with strongly differentiated texture horizons typical of the tropics. The presence of such soils there is due to a long period of landscape stability that has allowed sufficient time for them to develop, despite the climate not being tropical.

### Soil formation processes

The main processes of soil formation are:

- Accumulation of organic matter in the topsoil
- Washing of clays, iron, aluminium, and more soluble nutrients from the topsoil down the profile (leaching or eluviation).
- Accumulation of clays, iron, aluminium in the subsoil zone (illuviation)
- Weathering of parent materials throughout the soil profile.
- Oxidation / reduction (redox) reactions. These are important in the formation of potential acid sulfate soils in estuarine environments where anaerobic bacteria use iron from sediments and reduce sulfate in ocean water to produce iron sulfides. Redox reactions are also usually important in determining the colour of most soils via the oxidation and reduction of iron oxides. In well drained soils iron is oxidised and imparts a reddish colour while in soils with poor aeration iron is often in a reduced state giving the soils a dull yellowish or grey colour.

Soil formation begins with the development of an organic rich A1 horizon on parent material, before a B2 subsoil horizon forms as iron, aluminium and clay begin to accumulate lower in the

profile. Later, a texture contrast or duplex soil with a lighter textured topsoil and a heavier, more clayey subsoil may be formed as more and more clay is washed from the topsoil and redistributed to the subsoil with time. The most texture contrasting soil profiles, with lighter topsoil overlying heavier subsoil, are often the oldest soil profiles in the landscape.

The above soil forming processes may be interrupted by landscape processes such as flooding or mass movement (landslides) that deposit new sediment on top of the soil profile, or by erosion which washes or blows away the topsoil and sometimes the subsoil. In this situation the soil forming processes commence once again on the newly exposed soil surface starting with the accumulation of organic matter at the surface after vegetation re-establishes itself. A young alluvial soil profile on a levee bank is shown in Photo 4.12, while an older more developed soil profile from a higher river terrace which has a more developed texture contrast profile is shown in Photo 4.8.

### Soil distributions across the landscape

A cross section of an alluvial landscape showing soil distribution in the Herbert can be seen in Figure 1.2. There is an increase in the clay content in the soils on the active floodplain as you move away from the river. Here we have the river sand soil profile (Photos 4.12, 4.22) adjacent to the river and the 'river

overflow' soil, which is medium textured (Photo 4.10), further back from the river. On the larger areas of active floodplain there is often a low backswamp area at the back of the floodplain (furthest away from the river) and this area sometimes has heavy clay soils such as the cracking clay soil in Photo 4.14. The clay texture is due to heavier sand particles dropping out of suspension before the floodwaters reach here. Figure 1.2 shows how the alluvial landscape rises up to a higher level called a terrace above the active floodplain. The terrace represents a more ancient floodplain surface, which experiences flooding less often than the active floodplain and in many cases never under contemporary climatic conditions. This exclusion from deposits of flood sediment allows time for the soil forming processes to occur uninterrupted and for the soil profile to develop. Figure 1.2 shows that the soil on the terrace in this instance is a red loam soil. This soil profile has some changes in texture developed down the profile with the clay content gradually increasing with depth. The development of a red colour throughout the profile is a consequence of the weathering of the alluvial sediments over time that has released iron oxides into the soil. Some of the older and more elevated terrace land surfaces in the Herbert have been free from flooding for even longer periods of time and this has resulted in soil profiles with more pronounced soil horizons. Silty loam soils are quite common on these older terrace surfaces

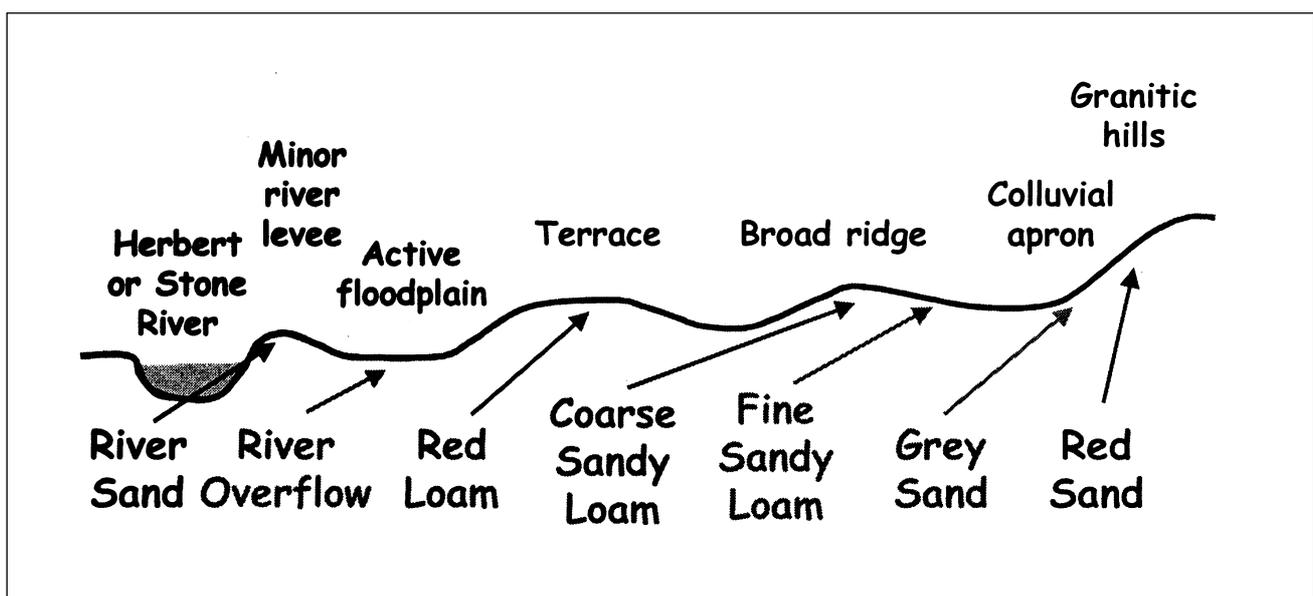


Figure 1.2. A soil – landscape cross section diagram showing the soil distribution in the Upper Herbert and Stone Rivers area (Wood et al. 2003).

(Photo 4.8). Grey and red sands that occur in the colluvial footslopes of the surrounding granite hills (Figure 1.2) are typically coarse textured soils. The colour of these two soils reflects the presence or absence of a watertable in the profile. This relates largely to landscape position with the grey subsoil colour associated with a flatter waning slope morphology and a lower landscape position (Photo 4.3) and the red sands with the more convex slopes further up the footslope.

Differences in parent material related to the underlying rock type or geology have a significant influence on the distribution of soils across hard-rock hill landscapes. Superimposed over the influence of parent material in such hill landscapes are the influences of past erosion and deposition events in the landscape. These processes redistribute soil materials and expose new surfaces for soil formation. Such mixtures of influences and processes can sometimes produce soil distributions that are quite complex. For example, the underlying geology has a significant influence on the distribution of soils in the Bundaberg district where red kandosol and dermosol soils are common on areas of sedimentary geology, while ferrosol or krasnozem soils are found on the few minor areas of basalt geology (Wilson 1997). Strongly sodic soils tend to be found in the lower landscape settings where the more soluble soil salts such as sodium accumulate (Nelson 2001).

### **Agricultural versus natural undisturbed soils**

Soil mapping by State and Federal Government agencies has usually focused on describing soil profiles at natural, undisturbed sites, rather than at sites disturbed by cultivation. As such it is often difficult to relate soils in these publications to those that are in a cultivated field. To do this one usually has to imagine that any horizons in the top 40 cm of the soil have been destroyed and mixed together into one topsoil layer. This publication is about characterising the soil in its current condition in the field, reflecting the impacts of agricultural practices on soil condition and form.

## **1.4 SOIL SCIENCE JARGON**

Most soil science terms used in this text have been defined in the text. It may however, still be necessary to look up some of the terms used. The 'Glossary of Soil Science Terms' of the Soil Science Society of America (2001) on the internet at [www.soils.org/ssagloss/](http://www.soils.org/ssagloss/) is very useful for this. Brady and Weil (2002) and White (1997) are two good textbooks on soil science that can help as well.

## **1.5 AIMS OF THIS PUBLICATION**

This publication aims to provide practical guidance and sound background information on:

- Selecting a trial or research site from a soil perspective.
- Adequate characterisation of the soils at the selected site.

What adequate characterisation is considered to be will vary depending on the research project. It can range from the minimum of collecting just enough information to classify the soil, to collecting additional soil water property and soil chemistry data to allow the research results to be modelled using a crop simulation model.

This publication is an attempt to provide a means for researchers in agriculture to look beyond the top 30 cm of the soil and assess the whole soil profile. The desired outcomes of this work are a greater understanding of soils as three dimensional entities that are variable in both lateral and vertical directions and an appreciation of the need to characterise this to improve site selection, the validity and interpretation of research results and the extension and extrapolation of these results to the surrounding country.

It does **not** aim to:

- Provide guidance on soil sampling strategies and laboratory analyses within the experiment. Soil sampling strategies within experiments will often need to vary with different properties and experimental design. For guidance in the area of soil sampling strategies and statistical analysis, readers are referred to Webster and Oliver (1990). Surface soil sampling is also covered

adequately by Brown (1999). Sugar industry soil sampling and analysis guidelines are outlined in Bruce (2000). For laboratory analyses it is always wise to search the scientific literature for the latest advances in analytical methods. Although sampling strategies are covered in this text they are covered with the objective of characterising the site in order to have the necessary

background soils information for site selection, result interpretation and simulation modelling.

- Provide guidance on regional or industry scale monitoring of soil condition as is done for resource inventories or sustainability assessments. For this application, readers are referred to McKenzie *et al.* (2002).

**Table 1.2** A quick help for finding the right section!

| Soil characterisation work planner                   |  |  |  |
|--|--|--|--|
| Soils work   | Data required  | Data collection method   | Section in book  |
| <i>A. Basic (most Agricultural research)</i>         |  |  |  |
| Site selection (recommended for all)                 | Soil information<br>Site information<br>Agronomic information (Section 2)  | Soil maps (state govt / soil information system-web)<br>Grower discussions<br>Discussions with advisors<br>Site visits (crop, infrastructure, soil core)<br>Survey (1.5m soil cores) | <ul style="list-style-type: none"> <li>• Site selection decision key (Section 2.2.14)</li> <li>• Site selection (Section 2)</li> <li>• Soil description (Section 4.4)</li> <li>• Soil classification (Section 4.7)</li> </ul>  |
| Soil profile classification (recommended for all)    | Soil classification data sets (Section 3.2.1 and Table 4.3)<br>Standard soil characterisation data set (Section 3.2.2) | Soil pit or core in representative area of site. <ul style="list-style-type: none"> <li>• Soil pits (Section 4.4.1)</li> </ul>   | <ul style="list-style-type: none"> <li>• Data sets 3.2.1 and 3.2.2.</li> <li>• Soil description (Section 4.4)</li> <li>• Sampling profile (Sections 4.6 and 3.3)</li> <li>• Soil classification (Section 4.7)</li> </ul>   |
| <i>B. Application specific (additional to Basic)</i> |  |  |  |
| Agricultural production modelling (APSIM)            | APSIM model data set (Sections 3.2.4, 3.2.5)   | Soil pit small core sampling for laboratory<br>Field core sampling for BD and gravimetric water<br>Nitrate profiles– several deep soil cores   | <ul style="list-style-type: none"> <li>• Small core sampling from a pit (Sections 6.5, 6.6)</li> <li>• Field determination of ) DUL and CLL (Section 6.9)</li> <li>• Calculations (Section 6.2)</li> <li>• Soil core sampling for nitrate profile (Sections 5.10, 5.10.6)</li> <li>• APSIM input files (Sections 3.2.4, 3.2.5, 8)</li> <li>• Infiltration (Section 7)</li> </ul> |
| National soil reference site (ACLEP)                 | Australian soil reference site data set (Section 3.2.3)  | Soil pit and field surface sampling and measurements   | <ul style="list-style-type: none"> <li>• Sections 4, 5, and 6</li> </ul>   |
| Acid sulfate soil site                               | Acid sulfate soil data set (Section 3.2.6)   | Soil core and gouge auger investigation  | <ul style="list-style-type: none"> <li>• Acid sulfate soils (Section 4.8)</li> </ul>   |

## 1.6 STRUCTURE OF THIS PUBLICATION

This publication is divided into nine main sections on soil characterisation.

*Section 2* deals with site selection for research sites and emphasises the importance of assessing soil spatial variability for all potential sites.

*Section 3* outlines the concept of application data sets and provides a number of data sets to be used for different levels of characterisation and different applications.

*Section 4* highlights the importance of soil morphology to agronomy and provides a 'step by step guide' to describing, sampling and classifying a soil profile.

*Section 5* provides background information on soil chemistry tests and indices important for characterising and classifying a soil profile.

*Section 6* deals with soil water properties associated with soil water storage and porosity. It provides guidance on creating adequate data sets for simulation modelling applications.

*Section 7* deals with measuring soil infiltration properties for irrigation scheduling and simulation modelling applications.

*Section 8* covers applications of modelling to research focusing on putting together soils information for the APSIM model,

*Appendix* provides examples of soil characterisation done for some of the CRC Sugar research sites.

*Table 1.2* provides a guide to finding the key information quickly by referring the reader to the section of the book most relevant to the soils work outlined in column 1.

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## Section 2. Selecting a field research site

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The book 'Soils: an Australian Viewpoint' (CSIRO 1983) starts by presenting the following quote from Francis Bacon 'They are ill discoverers that think there is no land, when they can see nothing but sea'. This quote is of course relevant to all aspects of research but it is especially relevant to researchers planning the layout of a field trial as they can ill afford to assume that the soil is homogenous and uniform through out, just because it looks that way on the surface.

This Section discusses some of the factors that are important in the selection of a field experimental site and presents a logical selection process with related guidelines. This process is then summarised in a decision key. The emphasis of this Section is on the soil aspects of this selection process.

### 2.1 FACTORS TO CONSIDER WHEN SELECTING A RESEARCH SITE

Six key factors to be considered when selecting a site for research trials and investigations are listed in the following Section. Of these, the factor most often overlooked is the soil. This can have serious implications as it is the characteristics of the soil that affect the supply of nutrients and water to the crop. Thus any variability in a number of key soil traits across the field has the potential to affect crop growth and therefore interfere with crop response. Any measured differences in crop response between plots may be due to variation in soil properties between plots rather than due to differences in treatment. For example, differences in topsoil or subsoil texture between trial plots across a site are likely to correspond to differences in the amount of plant available water that can be stored in the soil, and this is likely to produce differences in crop growth in drier seasons. To reduce the risk of soil properties confounding research results (i.e. crop response to treatments), it is therefore usually best to choose a site with a soil which is as homogenous as possible.

#### 2.1.1 Landscape factors

Landscape factors mainly involve considering any limitations presented by the landscape to crop growth (e.g. waterlogging, erosion) or to the running of the experiment (e.g. risk of flooding, access limitations). Often local knowledge via discussions with local growers is the quickest way to get this information, after a look at the landscape.

The list of soil map publications at the end of this chapter provides information on the landscapes and soil distributions of many of the sugarcane growing areas.

The following references will help you get the most out of the soil map publications for your district. They provide the required background information and theory on landscape processes that is needed to read the landscape. An overview of the relationships between soil formation and landscape processes in Australia can be found in CSIRO (1983).

- For alluvial or floodplain landscapes: Walker and Butler (1983), Butler (1950), Butler (1959), Butler (1967), Walker (1962), Walker and Coventry (1976).
- For hillslope landscapes: Dalrymple *et al.* (1968), Moss and Walker (1978).
- For coastal dune landscapes: Ward and McArthur (1983).

#### 2.1.2 Soil factors

Two very important aspects of a soil at a site are how representative it is of the soils in the surrounding district and how uniform it is across the site in regard to key soil properties such as texture and structure. Generally, the larger the site, the greater the likelihood that soil variation will be significant. Although, variation in soil properties can sometimes occur over very short distances (< 1 metre). A third aspect to assess is the presence of any inherent limitations to agriculture such as a shallow watertable, salinity, stoniness etc. The implications of these soil properties, which are not easily altered, are discussed further in Section 2.2.1.

### 2.1.3 Climatic factors

Climatic factors which need to be assessed are those which are likely to affect the agronomy of the crop, such as annual rainfall, rainfall distribution throughout the year, minimum, maximum and average temperatures, evaporation rates and humidity throughout the year. Such information can provide an indication of whether the crop will struggle in any part of the year as well as give an early indication of whether any supplementary irrigation will be required. The minimum data required for the SUGARBAG database system include solar radiation, temperature and rainfall (for further recommendations on required climate data refer to Mazzucchelli *et al.* 1997 and SUGARBAG via [www.sugar.jcu.edu.au](http://www.sugar.jcu.edu.au)).

### 2.1.4 Logistical and economic factors

Things to consider here include access to the site; proximity of the site to electricity supply; proximity of site to an existing weather station; water supply; risk of vandalism if monitoring data logging equipment is to be set up; the economics of doing field work at the site in terms of travel costs and the cost of transporting equipment etc.

### 2.1.5 Grower enthusiasm / co-operation

The importance of setting up a research site on the property of a grower who is cooperative and committed is obvious and this aspect of site selection is rarely overlooked.

### 2.1.6 Collaboration opportunities

In these days where funding dollars are hard to come by, any opportunity needs to be taken to collaborate and value add to existing sites for other projects. Such collaboration can provide real savings and greater output per funding dollar.

All of the above site selection considerations have been included in the decision key presented in Section 2.2.14. The following Section focuses on the soils component of site selection.

## 2.2 ASSESSING SOIL SPATIAL VARIABILITY

### 2.2.1 Why a soil survey is necessary

Soil surveys are an essential first step in evaluating prospective research sites. The survey attempts to quantify the extent of variability in observable soil properties across the potential research site. This is important to:

- Ensure variability in soil properties and soil types will not adversely affect the experiment.
- Ensure the soil type present on the site is representative of the soil type in the surrounding growing areas which it is supposed to represent.
- Allow the distribution of soil types and properties across a research site to be taken into account in the interpretation of results.
- Ensure soil sampling sites (e.g. soil pits) are in representative locations for soil characterisation.

Note that the soil survey methodology outlined in the following Section is applicable to investigations of individual fields or paddocks only. For soil surveys of larger areas such as whole farms or research stations, a professional soil surveyor should be consulted.

### 2.2.2 Pre-survey tasks

The following list of pre-survey activities can yield valuable information for a soil survey.

#### Check on any existing soil mapping

A search should be made for existing soil maps that cover the proposed research site area. Such soil map information will be useful for assessing how representative the soils at a site are for the region as a whole, as well as providing additional preliminary information on the soils at the site. Useful sources of information are given below.

- Internet based information systems, Government agencies and library databases.

The 'Enhanced Soils Information for Sugar Lands' system is an internet based information system that was especially developed for the sugar industry by NR&M and CRC Sugar. It

allows users to enquire about available soils information for an area of interest in the Australian sugar lands. This site is located on the internet at [www.nrm.qld.gov.au/Iris/webgis/sugarsoils/](http://www.nrm.qld.gov.au/Iris/webgis/sugarsoils/) and is administered by NR&M. The system is very user friendly and allows the user to zoom into an area of interest by clicking on its location on a map of Australia. Then the user can view a list of soil mapping reports for this area as well as the location of individual soil profile descriptions and sampling sites. At present, soil profile sites include those described for CSIRO and NR&M soil mapping projects and other investigations as well as the research sites in the SUGARBAG database. Once the relevant information is found, the user is then given direction on how to order this information from the relevant organisation.

A similar enquire system is available at the Department of Infrastructure, Planning and Natural Resources (DIPNR - formerly DLWC) web site for NSW soils. This system is called SPADE and is found on the SALIS soil database home page at [www.dlwc.nsw.gov.au/care/soil/salis/](http://www.dlwc.nsw.gov.au/care/soil/salis/). This system can assist researchers working in the NSW north coast sugar industry with their search for soils information.

- A list of NR&M, CSIRO, Agriculture WA, and DIPNR soil survey maps which cover sugarcane growing areas is provided at the end of this chapter.
- A very helpful key for identifying the soil types for areas in the Wet Tropics (from Cardwell to Cape Tribulation) has been developed by Murtha and Smith (1994).
- A soil handbook for identifying the soil types used for sugarcane production in the Herbert region is in the final stages of production (Wood *et al.* 2003).
- Donnollan (1991) provides a useful guide to identifying, understanding and managing Burdekin (BRIA) soils.

### Using soil maps

Soil maps are only a best estimate of the distribution of soil types across the landscape, achieved within the time and money constraints of the mapping programs. They depict a simplified version of the soil

distribution pattern in the landscape. The intensity of investigation and hence the reliability of map units may vary across the map. State departments and CSIRO have done most soil mapping at a scale of at least 1:50,000, while soils information for intensive research sites should be collected at an intensity of 1:5000 scale (Reid 1988). Desktop enquiries of soil map information can be used to quickly reject unsuitable, atypical soil areas and to select potential sites for further intensive soil survey investigations. They should not be used to substitute for an intensive soil survey of the site. However, the location of the soil profiles described in these broad scale mapping programs can often be found and the descriptions which were done by a professional soil surveyor can be accessed from either the map reports or soil databases. These data could be utilised best by choosing potential research sites as close as possible to described sites of a suitable soil type.

### Soil databases

Queensland Department of Natural Resources and Mines (NR&M), New South Wales Department of Infrastructure, Planning and Natural Resources (DIPNR formerly DLWC) and CSIRO Land and Water, all have databases containing soils information from their soil mapping and investigation work. It is worthwhile querying them to see if there is any available soils information for the area being evaluated as a potential site. The NR&M database is called SALI and is administered from the Indooroopilly office in Brisbane. The NSW DIPNR database is called SALIS and it is administered from its Parramatta office, while the CSIRO database is referred to as the National Soil Data Base, and it is administered from CSIRO Land and Water in Canberra. The CSIRO Sugarbag database contains soils information collected from research sites in the sugar industry and is administered by CSIRO Sustainable Ecosystems in Brisbane.

### Relating a mapping soil profile description to a cane field soil

Almost all of the soil profile information from mapping carried out by state agencies and CSIRO has traditionally described soil profiles from uncultivated natural sites. This means

that the surface horizons evident in the soil profiles described and illustrated in these publications will rarely appear like a soil from a sugarcane field. Therefore to interpret these maps one has to use one's imagination and try to picture how the natural soil would look if all of the layers in the top 40cm of the soil profile were mixed together into a homogenous topsoil (see topsoils in soil profile photos – Section 4). If this is done then the subsoil features (i.e. below 40cm) can be used to identify the soil that best relates to that in your cane field.

### Consult local office of relevant agencies

- The main agencies involved in soil mapping in sugarcane areas include NR&M, Department of Primary Industries (DPI), CSIRO, and CSR in Queensland, Agriculture Western Australia in the Ord irrigation scheme and DIPNR in the north coast of NSW.
- Talk to the grower / manager of the site. This can yield valuable local knowledge on any variations in the soil across the paddock, as well as the history of the paddock in regard to land forming activities, cropping practices etc. This is especially important in regions such as the Burdekin where land forming has often disturbed the soil to a depth of 1 metre.
- If possible, observe the previous crop on the proposed site, noting any evidence of variation in crop condition.
- If possible, observe the site when in a ploughed state, noting any differences in the topsoil condition.
- Determine a criterion to be used for accepting or rejecting the proposed research site on the basis of the distribution of soil types and properties across the site as found in the survey.

### 2.2.3 How many soil observations are required?

There is no universally valid answer to this question. The real answer is as many observations as is necessary to determine what soil types are present on the site and where the boundaries are between them. The required observation density will vary with the

complexity of the soil spatial distribution and with the size of the study area.

#### *Sugarbag minimum database*

For example, the recommendation of Mazzucchelli *et al.* (1997) for a 20 m x 20 m grid survey is quite acceptable for sites of 1 ha or less in size where the maximum number of descriptions would calculate out as 16 (allowing a 20 m buffer around the field's edge). But for sites of 6 ha or more, as was case for some of the water use studies in the Burdekin, this density becomes more demanding. For example, the number of required soil descriptions for a field with dimensions of 300 m x 200 m would be approximately 120 (allowing for a 20 m buffer around the field's edge).

#### *Australian Soil and Land Survey Handbook*

Reid (1988) recommends a soil observation density of 0.5 observations per cm<sup>2</sup> of map and a 1:5000 scale map for mapping the soils of research sites. At a 1:5000 scale, 1cm of map covers 0.25 ha of land. This equates to an observation density on the ground of 2 sites per hectare of land.

Reid (1988) recommended a breakdown of these observations as follows:

- 30% detailed soil profile descriptions, ideally to a depth of at least 1.2 m.
- 60-80 % less detailed mapping observations, ideally to a depth of at least 1.2 m.
- 1-5% deep borings of 2 m – 5 m, ideally to a depth of at least 2 m

These recommendations are adequate for the application for which they were originally intended, which is the mapping of the soil distribution on a research station, but they are inadequate for an intensive investigation of soil spatial variability that is required for an area intended for research trial plots. Table 2.1 compares the site observation density recommended by Reid (1988) with our recommendation.

#### *CRC Sugar recommendation*

The following guidelines on the required number of soil descriptions (Table 2.1) reflect the intensity of investigation which we found to be the minimum for adequately

**Table 2.1** CRC Sugar and Reid (1988) recommendations for the minimum number of soil profile observations for assessment of soil variability at a research site

| Minimum number of soil observations to assess different sized study areas |             |      |                     |       |                      |        |                             |        |
|---|-------------|------|---------------------|-------|----------------------|--------|-----------------------------|--------|
| Study area size (hectares)  | < 0.25 ha   |      | 0.25 – 2 ha         |       | 2 – 5 ha             |        | > 5 ha                      |        |
|   | CRC Sugar   | Reid | CRC Sugar           | Reid  | CRC Sugar            | Reid   | CRC Sugar                   | Reid   |
| Number and type of soil profile observations (see Section 2.2.4)          | 1 D<br>2 LD | 1    | 2 D<br>4 LD<br>6 QC | 1 - 4 | 4 D<br>8 LD<br>12 QC | 4 - 10 | 1 D/ha<br>1 LD/ha<br>2QC/ha | 2 / ha |

Abbreviations: D = detailed description, LD = less detailed observation, QC = quick check site.

characterising the soil spatial variability at potential research trial sites. It is envisaged that these observation numbers would be supplemented with more ‘quick check’ soil observations, where they are required due to more complex soil distributions or larger research site areas.

At least 1 deep soil core (2m+) per site would also be desirable for studies investigating crop soil water use, irrigation, or solute movement through the soil.

## 2.2.4 What types of soil observations are required?

The types of soil profile observations listed in Table 2.1 are similar to those outlined in Reid (1988) and these are defined below:

*Detailed* soil profile descriptions involve a full description of the soil profile morphology such as that outlined in Section 4.4, Describing a soil – step by step.

*Less detailed* observations often involve only a quick description of the soil horizons, noting horizon depths, texture, structure and colour, and a note of which detailed soil profile description they are most like.

*Quick check* observations involve as little as observing the soil profile to the top of the upper B2 horizon or subsoil (< 1 m) and simply noting soil colour (a general observation – yellow, brown, red, grey - not the Munsell book) and depths of horizons. Soil texture can be estimated by visual appearance and a quick feel between the thumb and forefinger for this description. These descriptions should take no

more than 10 minutes to do (20 minutes if the time to excavate the soil profile sample for description is included). A hit-in auger or standard Jarret or Dutch clay soil auger would be suitable for such rapid assessments of the soil (see Section 4). Quick check site evaluations of soil profiles are made easier by the practice of keeping a small sample of each different soil layer in a container as the survey proceeds. This allows a direct comparison, which is much faster than referring back to notes and Munsell colour charts (Photo 2.1). Another strategy with intact 1.5 m cores is to keep the remains of the described soil cores in lengths of half poly pipe next to each other in the back of the truck for visual comparison as the survey proceeds. It is desirable to do more "quick check soil observations" in between the initial grid survey observation sites, wherever possible. Such extra observations may help improve the precision of soil mapping boundaries across the field which will help in



Photo 2.1. Using an egg carton in a soil survey to keep samples of each described soil material for quick check descriptions.

designing the trial layout later.

*Deep borings* (2 m to 5 m+) are usually required where subsoil properties such as salt, watertable and impermeable layers are likely to affect land use, as on footslopes and alluvial plains. A full soil profile description is done and samples are taken of both the soil and the groundwater for these sites.

### 2.2.5 How deep should the soil descriptions be?

Observations to a depth of 1.2 m or to a depth necessary to classify the soil are adequate for rain fed agriculture while information to at least 2 m is considered necessary for investigations dealing with irrigated agriculture (Reid 1988). Some deep borings (2 m to 5 m+) are desirable in situations where subsoil properties are likely to affect land use e.g. high water table, salinity, impermeable layers and modelling groundwater systems. Deep soil corings to 5m can be achieved using cork screw augers or split core setups driven by drill rigs or proline. If soil conditions are right, cores to a depth of 2 m can often be achieved by hydraulic auger rigs, jackhammer samplers and hand augers with attachments. A sample to 3.5 m can be obtained by using a jack hammer sampler or hand augering from the bottom of a 1.5 m soil pit site. This is worth doing at all pit sites. Descriptions to 2 m should also be considered for each non-irrigation research site, as they can yield valuable information on the hydrology of the site.

### 2.2.6 Calculating the initial number of soil cores for the soil survey

The following calculations are based on the observation density and type recommendations outlined in Table 2.1.

#### **Example 1: Proposed site for an irrigation experiment is 4.4 hectares in size**

Survey would require:

Total number of soil description sites = 24

These 24 descriptions would comprise:

4 detailed soil descriptions to at least 1.2 m

8 less detailed soil descriptions to at least 1.2m

12 quick checks

Plus 1 deep soil description to 2 m (recommended)

Note that the number of quick check sites can easily be increased to suit the situation.

### 2.2.7 Suitable methods for sampling the soil profile for description

The main methods available for sampling a soil profile are outlined in Section 4.4.1. The best way of exposing a soil profile for description is a soil pit, but this is not a suitable option for an intensive soil survey due to both expense and site disturbance. The most suitable method for soil survey involves using steel push tubes (5 cm diameter x 150cm long) with either a hydraulic sampling rig or a jackhammer driven by a generator, with an attachment custom made to fit the top of the tube.

Hand augering is an alternative way of acquiring a sample of a soil profile to describe if the push tube option isn't possible. The main disadvantages of hand augering are that it can be strenuous and that it provides a disturbed soil sample for description, making it difficult to describe soil structure. Mixing also occurs across horizon boundaries and sampling depths require constant checking.

### 2.2.8 Describing the soil profile

A step by step guide on how to describe a soil profile is outlined in Section 4 of this book.

### 2.2.9 Soil survey methods

The preferred time for a soil survey in sugarcane land is either after harvest or during a fallow period when the cane is low and access is not a problem. The purpose of this initial survey in the site selection process is to assess the site for variability in soil profile morphology. Soil morphology is likely to correlate with many soil hydraulic properties and some basic nutrient storage properties such as cation exchange capacity (see Section 4), but may not correlate with the levels of soil nutrients available to plants. Soil nutrient levels are greatly influenced by any variation in fertiliser management across the field and this

would have to be assessed separately at a later date using a different sampling approach.

There are many ways to sample a field and these are outlined in detail in Brown (1999) and Webster and Oliver (1990), and also discussed further in Section 5. Sampling strategies can be systematic and non-random such as a grid survey or one that follows a traverse line across the landscape sampling at set distances from the start of the traverse. They can also be deliberately biased such as the common sampling approach in soil survey where a traverse line is followed across the landscape sampling at sites judged by the soil surveyor to be representative of an element in the landscape. In the simple random or random grid sampling approaches which are commonly used for sampling in research work, the sampling location is selected using random numbers that correspond to grid coordinates of the site, thus eliminating any bias from the process.

Despite its inherent bias in sample selection, the systematic grid survey approach is thought to be a satisfactory approach for assessing the spatial variability of soils across a potential research site in sugarcane lands for most situations. This is believed to be the case for the following reasons:

- A systematic regular grid provides even coverage across the whole site, while other methods mentioned previously may not. In this instance we are interested in the spatial distribution of soils across the site.
- Sugarcane fields are often flat and featureless due to land forming associated with laser levelling. As a result, little evidence of the previous surface landform features may be present, leaving little for the soil surveyor to base site selection on.
- A systematic approach at least provides the opportunity of narrowing the sampling grid to potentially isolate and delineate areas of variant soils when present in definite isolated areas.

### **A systematic grid survey**

A systematic grid survey is an effective and straightforward way of assessing soil variability, at least over a medium distance

range (i.e. areas of soil over 30 metres wide across a field), provided the grid is sufficiently spaced. It involves creating a sampling grid over the field site from two sets of traverse lines that run perpendicular to each other across the field. In the case of established cane fields, one direction of the traverse lines will run parallel to the rows and the other perpendicular to the rows. This allows a vehicle to be driven down the rows with its wheels in the interrow areas when collecting soil cores.

### **Creating the grid**

#### *Step 1 – Measure the dimensions of the field*

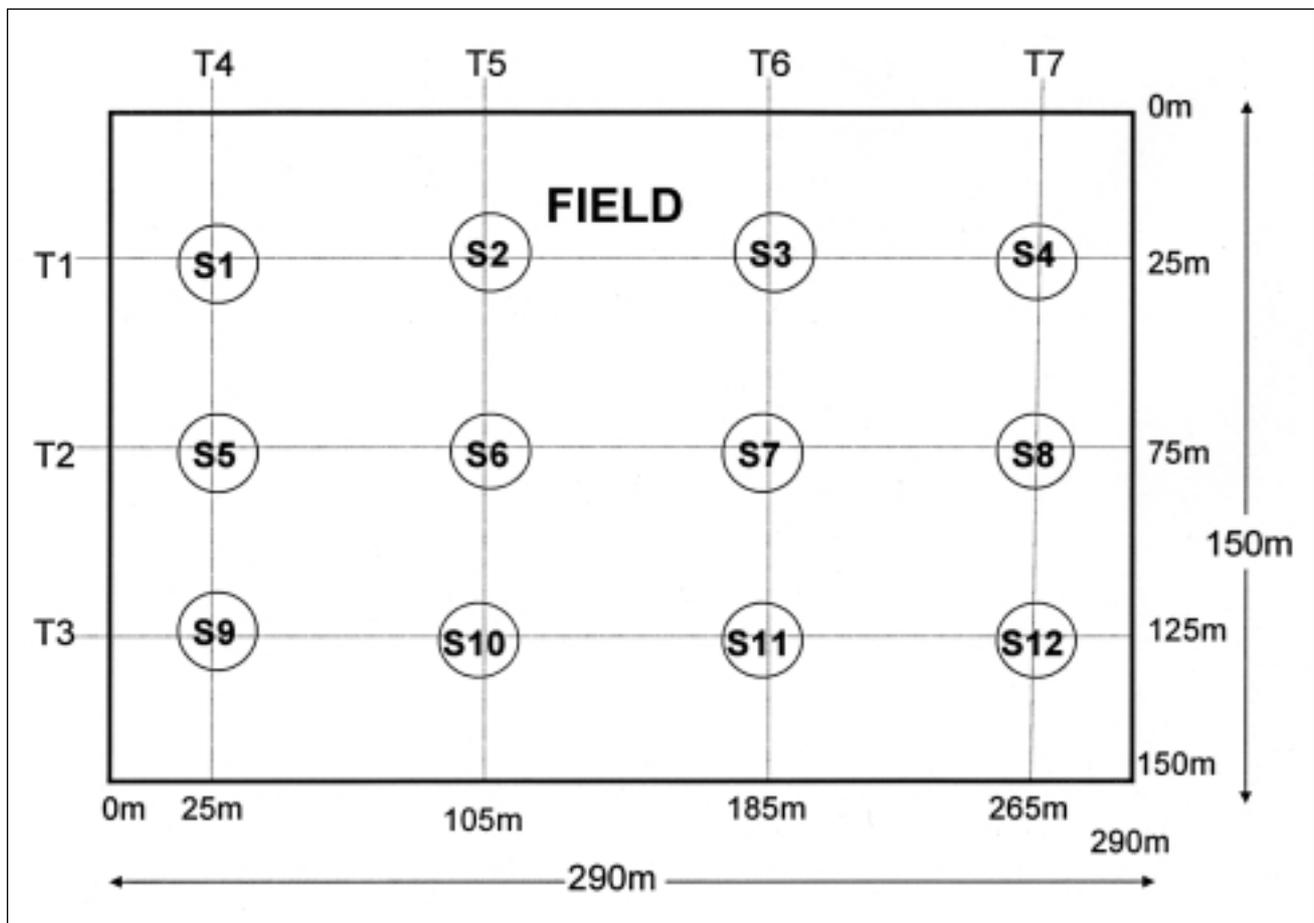
The first step in setting up a sampling grid is to measure the dimensions of the field. This is best done with a GPS recording waypoint at each corner of the paddock. This allows distances to be determined from the 'Nearest Waypoint' function on the GPS, which will list the waypoints and their distance from the GPS site. If the fields are not perfect rectangles, then waypoint location readings should also be taken at any kinks or inflection points in the paddock shape. A vehicle odometer can also be used for measuring the dimensions of the paddock and later sampling, but it is less accurate and a GPS will be required to record the soil core site locations later on in any case.

#### *Step 2 – Calculate the required number of soil cores/ descriptions*

Once the dimensions of the field are known, its area can be calculated. The required number of soil core samples for description can be calculated using the method in Section 2.2.6.

#### *Step 3 – Determine the spacing of the soil description sites*

When setting up a survey grid, it is important to first eliminate any field edge effects from sampling. This can be done by ensuring that any sampling traverse line is at least 15m in from the edge of the field. This aside, the objective of the sampling grid is to achieve an even coverage of the field while at the same time minimising bias in sampling locations. A grid spacing is determined which will provide an even coverage of the field and supply a sufficient number of soil core samples when



**Figure 2.1.** A survey grid created with 2 sets of transect lines for locating soil profile sampling/description sites. In this instance a 50 m x 80 m grid with a 25 m edge was used to locate 12 soil site locations. Transects T1, T2, and T3 run parallel with the cane rows while transects T4, T5, T6, and T7 run perpendicular to them, with sampling sites located where the two sets of transect lines intersect.

sampling at traverse line intersections. An example of this is provided in Figure 2.1 where a 4.4 ha field (150 m x 300 m) has been grided for the survey. Using the suggested guideline, this 4.4 ha site would require around 12 soil descriptions (4 detailed, 8 less detailed). These initial soil descriptions will be followed by the quick check soil descriptions at 12 sites located according to judgement based on the findings of the initial grid survey. In this case a 50 m x 80 m grid spacing with a 30m allowance around the field's edge was selected.

**Stratified grid sampling approach:** Where there is some expression of landscape features in the surface of the cane fields (changes in slope shape and inclination, hollows and rises etc) it may be worthwhile considering a stratified sampling approach. A stratified approach would involve first subdividing the field into areas according to such surface landform features and then sampling each of

them separately (Brown 1999). There is still an argument for the use of a systematic grid sampling approach in sampling each of these subdivided areas as this would ensure an even coverage of them.

**Built in flexibility (sampling different surface features):** It is important to allow for additional sampling of areas of noticeably different surface features or crop appearance when they are present in the field. They may correlate with a difference in soil type and should be investigated. Such features may take the form of a change in slope steepness or shape, site elevation, crop appearance, or observable differences in the colour or texture of the surface soil itself. Changes in crop appearance are sometimes found to be related to differences in topsoil thickness for example. Any areas with stressed crops or areas with evidence of other potential problems such as salt on the soil surface should also be

investigated. These additional samples are taken during the grid survey process whenever such areas are noticed. If these sites are found to have a different soil from that present in the rest of the field, they will require further sampling at the end of the initial grid survey in order to delineate the approximate location of the boundary between this soil and the surrounding soil. In many instances, observable differences in the landscape and crop may not reflect variation in soil profile features, but it is important to investigate differences to confirm if this is the case or not.

#### **Step 4 – Collect the core samples**

Once the grid dimensions have been determined they should be measured out and marked on the field using white pegs and/or bright survey flagging tape. When the field is bare, as at fallow or after harvest, the traverse lines for both directions can be marked on the field. But when the sugarcane is present, it is only practical to mark the start of the traverse lines running parallel with the rows as these are the only ones that will be visible when sampling commences along that line. It is worthwhile marking each sampling site with flagging tape as the survey proceeds as well. This will make it easier to check between sites at a later stage. GPS, vehicle odometer, tape measure, or a system of counting the rows (based on a standard row spacing in the cane) can be used to mark out the points.

The sampling locations can be found when driving along a traverse line through the cane by using a GPS unit. To do this, a waypoint location reading needs to be taken at the start of the traverse at the edge of the field. This will allow the 'Nearest Waypoint' function to be used to measure the required distance along the traverse from the field edge and locate each sampling point. A waypoint reading is taken at each sampling point, and the 'Nearest waypoint' function on the GPS unit then indicates when the required distance has been travelled from this site for the next sampling site location. Alternatively a vehicle odometer or long tape measure can be used to locate the sampling points where a GPS co-ordinate can then be recorded before sampling.

### **2.2.10 Presentation of soil survey information**

When assessing the spatial variability in soil properties across a field, a one dimensional map presentation is not always the best format to use. This is especially the case where the land surface is flat and featureless (as with most cane fields) and where there is significant short range spatial variability in subsurface properties. A stratigraphic presentation of soil cores across the field site, as presented in Figure 2.2, (see colour section, page 00) is a very effective way of communicating soil distribution and variability across a field. It allows a quick appraisal of the variation in soil properties and can help in making a quick decision on where the most representative area of the field is for more detailed characterisation work.

### **2.2.11. EM 31 / EM 38 technology applications**

Ground based electromagnetic induction instruments (Geonics EM-31 and EM-38) provide a measurement of the *in situ* electrical conductivity of the soil, termed apparent electrical conductivity (ECa). The hand held EM 38 instrument can sense ECa to a depth of 1.5m and as such is a useful diagnosis tool for identifying salinity stress in the root zone of crops. It is a component of the sodic soils kit (Nelson 2000) and is currently being used in the Burdekin and other sugarcane regions to identify areas of high salinity. The EM 31 is a larger instrument than EM 38 and it senses ECa to a depth of 6m from the soil surface (McNeill 1980).

The potential of an EM survey for assessing soil variability is due to the fact that the ECa measurement includes the effects of both soil water and solid particles on the conducting of an electrical current. Thus the ECa is dependent not only on soil water salinity but also on soil water content, clay content, bulk density and soil temperature (Slavich 2002). Soil ECa increases with increasing soil water salinity, water content, clay content and temperature, and decreases with increasing bulk density. The ECa of clay textured soils is higher than that of lighter textured soils

(loams) with the same soil water salinity. This texture effect is due to the fact that heavy textured soils hold more water and salt than lighter textured soils and therefore have more pathways for current flow (Slavich 2002).

Because of the influence of the above soil properties on EM measurements of ECa, indirect correlations have been found between ECa and other related soil properties in a number of investigations. This has resulted in the successful use of EM measurements in mapping areas of different soil sodicity (Gallichand *et al.* 1992, Nettleton *et al.* 1994), depth to clay pans (Sudduth *et al.* 1995), soil types (Jaynes 1996) and leaching rates (Slavich and Yang 1990) and in refining soil boundaries (Fenton and Lauterbach 1999) as well as in numerous investigations in geology and archaeology.

The production of ECa maps for a site allows the delineation of distinctly different areas of the field based on EM readings. This is very useful for assessing a potential research site as it provides another basis for targeting soil sampling (Beecher *et al.* 2002, Thompson *et al.* 2002). These different ECa areas may or may not end up correlating with other important

soil properties when targeted with soil sampling, but they provide a unique opportunity to map areas of soils that otherwise have little correlation with observable surface features. Even if one of the grid survey soil description sites manages to sample such an isolated soil distribution, the process of defining the boundary by intensive sampling is much more difficult and tedious without an ECa map.

This approach has the potential to provide a map of the spatial distribution of distinctly different materials (e.g. gravels / sands versus clays) across a site. This would be especially useful in delta areas where the distribution of soil materials can be highly variable spatially (e.g. Burdekin catchment), and also for many floodplain locations where sandy / gravelly deposits associated with infilled prior stream channels, for example, are scattered across the floodplain. A map of the continuous spatial distribution of gravelly and clayey soil materials across the site by EM 31 or EM 38 has potential to allow a site to still be used if plots can be located in such a way as to still ensure uniformity in soil type by avoiding the areas of variation (Figures 2.3 and Photo 2.2). The results of a grid survey, on the other hand, may



Photo 2.2. A typical flat featureless field following landforming, near the location of the ECa map in Figure 2.3. This field is not dissimilar in appearance to a sugarcane field after laser levelling. (Photo: BW Dunn, NSW Agriculture)

not provide the same level of confidence for interpolation between observation points and the detection of such soil profile variation within an area by grid survey may often result in the site being rejected.

Irrespective of the strength of correlation between the ECa map and other observable soil features, this information can still provide another level of soils information that can be used to define the best sites based on uniformity and also to decide on the location of individual plots and treatments (Thompson *et al.* 2002). Treatment plots can be located in areas of the field that have more uniform spatial distribution of ECa values, while avoiding any areas that are highly variable or atypical. Thompson *et al.* (2002) have recommended EM surveys be done prior to laying out irrigation experiment plots. This is to ensure that any underlying soil stratigraphic differences that have the potential to confound research results are detected, and the site either rejected or the layout altered to avoid these areas. EM surveys can also be used to review and explain problems with results at the end of

an experiment (Thompson *et al.* 2002), but this is obviously a less desirable option.

### Carrying out an EM survey

The EM 31 can be either carried by hand during a survey or mounted on a 4WD agricultural bike and driven over the site (Photo 2.3). An electromagnetic induction survey with a Geonics EM 31 combining EM data with real time differential GPS data stored in a data logger can be used to produce an ECa contour map using the software program SURFER (Beecher *et al.* 2002). Similarly, a systematic grid EM survey of a site can be done manually with a hand held EM 38 by walking a grid pattern across the field, taking EM and GPS readings at regularly spaced intervals. Nelson (2000) provides some tips for this procedure. The EM 38 can also be set up on a sled arrangement and dragged over the site by a 4WD agriculture bike for a rapid survey similar to the EM 31 approach outlined above (Photos 2.4, 2.5, and 2.6).

An EM survey should in no way be treated as a substitute for a soil survey of the research site,



Photo 2.3. An EM 31 sensor mounted on a 4WD Ag bike with a differential GPS and continuous data logger. This allows a rapid coverage of a site to produce an ECa map. (Photo: Brian Dunn, NSW Agriculture).



Photo 2.4. A sled arrangement that allows the smaller EM 38 sensor to be dragged over a field site, giving a continuous feed of ECa and GPS readings to a data logger on the bike. Such a sled arrangement would be suitable for flat laser levelled fields, but not for mounded fields.(Photo: Brian Dunn, NSW Agriculture)

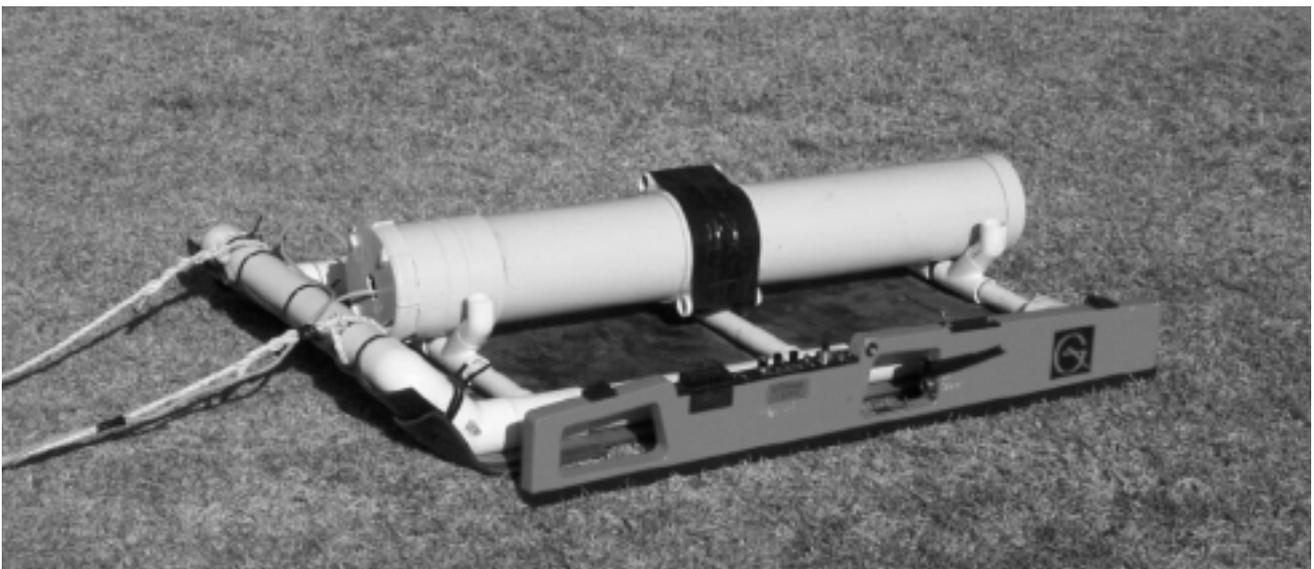


Photo 2.5. A close up of the sled showing the EM 38 sensor set up in vertical dipole mode which has a measurement depth of approximately 1.5m. (Photo: Brian Dunn, NSW Agriculture)

but rather be used as an additional resource to add value to this assessment. It is important to carry out a soil survey of each potential site following the procedure outlined earlier. Probably the best approach is to first assess the ECa map in light of the initial soil survey findings before then carrying out a targeted sampling approach to evaluate the ECa contour map for any possible correlations with soil

properties. EM survey information can be a great resource for evaluating potential research sites, provided it is only used as an additional tool to aid the location of additional soil profile descriptions and that it is used with a healthy degree of caution. No soil - ECa relationships should be assumed without overwhelming evidence from numerous soil profile descriptions and samplings in the field.



Photo 2.6. Showing the EM 38 sensor set up on its side in the sled for horizontal dipole mode measurements which provide an effective measurement depth of 0.75m. Note the cable which continuously feeds readings to the data logger on the bike. (Photo: Brian Dunn, NSW Agriculture)

### 2.2.12 Deciding to accept or reject a research site

To decide whether to accept or reject a research site on the basis of soil variability, one must first define whether soil uniformity or soil representativeness, or both, is desired.

Uniformity is usually a priority to ensure a crop response is due to a treatment and does not reflect soil variation. How much variability in soil properties is acceptable has to be judged against the relative effect of that variation on soil function and soil - plant interactions and whether or not such variation is likely to affect the experiment results. For example, large variations in soil texture from sand to clay will obviously have a big influence on the soil's ability to store water and nutrients and to drain, whereas minor variation from clay loam to clay is likely to be less drastic. Variation in transient properties such as soil surface pH can easily be amended and are not usually a concern, although this would obviously be a problem for a lime trial.

For decisions regarding the significance of variation in soil morphology across a site, consult the table on soil morphology in Section 4. The following points provide a few tips for when assessing such properties. As a general

rule, any variation that causes significant differences in drainage, water and nutrient storage across a site should be avoided. A quick glance at the table in Section 4 of this publication reveals that soil profile form, texture and structure are all important for these properties. For the soil texture property, the texture groupings by Isbell (1996) in the family level of the Australian Soil Classification are fairly practical in terms of soil function. Isbell groups the sands, loamy sands and clayey sands together as the 'sandy' grouping (up to 10% clay content), the sandy loams and loams together as the 'loamy' grouping (10-20% clay), the silty loams and silty clay loams together as a 'silty' grouping (25-35 % clay and silt 25% or more), and the light clay, medium clay and heavy clay textures together as the 'clayey' grouping (>35% clay). Variation from

one texture grouping to an adjacent grouping (e.g. from clay loam to clay) is less significant than say from sand at one end of the spectrum to clay at the other. When assessing differences in profile form, it is best to group uniform and gradational soil profiles in one grouping and duplex or texture contrast profiles in another for assessing a soil in terms of drainage. Any assessment of profile form in terms of drainage must take texture, structure and colour into consideration simultaneously. For any assessment of the relevance of soil structure, the shape of the soil peds is very important. The influence of soil structure on soil drainage needs to be assessed in the light of soil texture. For example, a sandy loam soil with a massive soil structure will most likely be well drained because of the pores resulting from the packing spaces between individual coarser sand grains in the soil. Colour is usually a reliable indicator of soil drainage. A notable exception to this are those soils with shallow water tables due to landscape position. Here it is possible to have a sandy soil profile with good internal drainage but, because of its position in the landscape, it has a shallow watertable that rises up from below and gives the soil a grey, yellowish or white soil colour (see the grey sand soil profile in Photo 4.3).

This example in particular highlights the need to assess soil morphological properties together in order to more effectively interpret soil profile information.

A highly variable soil distribution may be considered acceptable in cases where variability is typical of a large proportion of the growing area (e.g. some areas of the Burdekin catchment). If this is the case the need for the site to be representative may outweigh the desire for uniformity. The questions outlined below can help with decisions on the suitability of a site in terms of soil variability.

### **Some key questions that need to be asked**

**Question 1.** Is it important for the experiment site to have a fairly uniform soil type and morphological properties?

The answer to this question will in most cases be yes as any variation in soil properties which affects soil function in terms of soil-plant interactions has the potential to confound treatment results.

**Question 2.** Were the variations in soil properties across the site detected in the survey different enough to translate into significant differences in soil function for soil-plant interactions?

If not significant, it may be acceptable to ignore the variation.

**Question 3.** If variation is significant, was it possible to separate out and delineate its spatial distribution in the field using the soil survey?

If the distribution of the variant soils/properties is scattered in patches throughout the site, there may be little opportunity to avoid these areas through experimental plot layout and the site may need to be rejected.

If the spatial distribution of the variant soil profiles / properties could be delineated and is minor in its distribution, there may be opportunity to design the plot layout to avoid this area.

### **Variation in soil nutrient levels**

The extent of variability within soil nutrient levels across the experiment site can be

effectively minimised as much as is practical by locating all individual plots within a single field which has received the one fertiliser management over time, provided the soil type is consistent across the site. Where this is not possible the differences in nutrient status will need to be documented and accounted for in the experiment design and protocols.

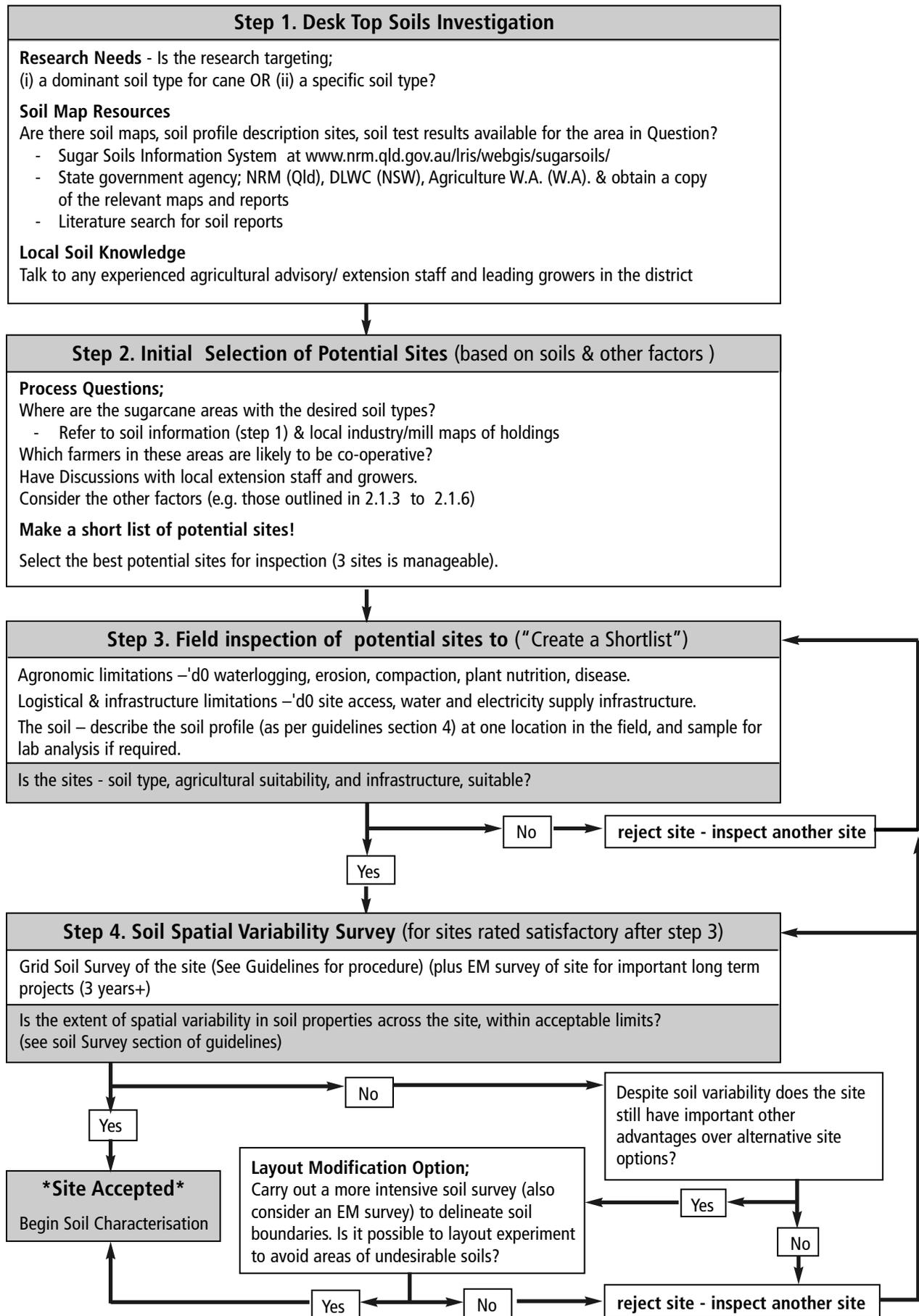
### **Variograms**

For long term research sites that are likely to be used extensively for research over many years (e.g. Regional Agricultural Research Stations), it would be worthwhile to also determine the spatial variation functions (variograms) for key soil properties across the site (especially soil chemistry). Such information can be valuable for designing plot layouts and developing soil sampling strategies. Variograms can be determined from systematic soil sampling using the geostatistical theory of regionalised variables (refer to Burrough 1991, Davis 1986, Webster 1985, Burgess and Webster 1980a and 1980b).

### **2.2.13 Locating the soil pit site for a detailed soil characterisation**

Once a site has been approved for an experiment using the previously outlined procedure, a representative area of the field can be selected for soil profile characterisation. The selection of the location of this soil characterisation site is based on profile descriptions from the soil survey, ensuring that the site has a soil profile that is typical or modal for the field as a whole. Commonly a soil pit is excavated to characterise the soil and there are a number of additional factors to consider for this (see Section 4). At this site the soil morphology should always be characterised (Section 4), and usually the soil chemistry (Section 5) as well. Sometimes soil porosity and water storage properties (Section 6) or soil infiltration properties (Section 7) may also need to be characterised, depending on the objectives of the study. Application data sets are presented in Section 3 to provide some assistance in decisions on what soil data may need to be collected to adequately characterise the soil for a given project.

## 2.2.14 Decision key for selecting a research site



## 2.2.15 Soil survey list (sugar cane lands)

### **DNR / QDPI soil mapping**

Queensland Government Agencies (NR&M and QDPI) have carried out a great number of soil mapping projects across all of the major sugarcane growing regions from Tully in the wet tropics to the NSW border. Information about this mapping is readily accessible at the 'Enhanced Soils Information for Sugar Lands Information System' located on the internet at [www.nrm.qld.gov.au/lris/webgis/sugarsoils/](http://www.nrm.qld.gov.au/lris/webgis/sugarsoils/). Nelson (2001) also provides a substantial list of some of the DNR / QDPI soil mapping done in the sugarcane growing regions of Queensland. Some of the relevant soil mapping work by other agencies and in other sugarcane growing states is not as easy to access or search as the DNR / QDPI mapping above and because of this a list of relevant soil mapping by these agencies is listed below.

### **CSIRO soil mapping in the Wet Tropics (Herbert to Tully)**

Soils of the Cardwell Tully area, north Queensland, CSIRO Aust. Div. Soils, Divl. Rep. No.115. - Cannon, M.G., Smith, C.D., and Murtha, G.G.(1992)

Soils of the Tully-Innisfail area, North Queensland. CSIRO Aust. Div. Soils. Divl. Rep. No. 83. - Murtha, G.G. (1986)

Soils of the Mossman-Cape Tribulation area, North Queensland. CSIRO Aust. Div. Soils, Divl. Rep. No. 102. - Murtha, G.G. (1989)

Soils of the Babinda-Cairns area, North Queensland. CSIRO Aust. Div. Soils. Divl. Rep. - Murtha, G.G., Cannon, M.G., and Smith, C.D. (1994).

Soils and land use on the Atherton Tableland, North Queensland. CSIRO Aust. Div. Soils. Soil and Land Use Series No. 61 - Laffan, M.D. (1988)

Key to the soils and land suitability of the Wet Tropical Coast: Cardwell to Cape Tribulation. CSIRO Aust. - Murtha, G.G., and Smith, C.D. (1994).

### **New South Wales (Queensland border to Clarence catchment)**

Soil landscapes of the Murwillumbah-Tweed Heads 1:100,000 Sheet. DLWC. Morand, D.T. (1996)

Soil landscapes of the Lismore-Ballina 1:100,000 Sheet. DLWC. Morand, D.T. (1994)

Soil landscapes of the Woodburn 1:100,000 Sheet. DLWC. Morand, D.T. (2001).

### **Western Australia (Ord River Irrigation Area)**

Weaber Plain soil survey - 1:50,000 map. Agriculture Western Australia Resource Management Technical Report No. 152. - Jim Dixon (1996).

Packsaddle infill area soil survey - 1:20,000 map. Agriculture Western Australia. Resource Management Technical Report No. 157 - N. Schoknecht (1996)

Packsaddle North West soil survey - 1:20,000 map. Agriculture Western Australia. Resource Management Technical Report No. 156 - N. Schoknecht.

Ivanhoe West Bank soil survey - 1:25,000 map. Agriculture Western Australia. Resource Management Technical Report No. 155 - N. Schoknecht & C. Grose.

Knox Creek Plain soil survey - 1:25,000 map. Agriculture Western Australia. Resource Management Technical Report No. 153 - N. Schoknecht, C. Grose, D. Fett, S. Johnston (1996)

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# Section 3. Soil data sets

## 3.1 CONCEPT OF APPLICATION SOIL DATA SETS

An 'Application Soil Data Set' is a list of soil properties considered essential for a specified application e.g. soil classification or simulation modelling. They are a guide to ensure that essential information is collected for a defined task. Data sets are listed in this Section. They include firstly the necessary data to classify the soil (data set 1) and also allow for a basic characterisation of the soil for agriculture (data set 2). Additional 'application specific' data sets are also provided which list the additional data to be collected for those applications e.g. data sets 4 and 5 are for crop production modelling applications with APSIM. These additional data can be added to data sets 1 or 2 to determine what soil data are required to both characterise the soil and utilise the desired applications. Data set 3, "The Australian Soil Reference Site Data Set" (McKenzie *et al.* 1995), was included to illustrate the detailed soils information that is required for a soil reference site considered to be of regional significance.

It must be stressed that these data sets are not

intended to cover the needs of every application, but rather the requirements for basic soil characterisation in most cases.

The concept of application data sets embraces the principle that some soil tests are more relevant than others for different soil investigations while at the same time accepts that a few soil tests are essential for all soil investigations.

For the following data sets, those soil tests rated as

- *Essential* should be compulsory for all soil investigations.
- *Recommended* should be considered compulsory for most standard soil characterisations. These are tests that can add great value to understanding the limitations of a soil.
- *Optional* are soil tests that can provide some additional valuable information but are not considered essential for the immediate application. It is up to the individual to judge if this information is of relevance to their investigation.

## 3.2 SOME APPLICATION SOIL DATA SETS

### 3.2.1 Data set 1 - Soil classification data set

#### Soil morphology (essential)

The following properties should be described for each soil horizon to classify the soil:

- Layer number
- Horizon designation
- Depth to lower boundary of each soil layer from the soil surface (values increasing with depth from the soil surface)
- Horizon boundary shape and distinctiveness (especially between the bottom of the A/ B1 and the top of the B2 horizon)
- Matrix colour (Munsell - moist / dry)
- Mottle colour (Munsell - moist) and %
- Segregations - type, form, and size
- Coarse fragments (% of soil volume, size, mineralogy, shape, distribution)
- Field pH (Raupach or pH 1:5 soil water)
- Texture grade
- Structure - grade size and shape.
- Pans (if present)

- HCl reaction for alkaline soils (pH 8 and above)
- Presence of slickensides, stress cutans or lenticular peds in soil horizons.
- Soil surface condition - cracked, crusted, hardset, soft, friable etc.
- Evidence of cracking in the soil or gilgai on ground surface

### **Soil morphology (recommended)**

Describing the following properties for each soil horizon provides very useful information:

- Consistence
- Aggregate stability test.
- Porosity
- Roots (abundance and size)
- Soil moisture status

### **Site information (essential)**

- Site location: Australian Map Grid Reference (GPS or Topographic map) - eastings and northings to within 25 m and brief description of locality (distance and direction from nearest town, road, natural or cultural feature, property owners name etc.).

### **Other essential information**

- Date of description.
- Name of person who described the soil and their organisation. Whether or not soil samples were collected.

### **Site information (recommended)**

- Vegetation: if still under native vegetation - refer to McDonald et al. (1990).
- Land surface: aspect, elevation, slope, micro relief, erosion.
- Landform element: hillcrest, footslope, floodplain, terrace)
- Substrate: lithology type, parent material, observation type (soil pit, rock outcrop etc).

### **Chemical properties** (Refer to Table 4.4 for which soil horizons to test)

- Soil pH (1:5 soil water suspension)
- Electrical conductivity (EC dSm<sup>-1</sup>) of groundwater (Hydrosols)
- Electrical conductivity (EC) 1:5 soil water extract (Rudosols)
- CaCO<sub>3</sub> % (only for soils pH > 7.5)
- Cation exchange capacity
- Exchangeable cations
- Exchangeable acidity (only for soils pH < 6.0)
- Free iron (suspected Ferrosol soils only)
- Organic carbon or loss on Ignition (LOI)

### **Physical properties**

- Particle size analysis (2µm, 20µm, 0.2mm, and 2mm).
- Coarse fragments (>2mm)
- Linear shrinkage or modified linear shrinkage (an option for suspected Vertosol soils only i.e. when the clay soil is observed in the field in a moist condition with no cracks evident at the surface)

**Note:** the laboratory analyses required to classify a soil using the Australian Soil Classification (Isbell 1996) are outlined in more detail in Section 4.7 Soil Classification

### 3.2.2 Data set 2 - Standard soil characterisation data set

**Soil morphology** = both essential and recommended in data set 1

**Other features** = those features outlined in data set 1

**Site information** = both essential and recommended features in data set 1

#### **Chemistry (essential for each soil horizon)**

- Soil pH (1: 5 soil water suspension)
- Electrical conductivity (EC) 1:5 soil water extract
- Cation exchange capacity
- Exchangeable cations
- Exchangeable acidity (only for soils pH < 6.0)

#### **Chemistry (essential for topsoil (A) horizons)**

- Organic carbon or loss on ignition (LOI)

#### **Chemistry (recommended for topsoil (A) horizons)**

- Extractable P
- P sorption / retention
- Total N
- Plant available silica (optional)

#### **Chemistry (recommended for subsoil (B) horizons)**

- Free iron (suspected Ferrosol soils only)

#### **Physics (essential for each soil horizon)**

- Particle size analysis (2 $\mu$ m, 20 $\mu$ m, 0.2mm, and 2mm) (Vertosol soils only)
- Coarse fragments (>2mm)
- Emerson aggregate test

#### **Physics (recommended for each soil horizon)**

- Bulk density
- Plant available water capacity (PAWC)

#### **Physics (optional for selected soil horizons)**

- Saturated hydraulic conductivity (Ksat) of surface (A) horizon and the most impermeable B horizon
- Unsaturated hydraulic conductivity (K) at suctions 1cm, 2cm, 3cm, for the surface (A) horizon and the most impermeable subsurface layer
- Liquid and plastic limits for the surface (A) horizon
- Linear shrinkage or modified linear shrinkage (subsoils of suspected Vertosol soils only)

### 3.2.3 Data set 3 - Australian soil reference site data sets

#### **Soil morphology**

- Descriptive standard
- Layer number
- Horizon
- Matrix colour (moist / dry)
- Mottle colour, %
- Segregations
- Coarse fragments
- Field pH
- Boundary shape / distinctiveness
- Texture
- Structure

- Depth
- Pans
- HCl reaction
- Classification (Australian)

### **Soil chemistry**

- Soil pH (1: 5 soil water suspension)
- Soil pH (1: 5 soil: 0.01M CaCl<sub>2</sub>)
- Electrical conductivity (EC) 1:5 soil water extract.
- % CaCO<sub>3</sub> (only for soils pH > 7.5)
- Cation exchange capacity
- Exchangeable cations (Ca, Mg, Na, K)
- Exchangeable acidity (only for soils pH < 6.0)
- Organic carbon
- Extractable P
- P sorption / retention
- Total N\*
- Total P
- Total K

### **Soil physics**

- Water retention curve
- Hydraulic conductivity
- Bulk density
- Particle size
- Liquid / plastic limits
- Aggregate stability
- Shrinkage potential

### **Site details**

- Location, access, date, agency code, land use, type of observation, site no., landholder, images, described by, tenure

### **Climate (monthly)**

- Average maximum and minimum temperatures, average rainfall, potential evaporation

### **Landform**

- Slope, morphological type, relief / slope class, landform pattern, landform element, drainage

### **Vegetation**

- Type, tallest stratum form and species, mid-stratum form and species, ground cover form 7 species

### **Land surface**

- Aspect, elevation, micro relief, erosion, surface coarse fragments

### **Substrate**

- Type of observation, lithology type, parent material, mineral composition, structure, grain size, texture, structure, strength

### **Data quality**

- Completeness, spatial relations, significance, positional accuracy, validation status, map unit resolution, class definition, accessory

### 3.2.4 Data set 4 - APSIM - SoilWat model soil data set

(Essential soils input data for the APSIM Agricultural Production Simulation Model)

- Drained upper limit (DUL) in  $\text{mm}^3 \text{mm}^{-3}$
- Crop lower limit (LL) or 15 bar (-1500kPa) lower limit (LL15) in  $\text{mm}^3 \text{mm}^{-3}$
- Volumetric water content at saturation (SAT) in  $\text{mm}^3 \text{mm}^{-3}$
- Air dry moisture content ( $\text{mm}^3 \text{mm}^{-3}$ )
- Nutrient profile, especially soil N file inputs [mineral N:  $\text{NO}_3$  and  $\text{NH}_4$  ppm, organic C%, total N%, and pH with profile depth (to 150+ cm) for field composite samples from > 15 deep soil cores]\*.
- Maximum potential rooting depth in mm
- Layer depth interval in mm

(Refer to modelling section for more details - Section 8)

\* Soil profile morphology should be characterised for fields where these data are collected.

### 3.2.5 Data set 5 - SWIMv2 model soil data set

(Basic soils data for SWIM model but also applicable to HYDRUS)

#### Soil physics (ideally for each soil horizon)

- Soil water retention curve  $\psi(\theta)$  for several suctions or soil water potential ( $\psi$ ) points between saturation ( $\psi = 0$  kPa) and wilting point ( $\psi = -1500$  kPa).
- Saturated hydraulic conductivity
- Unsaturated hydraulic conductivity at a couple of tensions (e.g. 2 cm, 4 cm)
- Layer (horizon) depth intervals
- Solute concentration depth profile in soil (starting point) required for some applications

\* These measurements should at the very least be done for the surface of the topsoil (row and interrow if present) and the most impeding subsoil layer.

- Nutrient profile, especially soil N file inputs [mineral N:  $\text{NO}_3$  and  $\text{NH}_4$  ppm, organic C%, total N%, and pH with profile depth (to 150+ cm) for field composite samples from > 15 deep soil cores] for APSIM applications.

\* Soil profile morphology should be characterised for fields where these data are collected.

### 3.2.6 Data set 6 - Acid sulfate soil data set (supplement)

#### Soil chemistry

- Chromium reducible sulphur (Scr %) (Method 22b ASSMAC, Ahern *et al.* 1998)
- Soil pH ( $\text{CaCl}_2$ ) (Method 4B1, Rayment and Higginson 1992)
- Total actual acidity (TAA) (Method 21F ASSMAC, Ahern *et al.* 1998)
- Electrical conductivity (EC) (Method 3A1, Rayment and Higginson 1992)
- Soluble chloride (Method 5A, Rayment and Higginson 1992)
- Soluble sulfate
- Total carbon (%) (by Leco combustion, Method 6B3, Rayment and Higginson 1992)

Note: It is advisable to check with QASSIT, NR&M for advice on the latest information on suitable laboratory tests, as tests are continually being refined and developed.

## 3.3 RATIONALISING THE SOIL TESTING TO BE DONE

### 3.3.1 Deciding which samples from the soil profile can be left out

If finances do not allow for each sample from each horizon to be tested for chemical and physical properties, decisions have to be made on which samples to exclude.

Guidelines on appropriate ways to sample a soil profile using either the more intensive approach of continuous sampling at successive

depth intervals down the profile or a more selective approach are provided in Section 4.6. The following discussion is based on dealing with soil samples collected using the more intensive sampling approach. Samples are collected as a series of soil samples which cover the whole soil profile as a continuum while horizon boundaries (defined using the guidelines in Section 4) are used as the basis for sampling subdivisions. This sampling provides a large collection of soil samples to be analysed for each soil profile. If every recommended test in the data set was to be carried out for each sample it would be very expensive, so some sort of rationalisation of laboratory testing usually has to be done to keep within budget constraints.

The following example shows a sequence of decisions that can be made to scale back the number of samples to be tested and the logic or rationale for each of those decisions. It is presented from option 1 (most expensive option) to the last resort (cheapest acceptable option). Option 3 is probably the most sensible option for most situations as it represents the best value for money.

**Option 1.** Test every soil sample (i.e. a sample from every sampling depth interval) within each soil horizon.

**Option 2.** Test all topsoil (A) horizon samples plus samples from at least the top half of the subsoil B horizon plus only one sample from each other horizon. The rationale for this decision is: A horizons are dynamic in terms of soil nutrient levels and justify extra attention; analysis of the top and major part of the subsoil B horizon, is often a requirement of the Australian Soil Classification System.

**Option 3.** Test the surface sample of the topsoil horizon (0-10 cm) plus samples from at least the top half of the subsoil horizon plus one sample from each other soil horizon (samples between 10 cm and 30 cm thick). The rationale for decision is: the upper part of the A1 horizon is the most important for nutrient storage and supply for plants; subsoil rationale as above.

**Option 4.** (Last resort). Test the top of the A1 horizon (0-10 cm) plus the samples from the upper half of the subsoil B horizon. The rationale for decision is as above. This approach provides enough data to classify the

soil, but little else.

### 3.3.2 Deciding which tests can be left out

The soil tests selected for data sets 1 and 2 are essential for good soil characterisation and there is little justification for not doing these tests. So the first cut back in soil analysis would have to be not to do the tests classed as optional in these data sets. The second option would be to cut out the tests labelled recommended.

Before cutting back the number of soil tests to be done, it may be preferable to first cut back the number of soil samples to be tested as outlined in options 1 to 4. This is because it is usually better to have a lot of information about those zones of the soil that are of most importance for soil function, for example the upper part of the topsoil and sometimes the upper part of the B2 horizon, than to have a limited amount of information on the whole soil profile. If there are still funds available it is then worth considering getting the essential tests done on one soil sample from each of the other soil horizons.

## 3.4 SUGARBAG DATABASE AND MINIMUM DATA SET

SUGARBAG is a database system developed for the storage of sugarcane crop growth, climate, soils and management data which have been collected from experiment sites in the sugar industry (Prestwidge and Mazzucchelli 1998). The data base is designed to store experimental data listed in the minimum data set (data set 7) using the procedures of collection outlined in the minimum data set publication of Mazzucchelli *et al.* (1997). CSIRO Sustainable Ecosystems, Brisbane, administer the database. Some of its aims are to assist in the identification of production constraints by allowing comparisons across regions and to facilitate the use of model analysis in conjunction with historical climate data in research and policy decisions (Prestwidge and Mazzucchelli 1998). The methodology outlined in the minimum data set involves soil fertility analyses for

standard 0-20 and 40-60 cm depth intervals. The assessment of the field's soil for both morphology and physical and water storage properties is done for set depth increments (0-20, 20-40, 40-60, 60-90, 90-120, 120-150, 150-180 cm) according to the minimum data set method.

### 3.4.1 Suitability of using set depth interval approach

The set depth interval basis of sampling is acceptable for diagnosing soil fertility status as this is the standard approach. The set depth interval approach for soil water and porosity properties is the same approach outlined and recommended by Dalgliesh and Foale (1998) and is suitable for uniform texture soil profiles or for soil profiles which increase only gradually in clay content and texture grade with depth. However this approach is less suitable for soil profiles that change in texture abruptly with depth or contain thin stratified layers (refer to discussion in Section 6). For the description of soil morphology, the set depth interval approach is certainly not desirable as it is the identification of individual soil horizons and the depths of their boundaries that forms the actual framework of the profile description.

The fact that some of the guidelines in this publication differ from those of the minimum data set guidelines that were written specifically for SUGARBAG is not a problem as this data can still be stored in the SUGARBAG database. This is because SUGARBAG is quite flexible and is capable of storing soil data collected at a number of different depth intervals for an individual field site. All that is required is the entering of the upper and lower depths of the section of soil that is being described. Storage of experiment site data in the SUGARBAG database is to be encouraged as it maximises the value to the industry of such characterisation work. The minimum data set is listed in data set 7 and the tests for each of these properties are outlined in Mazzucchelli *et al.* (1997). For the latest list of the minimum data set refer to the CRC Sugar web site ([www.sugar.jcu.edu.au](http://www.sugar.jcu.edu.au)) and search for SUGARBAG. It can be seen from a perusal of data set 7 that the SUGARBAG database is capable of storing much of the data generated in data sets 1 to 6.

### 3.4.2 Data set 7 - SUGARBAG minimum data set

#### Site and sample information

- Sample number
- Plot identification
- Date
- Upper depth
- Lower depth
- SUGARBAG soil variable code
- Amount

#### Residue data

- Amount of residue
- Residue C:N ratio

#### Soil chemistry data

- Total nitrogen
- Dry bulk density
- Boron (hot CaCl<sub>2</sub>) mg/kg
- Calcium (amm.ac.) meq / 100 g
- Cation exchange capacity
- Chloride
- Copper
- Electrical conductivity
- Iron
- Magnesium (amm.ac.) meq / 100 g
- Manganese (DTPA) mg/kg
- Ammonium N concentrations in dry soil
- Nitrate - N concentrations in dry soil
- Organic carbon
- Nitrogen
- Soil pH
- Phosphorus (BSES)
- Phosphorus (Colwell)
- Potassium
- Sodium
- Sulphur (mg / kg)
- Zinc
- Water table nitrogen concentration (when sampled)

#### Soil field characteristic data

- Potential maximum rooting depth
- Runoff curve number
- Depth to watertable (at crop start)

#### Optional soil data

- Soil Classification or description
- Clay mineralogy
- Swelling
- Bare soil albedo
- Evaporation bare soil albedo
- Evaporation stage 1; upper limit

- Hard setting

#### Soil depth increment characteristic data

- Saturated water content
- Drained upper limit
- Lower limit
- Bulk density
- Organic carbon (start of crop)
- Nitrogen content (start of crop)

#### Optional soil data

- Particle size
- Structure dispersion
- Saturated hydraulic conductivity (mm/hr)
- Water content at 0.1 bar, 0.3 bar, 1.0 bar, 15 bar
- Drainage coefficient
- Coarse fragments
- Field pH
- Boundary shape / distinctiveness
- Texture
- Structure
- Depth
- Pans
- HCl reaction
- Classification (Australian)

#### Soil chemistry

- Soil pH (1: 5 soil water suspension)
- Soil pH (1: 5 soil: 0.01M CaCl<sub>2</sub>)
- Electrical conductivity (EC) 1:5 soil water extract
- % CaCO<sub>3</sub> (only for soils pH > 7.5)
- Cation exchange capacity
- Exchangeable cations (Ca, Mg, Na, K)
- Exchangeable acidity (only for soils pH < 6.0)
- Organic carbon
- Extractable P
- P sorption / retention
- Total N\*
- Total P
- Total K

#### Soil physics

- Water retention curve
- Hydraulic conductivity
- Bulk density
- Particle size
- Liquid / plastic limits
- Aggregate stability
- Shrinkage potential

\* For the latest version of the SUGARBAG data set, refer to SUGARBAG by searching the CRC Sugar Web site ([www.sugar.jcu.edu.au](http://www.sugar.jcu.edu.au)).

## 3.5 REFERENCES

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# Section 4. Characterising soil morphology

## 4.1 IMPORTANCE OF SOIL PEDOLOGY

Pedology is that area of soil science that studies the process and factors involved in soil formation including the quality, extent, distribution and spatial variability of soils (Wilding 2000). It is basically the study of soil morphological features present in the soil profile and their distribution across the landscape. Pedology is widely recognized for providing an understanding of how soils form and why they are distributed as they are throughout the landscape. It is the basis of all

soil classification systems.

A valuable aspect of pedology is the direct relevance of soil morphological features to important agronomic properties, such as soil drainage, water storage, nutrient storage, aeration, root penetration, and seedling emergence. To highlight this point, Table 4.1 outlines the practical relevance of a number of important soil morphological properties to agricultural management. All of the properties outlined in the table are defined and discussed in more detail in Section 4.4.

**Table 4.1.** Importance of soil morphology to agriculture

| Soil morphological properties  | Relevance to agriculture   |
|--|--|
| <p><b>Soil profile form</b><br/>(Uniform, Gradational, or Duplex texture profiles)</p> <p>Uniform = uniform texture for whole soil profile.</p> <p>Gradational = gradual increase in texture grade and clay content with depth</p> <p>Duplex = abrupt change topsoil (loam, sandy loam) to the clay subsoil.</p> | <p><b>Important for drainage (D) and root penetration (RP)</b><br/>Duplex profile = poor D and RP (except profiles with strong fine subsoil structure)<br/>Uniform and Gradational profiles + sandy or loam texture = good D and RP<br/>Uniform and Gradational profile + clayey texture + no structure = poor D and RP<br/>The drainage on young layered floodplain soils can sometimes be impeded when there is a clay depositional layer with poor structure close to the surface.</p> <p><b>Indicator of flooding frequency in alluvial flood plain landscapes</b><br/>Frequently flooded soils have many layers, buried A horizons, and no B horizon. Soils on higher ground (e.g. terraces) with decreasing flooding frequency tend to have a deeper soil profile and the development of a B horizon, as the soil has more time to form texture from in the light textured without being buried by deposits of flood sediment.</p>   |
| <p><b>Topsoil colour</b></p>   | <p><b>Indicator of the amount of organic matter present in the soil</b><br/>Darker colours often indicate relatively higher amounts of organic matter.<br/>Organic matter content is often correlated with the soil's capacity to store nutrients (CEC) and water (PAWC).</p>  |
| <p><b>Subsoil colour</b></p>   | <p><b>Indicator of soil drainage conditions *</b><br/>Subsoil colour is one of the most reliable qualitative indicators of soil drainage. This is largely due to the oxidation state of the iron (Fe) oxides present in the soil.<br/><i>Uniform bright red or brown soil colours</i> – indicate a well drained soil, due to Fe oxides being present in an oxidized form.<br/><i>Pale grey and yellow colours</i> – indicate a poorly drained soil, due to Fe oxides being present in a reduced form because of intermittent waterlogging and also due to the Fe actually being washed out of the profile under such water logged conditions.<br/><i>Gleyed colours such as blue grey, blue, green, or purple</i> – often indicate near permanent water logged conditions.<br/><i>Orange rust coloured spots and precipitates along fine roots</i> – indicates prolonged waterlogging.<br/><i>Mottles (or blotches) in the soil with colours such as orange, yellow grey and red</i> – a</p> |

| Soil morphological properties    | Relevance to agriculture  |
|----------------------------------|---|
|                                  | <p>good indicator of poor soil drainage and periodic waterlogging.</p> <p><i>Bleached or whitish coloured horizons (when dry)</i> – can indicate that water is sitting in this layer due to an impermeable layer below it. Alternatively it can indicate leaching of Fe and Al and clay from this horizon.</p> <p><b>Indicator of high P-sorption soils</b><br/> Related to the presence of iron oxides in the soil. Very bright red soils sometimes contain high concentrations of iron oxide giving them a high phosphorus-sorption characteristic e.g. Krasnozems or Ferrosol soils.</p> <p>Note that the above inferences about drainage can then be extended to comments on other properties related to drainage. e.g. denitrification is greater in poorly drained soils than in well drained soils.</p> <p>* Refer to Wilson (1985) for a more detailed assessment of the relationship between soil colour / mottling and drainage for the Ingham area of the wet tropics.</p> <p>Refer to Photos 4.1 to 4.22.</p>   |
| <p><b>Soil texture</b></p>       | <p>Soil texture is one of the most important soil properties. It is an estimate of the proportions of sand, silt and clay sized particles in the &lt; 2 mm size fraction of the soil.</p> <p><b>Indicator of:</b></p> <ul style="list-style-type: none"> <li>(i) Soil water holding capacity</li> <li>(ii) Soil nutrient storage capacity (CEC)</li> <li>(iii) Soil drainage</li> <li>(iv) Soil aeration</li> <li>(v) Root penetration</li> <li>(vi) Soil erodibility (water, wind, mass movement)</li> <li>(vii) Soil phosphorus sorption</li> </ul> <p>Generally, the higher the clay content, the higher the soil is in properties (i), (ii), and (vi) if pulverised, and the lower the soil is in properties (iii), (iv) and (v).</p> <p>Soils with a high fine sand and silt fraction are also more susceptible to water erosion and mass movement (vi).</p> <p>For properties (i) and (ii), the extent of the differences between soils of different textures will vary with clay mineralogy. In some of the highly weathered tropical soils where kaolin is the dominant clay mineral, the differences may be less pronounced than in shrink-swell soils where smectites are the dominant clay mineral.</p> <p>For (iii) soil drainage, a strongly developed fine soil structure can override any potential drainage limitations related to texture.</p> <p><b>(viii) Landscape position on a floodplain</b></p> <p>Soil material deposited on the floodplain further away from the river bank has a finer texture. At the levee bank close to the stream, the soils are usually sandier as the coarser sand particles drop out of the flood waters first. By the time the flood waters reach the relatively still back swamp areas, only the finer clay sized particles are in suspension in the water, so the soils here tend to be deep clay soils.</p> |
| <p><b>Gravel content (%)</b></p> | <p>Gravel, the coarsest particle size component of the soil (2-60 mm), affects many of the same properties as texture.</p> <ul style="list-style-type: none"> <li>(i) Soil water holding capacity</li> <li>(ii) Soil nutrient storage capacity</li> <li>(iii) Soil drainage</li> <li>(iv) Soil aeration</li> <li>(v) Root penetration</li> <li>(vi) Soil erodibility (water, wind, mass movement)</li> </ul>  |

| Soil morphological properties                                    | Relevance to agriculture   |
|--|--|
| <b>Geology of gravels</b>  | <p>The higher the gravel content of a soil, the lower its values are likely to be for properties (i), (ii), and (vi). Properties (iii), (iv), and (v) are likely to be higher with increasing gravel content depending on the soil texture, but especially if the gravel is fine (&lt; 10 mm).</p> <p>Surface gravels can also interfere with cultivation practices, increasing the wear and tear on equipment.</p> <p>Geology is sometimes an indicator for nutrient management e.g. presence of pink granite (with K-feldspar minerals) and shiny gold coloured mica minerals can indicate that the soil is likely to have significant reserves of non-exchangeable potassium (K<sup>+</sup>), especially if the gravels are highly weathered. If the gravels are only slightly weathered, the reserves of non-exchangeable K are less likely to be substantial.</p>   |
| <b>Soil structure</b><br>(including grade, shape and macropores) | <p><b>Indicator of:</b><br/> <b>Drainage (D)</b><br/> <b>Aeration (A)</b><br/> <b>Ease of root penetration (RP).</b></p> <p>Soils with a moderate to strong grade of structure (&gt; 1/3 peds) and fine (&lt; 20 mm diameter) granular, crumb or polyhedral shaped peds are typically associated with good (D), (A), and (RP) (Fitzpatrick <i>et al.</i> 1999). Refer to Figure 4.1 and Photo 4.39.</p> <p>Coarser (&gt; 20 mm) angular blocky, prismatic, subangular blocky or columnar shaped peds tend to be associated with poorer (D), (A) and (RP), even when the structure is strongly expressed (&gt; 2/3 peds).</p> <p>Massive soil structure is associated with poor (D) when present in medium to heavy textured soils (clay loams and clays) but sands and loams usually have good (D) due to holes in the soil fabric due to packing of coarser sized particles against each other. Refer to Photo 4.10.</p> <p>Macropores (holes visible to the naked eye) created by soil fauna such as earthworms and by root exploration also contribute significantly to (D), (A) and (RP). For example a heavy clay soil with a massive structure can have a high (D), (A) and (RP) if it has many macropores present, as is often the case in the row areas in clayey sugarcane soils.</p> <p><b>Indicator of soil compaction</b></p> <p>Platy shaped soil structure (like horizontal sheets) is associated with soil compaction damage to a soil. This is often present in the topsoils in the interrow areas of cane fields.</p> <p><b>Indicator of shrink-swell activity</b></p> <p>Lenticular shaped peds (crescent shaped like the lens of an eye) are indicators of shrink-swell activity in a clay soil (Photo 4.40).</p> |
| <b>Structural stability</b><br>(Emerson's aggregate test)        | <p><b>Indicator of:</b><br/> <b>Insufficient organic matter in the topsoil (slaking)</b><br/> <b>A sodic soil (dispersion)</b></p> <p>Used to test whether a soil could benefit from additions of gypsum or organic matter (refer to Photo 4.42 and Figure 4.2).</p>   |
| <b>Segregations or concretions</b>                               | <p><b>Indicators of:</b><br/> <b>Seasonal waterlogged conditions</b></p> <p>In the case of iron and manganese segregations and nodules (Brewer <i>et al.</i> 1983). (refer to Photos 4.9 and 4.11)</p> <p><b>Impermeable layers</b></p> <p>In the case of cementing of nodules into pans.</p> <p><b>Alkaline conditions</b></p> <p>In the case of carbonate nodules and segregations, which are typically only present when the soil pH is 8 or above.</p>   |

| Soil morphological properties   | Relevance to agriculture   |
|---|--|
| <b>Cutans</b><br>(clay coatings)  | <b>Indicators of:<br/>Soil forming processes</b><br>Clay coatings (argillans) around soil peds indicate that clay is being washed through the soil (illuviation), increasing the clay content in the lower horizons.<br><br><b>Drainage in a soil horizon</b><br>The preferential movement of clay between soil peds rather than through the soil fabric as a whole may indicate poor drainage in soils with coarser blocky structure. |
| <b>Slickensides</b>   | <b>Indicators of shrink - swell activity in a soil</b><br>The presence of shiny surfaces in the soil, often with a fine tongue and groove surface etching, is typical along planes of movement that have resulted from shrinking and swelling within the soil as it wets and dries (Photo 4.41).   |
| <b>Soil consistence</b><br>(soil strength or coherence)                             | <b>Impeded root growth<br/>Restricted drainage</b><br>Soils with loose to weak soil strength are unlikely to impede root growth and drainage. Soils with a firm to very firm consistence are likely to provide some impedance, while soils with very strong soil strength are likely to severely restrict both root growth and drainage (Fitzpatrick <i>et al.</i> 1999).  |
| <b>Soil surface condition</b><br>(hard setting, self-mulching, crusted, or cracked) | <b>Indicator of many potential agronomic problems such as:<br/>Seedling emergence problems (crusted and hard set soils)<br/>Poor drainage<br/>Restricted root development</b><br><br><b>The presence of a shrink - swell soil (vertosol)</b> - a soil surface with numerous large cracks (Photo 4.48).   |

The terminology for describing these properties is documented by McDonald and Isbell (1990). A step by step approach to describing a soil profile is outlined in Section 4.4

## 4.2 SEEN ONE SOIL - SEEN THEM ALL?

Growers and researchers in the sugar industry are well aware of the differences between soils that are evident at the surface. For example: some soils have heavier clay texture at the surface while others have a lighter sandier texture; some soils are well drained while others are poorly drained and boggy; some soils are easily ploughed while others are problematic; some soils grow good crops while others produce poorer crops; some soils are good at storing water while others dry out quickly. Even though the awareness of surface soil features is generally high, the same cannot be said for the rest of the soil profile as people rarely take the opportunity to see what lies beneath the surface, especially in an undisturbed state.

It is only by examining the whole soil profile

(including the subsoil), that these observable differences in surface condition and crop growth can be fully understood. Subsoils can often exert a strong influence over drainage, soil water storage, erosion and, in some cases, nutrient storage and leaching. Any damage to soil structure by compaction can often be observed below the soil surface. It is only by looking at the soil profile as a whole that we can gain a better understanding of how a soil functions, and from that develop better soil management practices.

To illustrate this point, the following photographs of just a small selection of the many different soil types on which sugarcane is grown in tropical Australia are presented (Photos 4.1 to 4.22 see page 43 to 48). It can be seen that most of these soils have dark topsoils that look fairly similar, but the root zone also extends down into the subsoils, which are much more diverse.

## 4.3 DESCRIBING A SOIL PROFILE - THINGS YOU WILL NEED

### 4.3.1 Skills required

All one needs to describe a soil profile is a basic field kit, an understanding of the properties to be described (from key reference books), and the basic senses (sight, hearing, touch, and smell). An additional skill which is very important is the ability to determine a soil's texture grade by shearing (pressing out) a ball of moist soil (a bolus) between the thumb and forefinger to produce a diagnostic length of soil ribbon. This procedure takes practice to master.

### 4.3.2 Key reference books

The key reference book for describing a soil profile in Australia is the 'Australian soil and land survey field handbook' by McDonald *et al.* (1990). This book contains all the necessary terminology for describing a soil profile and the landscape.

A key reference book on soil survey procedure is the 'Australian soil and land survey handbook Volume 2 - Guidelines for conducting surveys' (Gunn *et al.* 1988).

For soil classification in Australia, the Australian Soil Classification (Isbell 1996) is the preferred classification system to use, although the great soil group system (Stace *et al.* 1968) is still occasionally referred to. For papers in international journals, it is usually essential to also classify the soil according to either the FAO classification system (FAO-ISRIC-ISSS 1998) or the US Soil Taxonomy classification system (Soil Survey Staff 1998).

Appendix 5 in Isbell (1996) provides an approximate correlation between these classifications (also refer to Table 4.4).

### 4.3.3 Basic field kit

Apart from the equipment used to obtain the sample of soil to be described (hand auger, shovel, hydraulic gear, backhoe, proline drill rig etc), the basic soil kit is really quite simple (Photo 4.23). It consists of the following:

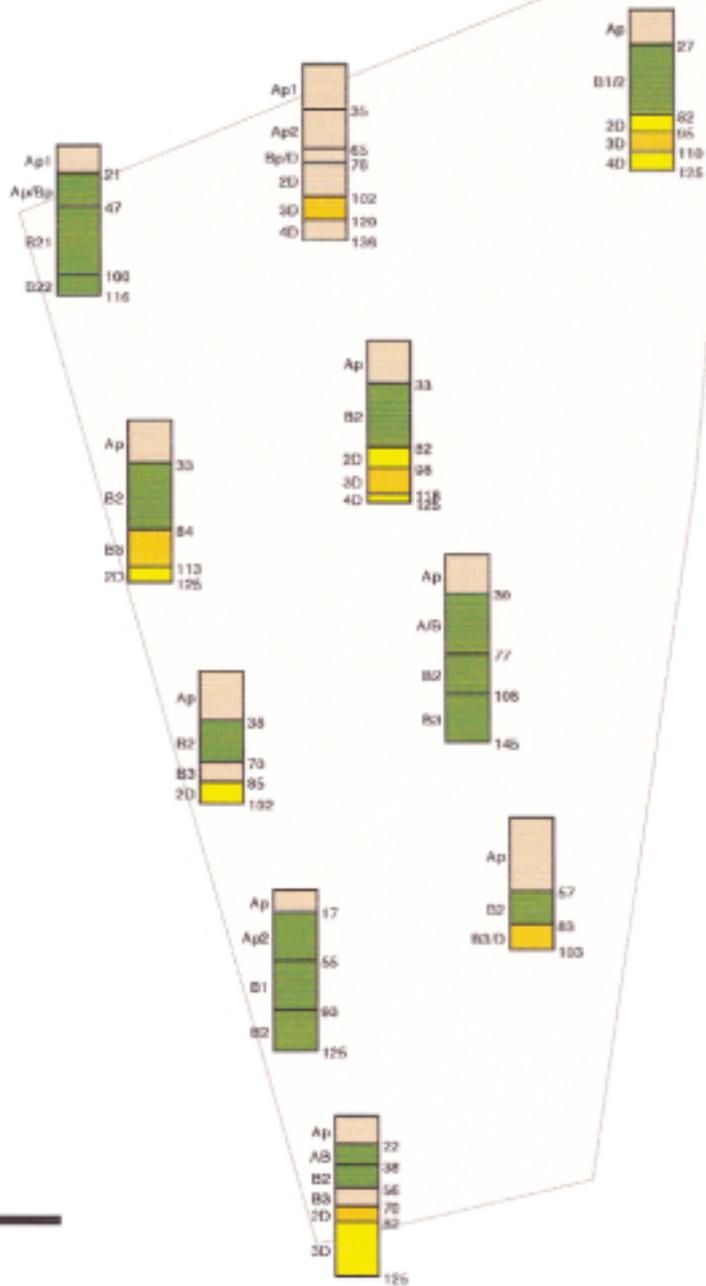
#### Basic soil field kit

- |  |                           |
|--|---------------------------|
| 1 Australian Soil and land survey field handbook | 11 Pedologists spade      |
| 2 A soil description sheet                       | 12 Geologist hammer       |
| 3 Munsell soil colour charts                     | 13 Dilute HCl solution    |
| 4 Soil pH kit                                    | 14 Petri dish             |
| 5 Measure tape (soil pit photos)                 | 15 Distilled water        |
| 6 Tape measure                                   | 16 10 x magnifying glass  |
| 7 2 mm mesh sieve                                | 17 Compass                |
| 8 Mortar and Pestle                              | 18 Clinometer             |
| 9 Knife or spatula                               | 19 Portable EC / pH meter |
| 10 Trowel  | 20 First aid kit          |



Photo 4.23. A standard soil kit for describing a soil profile (Photo Joseph Kemei, CSIRO)

- Australian soil and land survey field handbook (McDonald *et al.* 1990)
- Soil description sheets from McDonald *et al.* (1990) and pens (or your own customised description sheets).
- Munsell soil colour charts (Munsell 1992) to describe soil colour



# Soil Profiles Block: Kalamia

- Heavy Clay
- Light Clay
- Clay Loam
- Sand

Soil code and max depth (in cms) are indicated for each layer in profile

Figure 2.2. A stratigraphic representation of variability in soil profile texture across a research site at Kalamia, Burdekin Catchment.

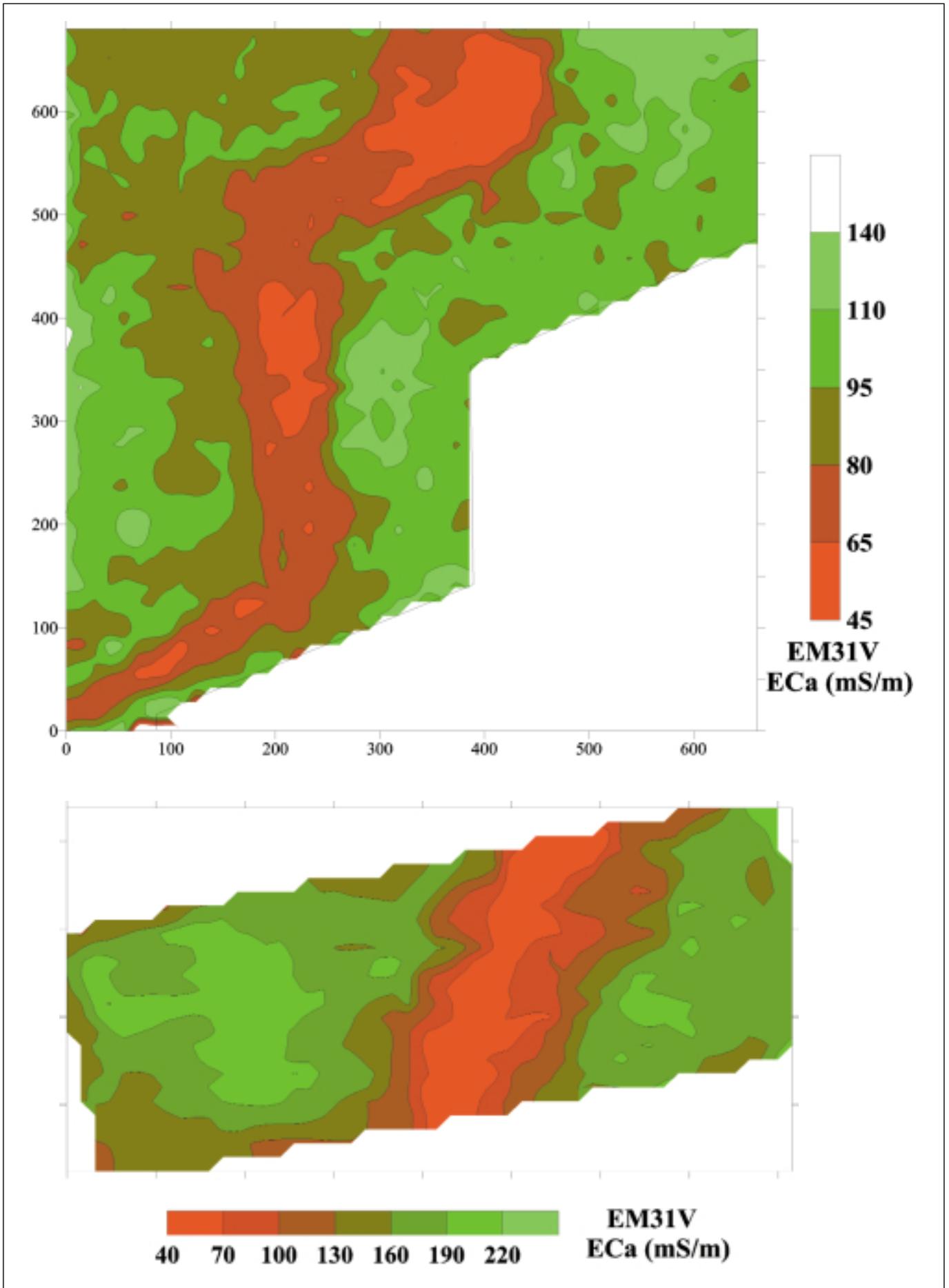


Figure 2.3. ECa maps of two landformed rice fields in the Riverina district of NSW showing areas of low ECa values in the middle of the fields which corresponds to a coarse textured gravelly soil (prior stream deposit). This soil change was not observable in the land surface. (Map source: BW Dunn & HG Beecher, NSW Agriculture)

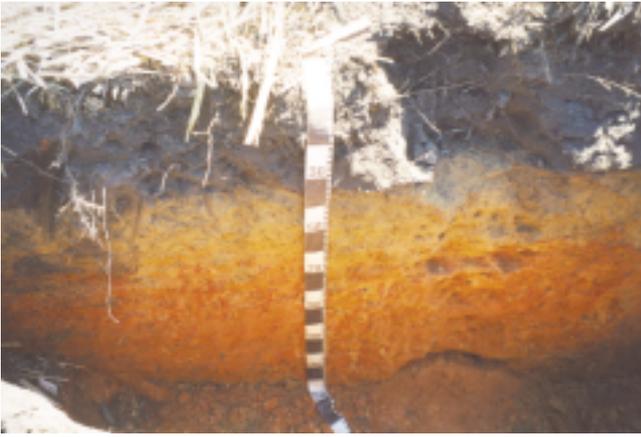


Photo 4.1. Red Kandosol soil on a river terrace at Bundaberg. The red mottle is due to the presence of ironstone nodules.

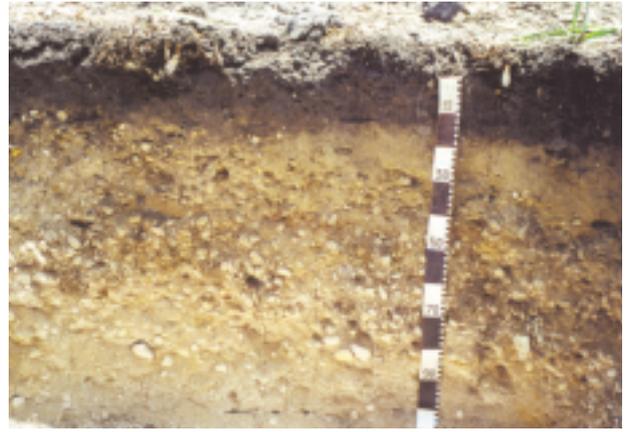


Photo 4.4. Kandosolic Oxyaquic Hydrosol soil (Fine black sand-CSR soil map unit) in the Herbert. The rounded pebbles throughout the soil profile indicate that this site was a prior stream location, and these pebbles reduce the water holding capacity of the soil.



Photo 4.2. Tenosol / Hydrosol soil at Fairymead near Bundaberg. The bleached white sand was originally blown in from coastal dunes, but much of the topsoil is alluvial in origin. Note the presence of a shallow water table.



Photo 4.5. Red Kandosol soil, near Childers. A deep well drained profile.

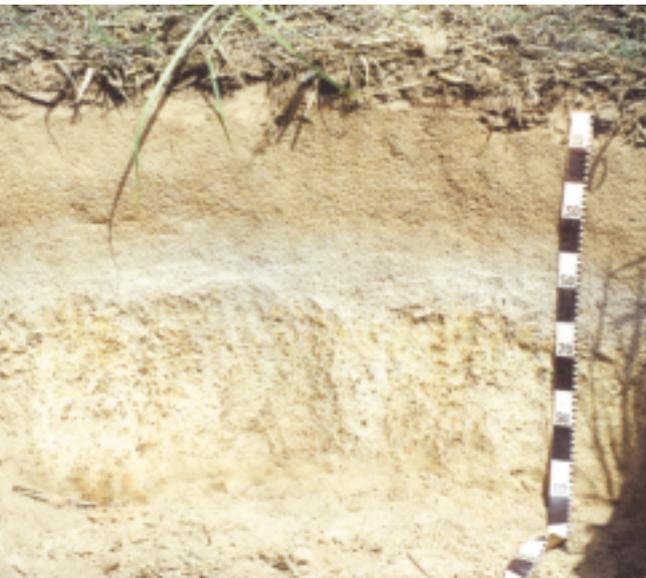


Photo 4.3. Kandosolic Redoxic Hydrosol soil (Grey sand-CSR soil map unit) on a waning footslope in the Ingham area. Note the bleached A2 horizon, massive structure, and fine iron manganese concretions in the lower half of the profile. i.e. often dry on top, but wet underneath.



Photo 4.6. Vertosol soil (cracking clay), near Kalamia in the Burdekin catchment. The cracks close up when the soil is wet.

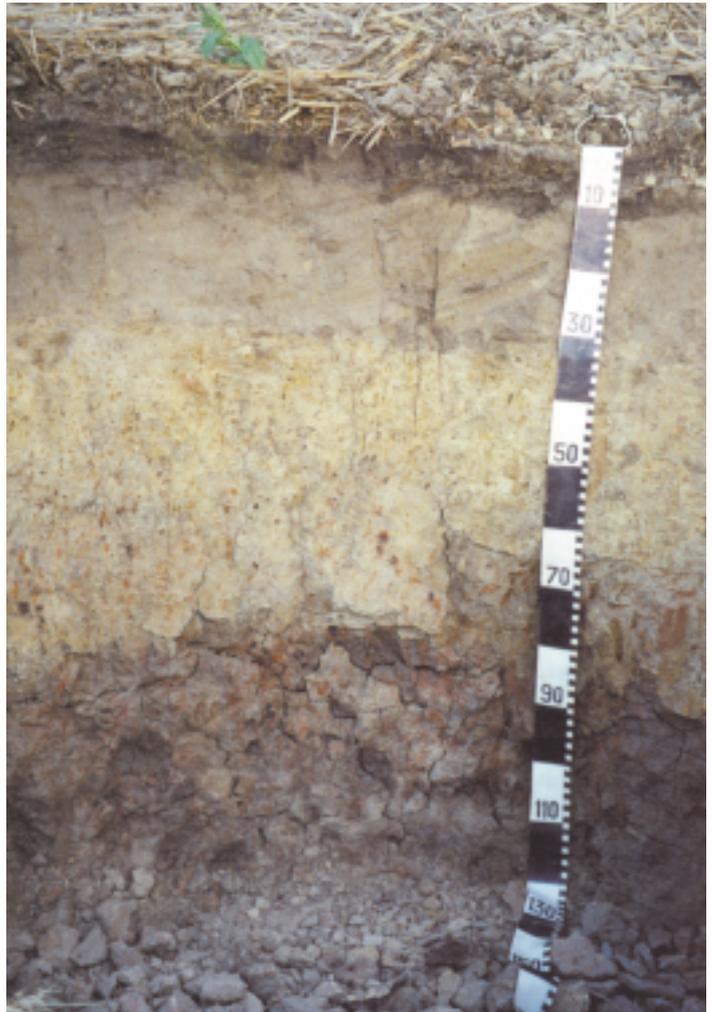


Photo 4.8. Dermosolic Redoxic Hydrosol soil (Terrace silty loam-CSR map unit) in the Herbert Catchment, Ingham. Note the very distinct abrupt boundaries between soil horizons.



Photo 4.7. Red Kandosol soil, Mackay district with a typical poorly structured dense subsoil.



Photo 4.9. Dermosolic Redoxic Hydrosol soil (Clay loam soil - CSR mapping unit), on Herbert floodplain, Ingham area. Note the black iron-manganese nodules lower in the profile.



Photo 4.10. Brown Dermosol soil (River Overflow unit - CSR) on a levee bank, Ingham area. Note the massive topsoil structure and the strongly developed structure in the Subsoil



Photo 4.11. Kandosolic Redoxic Hydrosol soil (Sandy clay soil - CSR mapping unit) on the Herbert floodplain, Ingham area. Note the bleached A2 horizon, massive structure, iron manganese concretions and blue gleyed colour of subsoil. Note the effect of moisture on soil colour in the sprayed section down the middle of the profile.

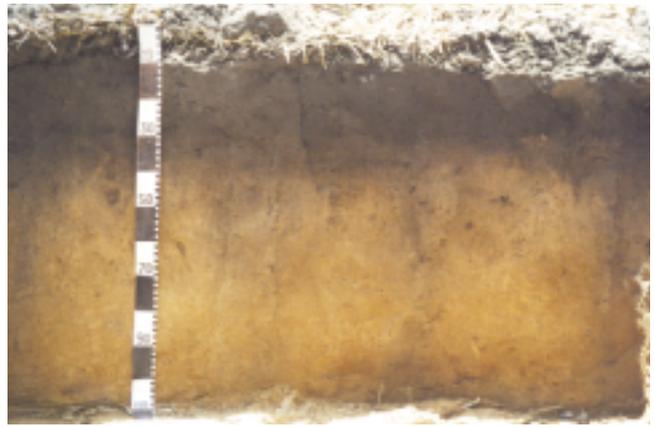


Photo 4.12. Chernic Tenosol soil (Riverbank - CSR unit) on an old levee bank on the Herbert, Ingham area. A deep sandy soil more typical of levee bank sites.

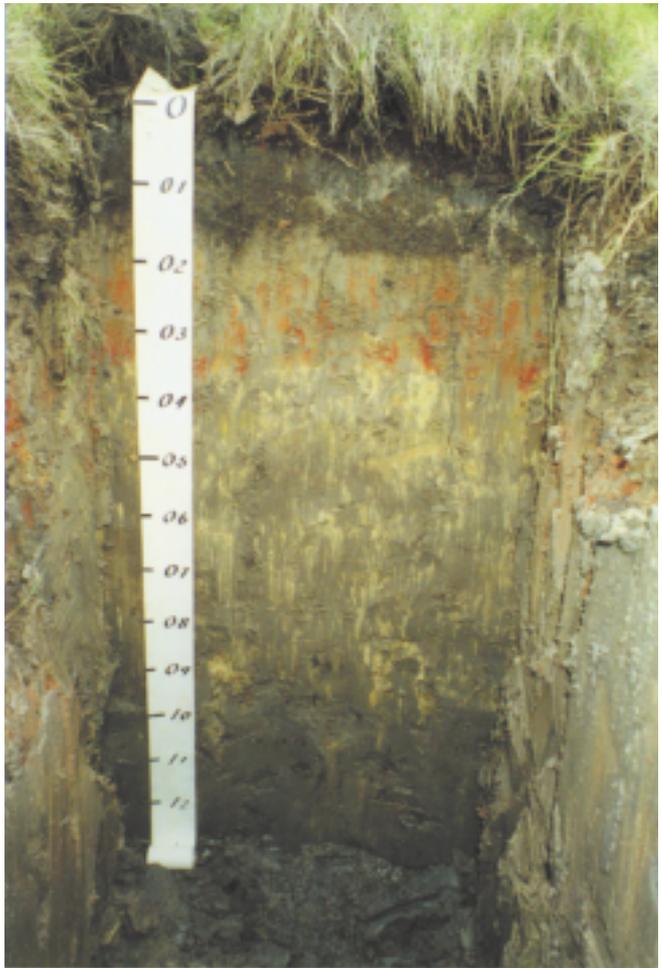


Photo 4.13. An acid sulfate soil from South - East Qld, with yellow jarosite mottles and a dark grey Potential Acid Sulfate Soil (PASS) layer at depth (Photo FJ Cook)



Photo 4.14. Aquic Grey Vertosol Soil (Heavy clay - CSR map unit) in low area of floodplain, Herbert district, Ingham. Note the lenticular or wedge shaped peds in the middle and lower part of the profile. These are an indicator of shrink-swell activity and cracking clay soils (vertisols).



Photo 4.15. Redoxic Hydrosol soil (Silty clay - CSR map unit) on a flood plain in the Herbert district, Ingham. The cracks evident in this profile are shrinkage cracks which are due to the very dry conditions and related more to the high silt content of this soil than to reactive clay minerals.

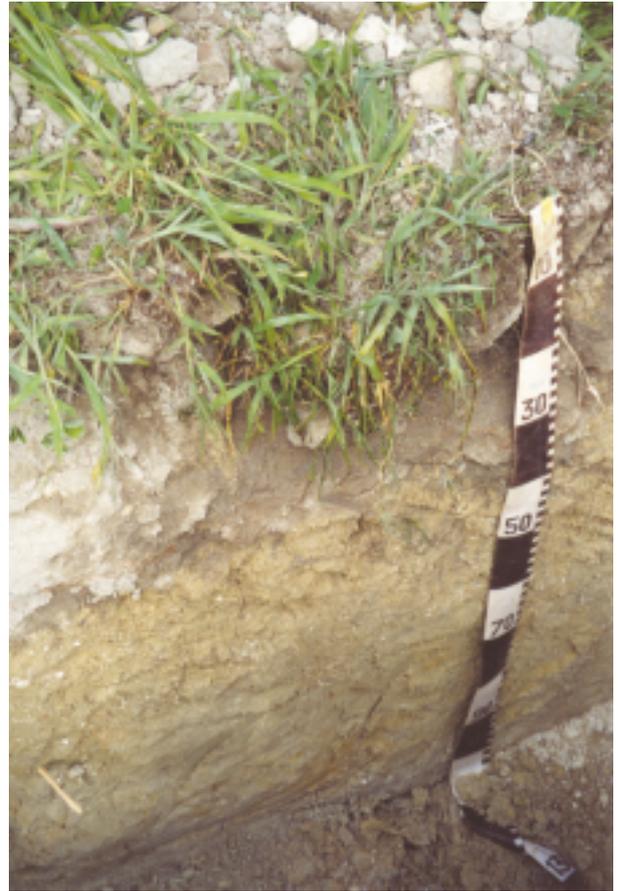


Photo 4.16. A yellow clay soil (Yellow Kandosol / Oxyaquic Hydrosol), in the Tully District.



Photo 4.17. A gravelly soil (Rudosol) in the Tully district. The clean gravels in this soil indicate that it is formed on the site of a prior stream



Photo 4.18. A man-made soil (Anthroposol / Rudosol) at Rita Island, Burdekin area. In this case, a layer of clay from a nearby swamp area was pushed over the sand to seal it off and thus allow furrow irrigation to occur.

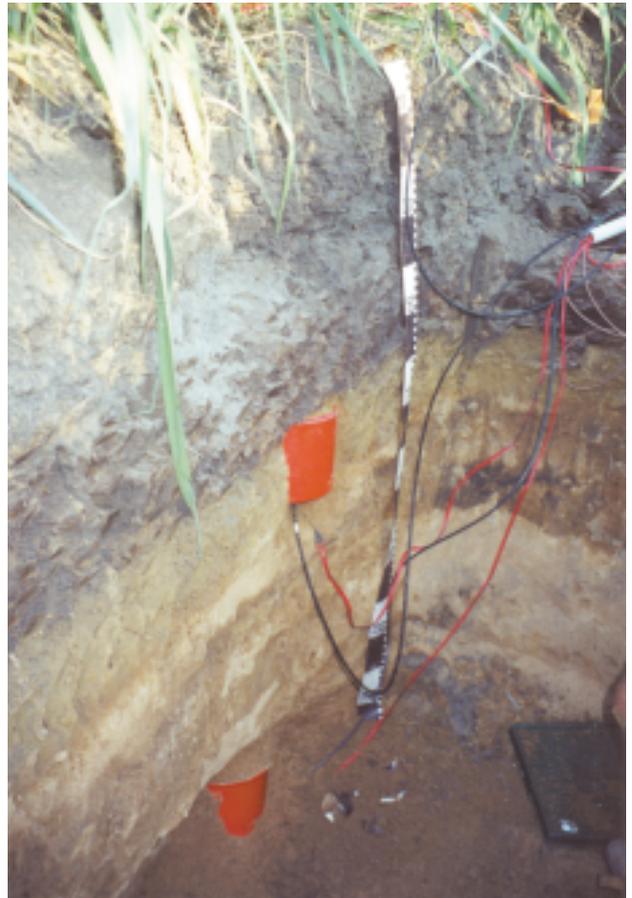


Photo 4.19. A Vertisol/ Anthroposol soil near Kalamia, Burdekin area. This soil exhibits natural layering below the topsoil with loose sand below 140cm. The topsoil has been modified by inputs of swamp clay during land-forming and mixing by ploughing.



Photo 4.20. A Rudosol soil, on a floodplain at Home Hill, Burdekin area. Note the dark black buried topsoil at depth. This area is occasionally flooded

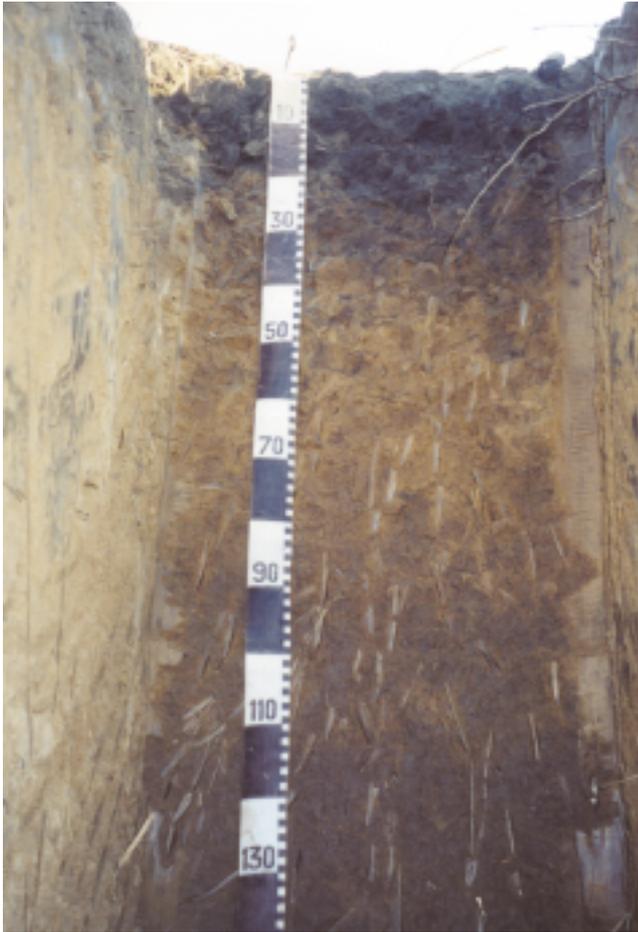


Photo 4.21. A brown Sodosol (Solodic) Soil, Brandon BSES station, Burdekin area.



Photo 4.22. A soil pit in the Ingham area demonstrating the value of pits for revealing lateral variation in soil distributions. In this instance the variable pattern is related to deep tillage practices. Also note the presence of an old natural buried topsoil at the bottom of the pit.

- a knife or spatula to poke the soil (consistency, strength, texture, compaction)
- a tape measure to measure upper and lower depths of horizons from a zero point (soil surface).
- A soil pH kit or pH meter.
- A clear plastic container or petri dish and distilled water (Emerson aggregate test).
- A 10 X magnifying glass to examine micro pedological features (fabric, slickensides, pores etc).
- A 2 mm mesh sieve to determine the gravel fraction.
- A wash bottle or pump spray bottle to wet up the < 2 mm fraction of the soil to mix the material to form a bolus for field texture determination.
- An EC meter (salinity).
- Dilute HCl for confirming nodules are carbonate.
- Mortar and pestle (or hammer and bag) to break up hard dry clay soil clods for texturing.
- Distilled water (for making up 1:5 soil water suspensions for EC/pH meters).
- Geological hammer to break up gravels and prise samples from the pit face.

#### *Optional extras*

- Sodic soils kit (BSES), especially in the Burdekin and other dry tropics sugar areas.
- Sample bags (calico or plastic) and tags (paper or aluminium).
- Portable fridge (see sample handling and storage, Section 4.6.3).

## 4.4 DESCRIBING A SOIL - STEP BY STEP

The 'Australian soil and land survey field handbook' (McDonald *et al.* 1990) provides all the necessary terminology for describing a soil profile, but what it doesn't provide is a step by step instruction of the description process. The following is an attempt to do this. The intention is for individuals to use these guidelines in conjunction with the handbook, which defines the description options for each soil property.

### 4.4.1 Step 1: Expose the soil profile for description

When describing the morphology of a soil profile in a field with an established cane crop, it is desirable to describe the soil in the area of the field where the crop is actually growing, which is on the row or raised bed sections of the field and not in the interrow (Photo 4.26). The soil core sample or exposure for this description should therefore be taken from these areas of the field. However when sampling to assess the field soil fertility, the row / interrow sampling question is more complicated (see Section 5).

There are several methods of exposing a section of soil profile for description and each has its advantages and disadvantages. Some common methods include: (1) a steel push tube with a truck or trailer mounted hydraulic ram setup or a portable jackhammer run off a generator, (2) a hand auger, (3) a narrow hit in auger, (4) a proline corer, and (5) a soil pit. Each of these methods has its pros and cons and is suited to certain types of soil investigations. These are discussed below.

#### **Thin walled steel push tube** (Photo 4.24)

A 50 mm diameter soil core is obtained by pushing a thin walled sampling tube (usually hardened steel) into the ground with either a hydraulic ram mounted on a truck or a jackhammer with an attachment to fit the collar at the top of the sampling tube (Photos 4.24, 4.25, 4.26).

#### *Application*

Best method for a soil spatial variability survey.

#### *Advantages*

- Quick and easy
- Provides an intact soil core suitable for description and laboratory analysis.
- Fine structure (< 3cm) can be observed.

#### *Disadvantages*

- Lateral soil variability cannot be observed.
- Coarse soil structure (> 3 cm) cannot be observed.
- Access to site can be a problem (trafficability of soil and standing crops).

Electric jackhammer samplers powered by



Photo 4.24. A truck mounted hydraulic rig for sampling with thin walled steel tubes.



Photo 4.25. Using a generator powered jackhammer to drive a steel sampling tube into the soil



Photo 4.26. A lever and ladder set up used to extract a steel tube and sample from the ground for the jackhammer method.

petrol generators can help overcome access problems by using lengths of electrical extension cord to gain access to the field. These are commonly used to sample soils in fields where sugarcane crops are well advanced, making vehicle access impossible. Access is limited only by the length of the extension cord. Note that Occupational Health and Safety (OH and S) issues are critical with the use of the generator powered jackhammer. Extreme caution has to be taken in putting together fieldwork protocols to eliminate the risk of electrocution (from the combination of power extension cord and sharp objects or water). Safety issues for the hydraulic rig are in relation to eliminating potential crush injuries and entanglement.

#### *Operational Hints*

A number of different approaches are needed to successfully collect a soil core sample and which approach to use depends very much on the soil conditions. These techniques are

explained in great detail by Dalgliesh and Foale (1998). When everything is going well in a soil sampling program, the soil cores are easily collected by the sampling tube and they are easily pushed out of the tube with a push rod. But this is not always the case. The following is a brief summary of some key methods of getting out of trouble when the soil core sampling is not going to plan.

#### Problem 1- Soil cores getting stuck in the tube

[Solution: mallet, wood block, mould oil, or silicon-based oil lubricant]

To get the soil core out of the sampling tube a combination of two techniques is used. Firstly the tube is turned upside down (cutting edge end up) and tilted on a 45° angle from the horizontal before being tapped along its length with a rubber or wooden mallet. Usually this will cause the soil core to vibrate out of the steel tube. When sections of the soil core are stuck further up the tube, a more aggressive approach is required. This involves bashing the end of the tube downward into a large block of wood to force the soil core down to the end of the tube. Once the soil core has been moved to the end of the tube, the mallet tapping approach is again employed, and so on until all of the soil core is out (Photo 4.27).



Photo 4.27. A soil core removed from the sampling tube. Note the rubber mallet on the tray and the wooden block on the ground which were used to help extract the sample from the steel tube.

Lubricating the inside of the sampling tube with mould oil can sometimes help reduce the extent of this problem. A good way to apply the mould oil is to use a "pull through" rag (Dalgliesh and Foale 1998). This consists of a rag moistened with oil tied to 2 m of rope

which is tied to a bolt at the other end. The bolt is dropped through the sampling tube and is then used to pull the oily rag behind it through the tube. Mould oil has been found to contaminate soil samples for organic carbon tests (Dowling *et al.* 1985), and as such should be avoided where this property is to be tested. Ways to get around this are not use mould oil, use mould oil on the deep core sample and then re-sample the topsoil adjacent to this core using an alternative method, collect the topsoil part of the core with a non-oiled tube before sampling the subsoil with an oiled tube, or alternatively use a silicon-based oil lubricant which has no risk of contaminating soil carbon results, but this oil is much more expensive.

#### Problem 2- Soil cores falling out of tube when it is pulled out of the ground, often due to wet subsoil conditions

[Solution; Paper clips, a gouge auger]

Three or four paper clips positioned around the cutting edge of the tube can help prevent losing the soil core by roughening the core surface, increasing the friction between the soil core and the tube, and possibly by allowing some equalization of pressure between the inside and the outside of the tube to negate groundwater suction effects as the core is pulled out of the ground (Dalgliesh and Foale 1998).

Another very successful approach is to use a gouge auger to sample the wet soil profile. This technique is very commonly used for soil surveying acid sulfate soil areas. A gouge auger is basically an open sampling half tube whose width tapers out from the bottom end to the top (Photo 4.28). When the watertable is not at the surface, a steel push tube is usually pushed into the ground with the hydraulic system of the truck to sample the soil to the depth of the watertable before the gouge auger can be used. At this point the gouge auger is pushed into the saturated soil by hand. It is then twisted 180 degrees and pulled out of the ground by hand (Photo 4.29). This usually successfully retrieves an intact 2-3 cm diameter soil core from the saturated soil, which can be sampled and described. Extensions can be added to the gouge auger to go to greater depths. The gouge auger however can be impeded by firm dry clay material below the water table. In this situation it is sometimes



Photo 4.28. A gouge auger for sampling saturated soils (Photo. Lowan Turton, NSW Agriculture).



Photo 4.29. Using a gouge auger to sample the saturated section of the soil profile below the watertable (Photo courtesy of NSW Agriculture)

possible to push the gouge auger through the firmer material with the hydraulic system of the truck that is used to push the thin walled tubes, but care needs to be taken not to bend the auger.

Coring the profile in stages (shorter depth intervals) can also improve retrieval, especially when the subsoils are sticky and compressible.

### Problem 3- Soil sampling tube failing to push through the soil due to dry conditions.

[Solutions: Jackhammer, smaller diameter tube, adding weight to sampling rig, abandoning sampling until conditions are right]  
Changing to a jackhammer sampler will often result in success if the layer which is stopping the sampling tube is sandy as the vibrating nature of the jackhammer sampler is more successful in penetrating dense sandy layers.

If the problem soil material being sampled is clayey and dry, success may be gained by using a narrower diameter sampling tube and by adding weight to the sampling rig (e.g. 200L drums of water or sand bags). If these strategies fail, then the only option is to abandon sampling until conditions are more favourable, such as after a period of good rainfall or an irrigation. If only one core is to be taken, a feasible option might be to wet up a small area the day before sampling, using one of the wetting up setups outlined in Section 6.

### **Hand auger**

The soil is hand augered and laid out on a plastic sheet corresponding to its depth below the surface. Auger heads are designed for specific materials and conditions, e.g. multipurpose Jarret augers, sand augers, Dutch clay auger and the gouge auger for waterlogged soils (Photo 4.30).

#### *Application*

An alternative method for a soil variability survey.

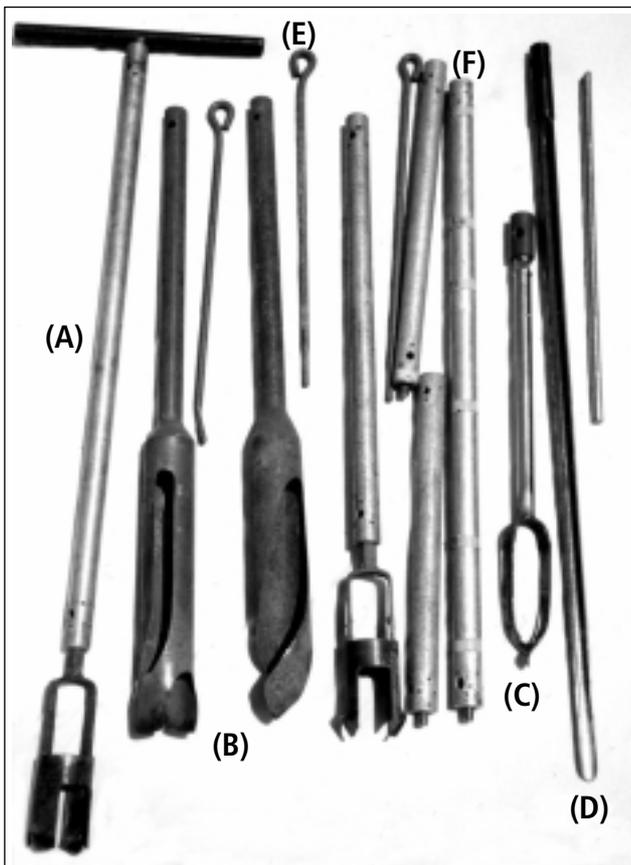


Photo 4.30. The variety of soil augers available for sampling a soil for description, including a multipurpose Jarret auger (A), sand augers (B), a Dutch clay auger (C), a hit in corer (D), iron bars for adding extensions to auger (E), and auger extensions (F). (Photo; Joseph Kemei, CSIRO).

#### Advantages

- Overcomes access problems associated with vehicles and trailers.
- Enough sample is obtained to describe most soil properties in the field.
- Can be used in any soil conditions above the watertable.

#### Disadvantages

- Labour intensive.
- Soil structure is often difficult to describe from soil augerings.
- Undisturbed samples cannot be collected.

#### Operational hints

- Before starting the auguring, a spade can be used to dig out an intact square sample of the surface A horizon and possibly the upper B horizon of the soil. This allows the structure to be accurately described for at least these surface samples.
- Mark 10 cm depth increments along the auger with a permanent marker pen or

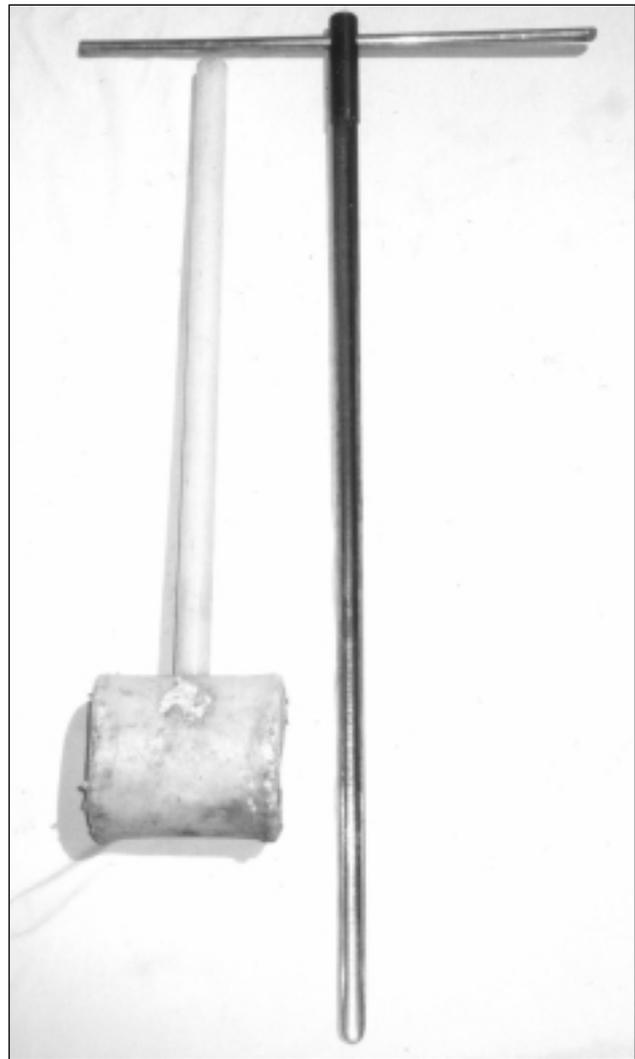


Photo 4.31. The hit in auger provides a quick check soil core if the soil conditions are soft and moist. (Photo: Joseph Kemei, CSIRO)

electrical tape to make it easier to lay the augered soil out according to soil depth on a plastic sheet. It is also worth recording the depth at which noticeable changes in the soil occur as you auger. Things to note are the crunch of sand and gravels and the stronger resistance of clayey materials.

- For some soils (especially duplex soils), it is possible to measure more accurately the horizon depths for the upper part of the soil profile with a tape measure by placing your arm down the auger hole and feeling for changes in texture etc on the hole wall.

#### Hit in corer

The hit in corer is a narrow (2 cm) gouge-style corer which is hit into the ground with a large plastic or wood mallet type hammer (Photo 4.31). The corer is usually pulled out of the ground by hand by slipping a cross bar in the

top of the tube, but sometimes a heavy duty hydraulic jack and chain set up is required to lift the corer out of the ground. It is more commonly used in Europe than Australia. It can however be useful for quick check descriptions in a soil survey as it provides sufficient soil sample to quickly check the soil horizon depth, texture and colour.

#### *Application*

Quick, low detail, site description component of soil surveys.

#### *Advantage*

- Provides a very quick method of sampling for less detailed survey check sites, where the main diagnostic horizons of the soil occur within a metre of the ground surface.

#### *Disadvantages*

- Shallow sample (<1metre).
- Very small sample of soil to describe (2cm diameter core).
- Cannot determine structure from sample.
- Difficult to sample soil which is dry and hard.

### **Proline drilling rig**

Proline drills provide larger undisturbed cores (100 - 150 mm diameter) which allow most soil structure to be observed (Photo 4.32).

#### *Application*

Provides a high quality soil observation for a detailed description and sampling (the next best thing to a soil pit).

#### *Advantages*

- Most soil structure can be observed.
- Can collect small undisturbed (intact) samples for some soil physical measurements.

#### *Disadvantages*

- The drill rig is very expensive.
- Sampling process is slower than push tube cores.
- Lateral soil variation and very coarse soil structure (>10 cm) cannot be observed.
- Limitations on sampling cores for soil physical analysis.
- Restricted by vehicle access to sites.



Photo 4.32. Collecting a large 15 cm diameter soil core with a Proline drill setup. A built in safety feature of this proline drill is the fact that it will not operate unless the safety cage is fully down. (Photo Lowan Turton, NSW Agriculture).

### **Soil pit**

Soil pits are excavations dug by a backhoe or by hand. They are usually > 1 m wide and at least 3 m long to allow access. They are usually < 1.5 m deep due to additional worksafe requirements for deeper pits (Photo 4.33). The additional work associated with the shoring of pit faces for deeper pits is usually enough deterrent to prevent deeper pits being dug. Before digging soil pits it is important to contact worksafe authorities to familiarise yourself with the latest guidelines for working in these excavation sites.

#### *Application*

Pits are often the best option for detailed soil characterisation work. They allow sampling of a soil profile for the determination of chemical, physical and hydraulic properties, as well as the measurement of subsoil hydraulic

properties in the field. Soil pits are normally used for detailed characterization work on a representative soil site after a soil survey has been completed.

#### *Advantages*

- Can observe the short range spatial distribution of soil materials (vertical and lateral).
- Large samples can be collected for soil physical measurements.
- Can observe large soil structure.
- Several pits close together can be dug quickly.

#### *Disadvantages*

- Site disturbance.
- Cost of hiring a backhoe and operator to dig and fill the pits.
- Hand digging soil pits is time consuming and very hard work.

### **Soil pits in cane land**

There is often initial resistance to the idea of excavating a soil pit in a research or investigation field. This is generally based on a fear that digging the pit may damage the crop and site and possibly affect results. But soil characterisation work by CRC Sugar has demonstrated that soil pits can be dug in a cane field with no observable impact on the crop. When planning to have a soil pit excavated at a site, the following points will need to be considered:

- OH and S regulations must be adhered to in regard to the dimensions of the pit constructed, required safety gear, and clear marking of the pit site area (Photo 4.33). The current guidelines in Queensland stipulate additional safety measures once a soil pit exceeds 1.5m in depth (consult Worksafe for advice). It is possible to extend the depth of observation below 1.5m at the pit site by either taking a 1.5 m deep core at the bottom of the pit using the jackhammer



Photo 4.33. OH and S considerations must be taken seriously for soil pits. This involves clearly marking out a soil pit with white posts and bright plastic ribbon, following OH and S regulations in regard to pit dimensions and promptly filling in the pit once all work is finished.

setup or else by hand auguring to a desired depth at the bottom of the pit.

- The proposed pit site is on a soil profile representative of the soil type in the investigation site (evident from intensive soil survey information). It is often desirable to have the pit dug at a spot where a soil core description was done in the earlier soil survey. If this can't be done, it is advisable to check that the soil at the proposed pit site is representative before having the pit dug. This can be done by hand augering down to at least a metre and will prevent unnecessary digging in unsuitable locations.
- Ensure that one side of the pit is parallel to the row mound and cuts along the edge of the row to show the extent of cane root growth through the profile.
- Site disturbance can be minimised by:
  - Excavating soil pits from the interrow area, orientating them lengthwise parallel to the row. This ensures that none of the sugarcane crop or its stools in the row mound will be damaged (Photos 4.34 and 4.35).
  - Digging soil pits after harvest and before the cane is up, where possible. This helps eliminate any possibility of disturbing standing cane with backhoe equipment.
  - Excavating the pit by hand (shovels, mattocks) when standing cane is above 1metre high. By again

excavating parallel to the row and along the edge of the cane in the interrow, the pit can be dug with virtually no disturbance to the cane.

#### 4.4.2 Step 2: Expose the natural faces of the soil for examination

For soil pits this simply means cleaning the smeared vertical face of the soil pit, first with a shovel and then with a knife or spatula, levering the soil off to expose its natural unsmeared surface.

For undisturbed soil cores it means levering off the top of the core with a knife or spatula to expose the inside of the core for the length of the soil profile.

For disturbed hand auger samples, the augered soil material needs to be broken open in the hands in order to find pieces of unsmeared material for colour, mottles and structure descriptions.

#### 4.4.3 Step 3: Determine where the soil layers (horizons) and their boundaries are

Determining the boundaries of soil horizons is the most important part of a soil profile description, as it sets the framework of the description. This process involves deciding

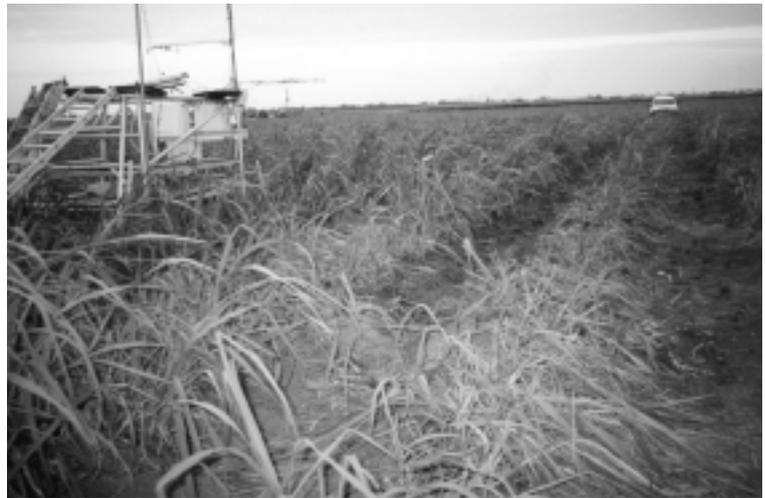


Photo 4.35. Low impact soil pits are the best approach! - A filled in pit site in the interrow area of a field near Kalamia, Burdekin. This soil pit was filled in by hand leaving almost no trace of where it was. However using a backhoe to fill in the pit followed by some shovel work to finish off the surface is the preferred option, as it is very hard work.

where soil layers begin and end. It also involves making judgements on whether a section of soil in the profile is an actual horizon or whether it is merely a gradual or diffuse boundary (a zone of transition) between two distinctive horizons.

Soil layers or horizons are distinguishable by differences in any one or more of the soil descriptors in following sections. But the dilemma is that the boundaries of these layers need to be determined before an accurate description of the properties which differentiate them is done. Thus simple techniques, which estimate differences in these properties quickly, are employed. These techniques simply involve looking at the soil, poking the soil with a knife and feeling the soil between the thumb and forefinger.

It is worth noting that boundaries will not always be straight and the mixing of horizons by tillage practices can sometimes obscure or smudge the natural contrast in profile features (Photo 4.22). Once boundaries are determined, their locations are marked on the soil core or pit face. This can be done by cutting a line with a knife or by lodging sticks, tent pegs or nails in the core or soil pit face at the boundaries (Photos 4.36 and 4.37).



Photo 4.34. This soil pit in the Tully area was dug with a backhoe on the edge of the headland area, along the first row of the sugarcane crop. This allowed the profile to be described and sampled and also allowed crop root growth through the profile to be assessed as well, all with minimal disturbance to the crop.

## Soil colour

Look for differences in darkness of colour and hue and for the presence of mottles or blotches in the soil. The A horizons are quickly separated from subsoil layers by their darker black to brownish colours resulting from organic matter. They can often be subdivided further on the basis of differences in the darkness of these colours. Colour differences in the subsoil and the presence and absence of mottles form bases for further division of the soil profile into layers.

## Soil resistance / strength / sound / feel

Simply digging a knife into the soil profile gives a very good indication of differences in soil texture, structure and gravel between layers. The more clayey a soil layer, the firmer the resistance to the knife. Sand and gravels can be felt and heard as the knife is inserted. Sometimes the detection of higher resistance to the knife turns out not to reflect any texture grade difference at all. When this occurs, the higher resistance in the layer of interest is rather a result of a higher bulk density due to soil compaction. Detection of this compacted layer is therefore still important. Fine sands and gravels can be detected when felt between the thumb and forefinger. Loams and silts are easily crushed in the hand, while clay loams and clays tend to be hard to crush by hand when dry. Silty loams are often like talcum powder when dry.

## Soil structure

Structure is often visible in the soil, while the presence or absence of structure as well as differences in aggregate sizes and shapes is also



Photo 4.36. The soil horizons in three soil cores marked out with flags.



Photo 4.37. Measuring the depths of soil horizon boundaries relative to the soil surface with a tape measure. Note how soil horizons are marked out with pieces of stick placed in the profile. Tent pegs are an even better option for marking horizon boundaries.

often apparent. Structure is also detected by poking a knife into the soil, as the presence of structure results in lower bulk density and less resistance to the knife. When the soil structure is strong, the soil will often crumble into its individual peds when dug with the knife.

### Record:

- **Upper and lower depths of each horizon.** Measurements are made with reference to the zero point which is defined as the top of the mineral soil surface below the organic litter, and these numbers increase with depth. The layers dominated by organic debris (O horizons) are measured as distance above the mineral soil e.g. O1 horizon 0.15 - 0.05m, O2 horizon 0.05 - 0m

## Horizon boundary distinctiveness

Horizon boundary distinctiveness refers to how abruptly the soil changes from one soil horizon to the next. The terms commonly used to describe this are sharp (change occurs within a distance of <5mm), abrupt (5-20mm), clear (20-50mm), gradual (50-100mm) and diffuse

(>100mm) (McDonald and Isbell 1990).

**Record:**

- **Boundary distinctiveness and shape (for soil pits).** The boundary between A and B2 horizons is of particular significance for soil classification.

**Horizon notation**

Horizon notation is usually determined at the end of the profile description when the morphology of each soil horizon has been fully described. It is best to determine horizon notation at the time of soil description when the soil is in front of you. The correct notation for top soil horizons (A horizons - A1, A2, A3 etc.) and subsoil horizons (B, D or C horizons) is explained in detail by McDonald and Isbell (1990). A brief overview of this is also provided in Section 1.

**Record:**

- **Horizon notation**

**4.4.4 Step 4: Describe the morphology of horizons**

Use McDonald *et al.* (1990) for more detailed definitions in conjunction with classes and the practical tips below. The following steps outline a desirable sequence that will help the describer avoid inadvertently destroying information in the sample before it is described.

**Soil colour**

Examination: Soil colours are determined using the Munsell Soil Colour Charts (Munsell 1992). The dominant soil colour (soil matrix) and the mottles (subdominant blotches and streaks of colour - see subsoils in Photos 4.9 and 4.11) are recorded. Moist colours are determined for the surface of a freshly broken aggregate of soil for all soil horizons (wet a piece of soil with water if it is dry). For the A1 and A2 horizons dry soil colours are also recorded (important for the Australian Soil Classification). Soil and Munsell colours should be compared outdoors in natural light. Sunglasses and fluorescent lighting should be avoided when comparing colours. The colour chip in the Munsell colour book which best

matches the soil colour is recorded as Hue, Value and Chroma, for example, 10YR 3/1. Here 10YR is the Hue notation located in the top RHS corner of the page of the Munsell colour book page, 3 is the Value notation corresponding to the row the colour chip is on (on LHS of page) and 1 is the Chroma value corresponding to the column the colour chip is on (located on the bottom of the page) (Photo 4.38).

**Record:**

- **Moist Munsell colour** (Hue, Value, Chroma) of the soil matrix for each horizon.
- **Dry Munsell colour** of the soil matrix of the A1 and A2 horizons.
- **Abundance, size and contrast** of the dominant (primary) and subdominant (secondary) soil mottles (see McDonald *et al.* (1990) for classes).
- **Moist Munsell colour** of the dominant and subdominant soil mottles.

**Root abundance and effective rooting depth**

Examination: Root abundance should be determined in a soil pit by placing a square wire frame (100cm<sup>2</sup>) over a cleaned vertical soil exposure for each soil horizon and estimating the number of visible roots (<2mm) within the frame. For a soil core simply break the core open, observe root density and estimate the number of roots for a 100cm<sup>2</sup> area. Refer to McDonald and Isbell (1990) for root abundance classes. The classes for number of roots/100cm<sup>2</sup> are as follows: few <10 roots, common 10-200, and abundant >200.

The effective root depth should also be recorded. The "effective root depth is the soil depth (measured from the soil surface) where the number of roots falls from 'abundant' or 'common' to the 'few' (<10 roots/100cm<sup>2</sup>) classification" (Fitzpatrick *et al.* 1999, p.68). This drop off in root density can be due to many factors including physical impedence and lack of nutrients or water (Fitzpatrick *et al.* 1999). Cass *et al.* (1999) suggested that effective rooting depth could also be used as a surrogate indicator for estimating plant available water status.

When evaluating effective rooting depth it is worth taking into account the growth stage of

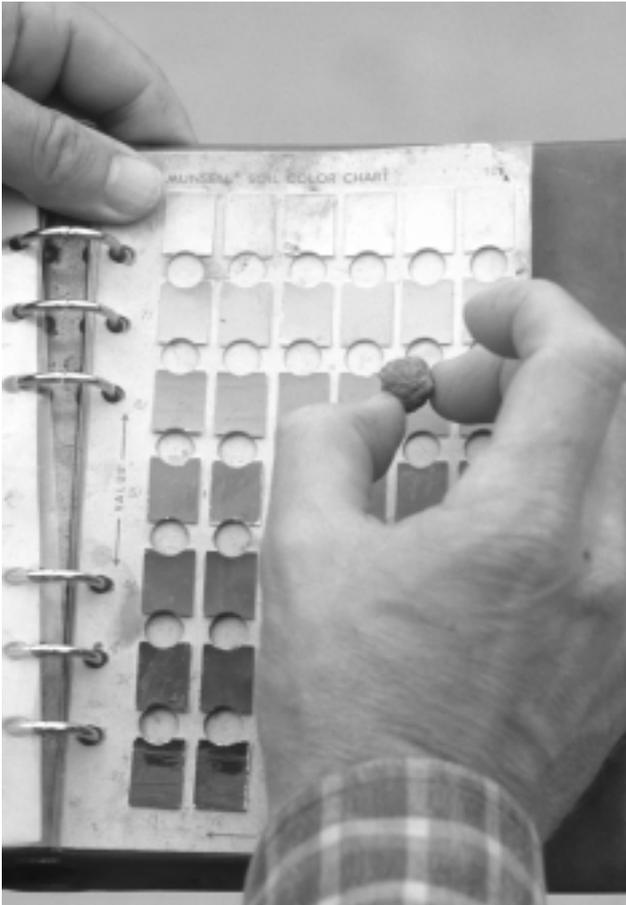


Photo 4.38. Using a Munsell soil colour chart to describe soil colour (Photo: Lowan Turton, NSW Agriculture)

the crop e.g. plant crop, 1st ratoon, 2nd ratoon etc for sugar.

It is also important to record the total rooting depth (depth to the lowest roots) as well, since agricultural production models such as APSIM often rely on the crop's potential rooting depth as an input for the model. Measurements of total rooting depth of sugarcane crops in advanced stages of growth, such as at the end of the 3rd ratoon, would be appropriate as model inputs. Studies in the sugar industry have shown that sugarcane crops utilise water at depth (below 2m) during dry times when soil moisture reserves in the upper horizons have been depleted (G.Inman-Bamber, pers.com. 2001)

**Record:**

- **Root size and abundance** classes for each horizon.
- **Effective rooting depth** (cm) for the soil profile (using above definition).
- **Lowest depth** at which roots occur (cm).

**Soil structure**

Soil structure refers to the way soil particles are bound together. Often they are bound together into structural units called peds. These vary in size, shape, distinctness and abundance.

**Examination:** Soil structure can be described reliably from a fresh vertical exposure (e.g. soil pit) or from a large soil core (15cm diameter). Commonly collected 5cm diameter soil cores are only adequate for describing finer soil structure (<3cm). Disturbed soil augerings are usually of little value for describing the structure of soil. It is sometimes possible to overcome this limitation by digging down to the top of the B2 horizon with a shovel to gain an undisturbed sample for description. To examine soil structure: take a piece (10cm x 10cm) of fresh, dry to slightly moist undisturbed soil and gently prize it open in your hands. If soil structure is present the piece of soil will easily break into numerous structural units (peds). If no soil structure is present, the soil is massive and will simply break up along jagged fracture planes as you break it open in your hands. The presence of soil structural units (peds) can be confirmed by the presence of accommodating soil surfaces between peds, as opposed to the presence of jagged fractured soil surfaces that result directly from you forcing the soil to fracture.

*Grade of pedality*

The degree of development of peds in a soil or the abundance of peds in a soil is referred to as the grade of pedality. The pedality grades are defined in McDonald and Isbell (1990). In short they are as follows:

- Single grained - structureless loose incoherent material.
- Massive - coherent material lacking distinct peds.
- Weak - < 1/3 of soil material is accounted for by soil peds.
- Moderate - 1/3 to 2/3 of soil material is accounted for by soil peds.
- Strong - > 2/3 of soil material is accounted for by soil peds.

Photo 4.39 shows two soils with strong pedality and a piece of soil with massive structure. The

soil profile in Photo 4.10 has a topsoil with a massive structure over a subsoil with strong pedality. Note how the topsoil in this photo looks smooth like a concrete wall, and how the subsoil is segmented and appears to be composed of small blocks.

#### Shape and size of peds

The size and shape classes for describing soil peds are outlined in detail in McDonald *et al.* (1990). The average least dimension of peds is used as a measure of the size of peds. Peds are then assigned to one of the following size ranges in mm: <2, 2-5, 5-10, 10-20, 20-50, 50-100, 100-200, 200-500, and >500.

The major classes of ped shapes are illustrated in Figure 4.1. Lenticular or wedge shaped peds, which are an indicator of high shrink-swell activity with cracking clay soils (Vertosols), can be seen in Photo 4.40.

Photo 4.39 shows two soil materials with strong pedality and a piece of soil with massive structure. The soil profile in photo 4.10 has a topsoil with a massive structure over a subsoil with a strong pedality. Note how the topsoil in Photo 4.10 looks smooth like a concrete wall, and how the subsoil is segmented and appears to be composed of small blocks.

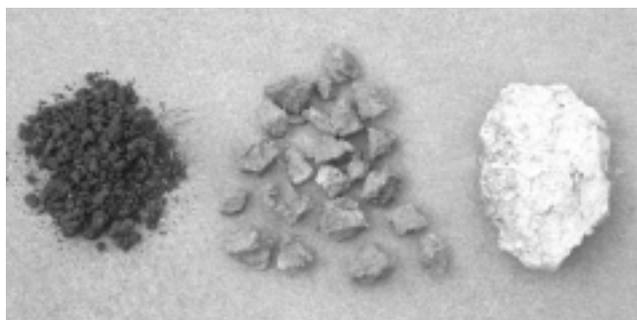


Photo 4.39. Examples of different soil structure. Left to right; strong fine crumb shaped peds, angular blocky shaped peds, massive soil with no peds present (Photo; Lowan Turton, NSW Agriculture).

#### Compound pedality

Sometimes larger peds in the soil can be further divided into smaller ped units. In this situation the smallest ped unit is referred to as the primary ped and the larger size peds are referred to as compound peds (McDonald and Isbell 1990). Both of these peds need to be described.

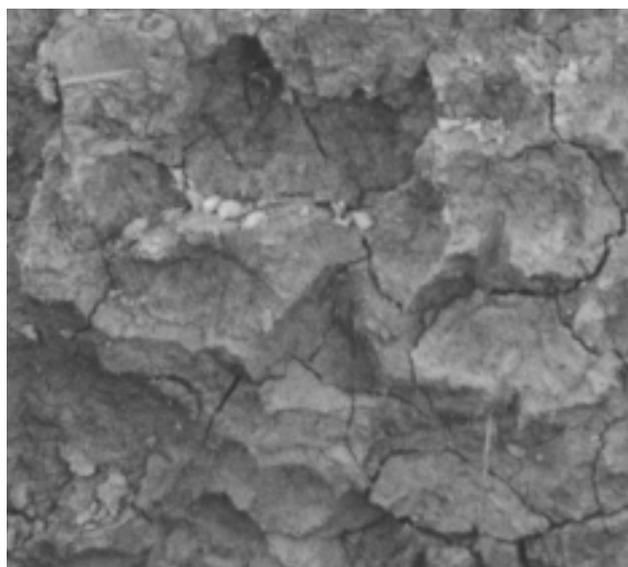


Photo 4.40. Lenticular peds up to 5cm long and 2cm thick are evident in the face of this soil profile. Lenticular or wedge / lensed shaped peds indicate shrink-swell activity in the soil.

#### Record:

- **Grade of pedality**
- **Shape of peds**
- **Size range of peds**

#### Presence of slickensides (*stress cutans*)

The presence of slickensides in soil material is another indicator of shrink - swell behaviour. McDonald and Isbell (1990) defined stress cutans as shiny or polished soil surfaces, modified by a shear stress experienced along planes of movement in shrink-swell soils. They defined slickensides as a type of stress cutan with smooth striations or grooves. It has however since become common practice to lump both grooved and non-grooved stress cutans under the term slickensides (e.g. Soil Taxonomy, South African Classification, Fitzpatrick *et al.* 1999). These features range from 10mm to 200mm across and are diagnostic of shrink-swell soils (Fitzpatrick *et al.* 1999) (Photo 4.41).

#### Record:

- **Occurrence of slickensides**

#### Macropores

Macropores are pores in the soil which are visible to the naked eye (> 0.075mm diameter).

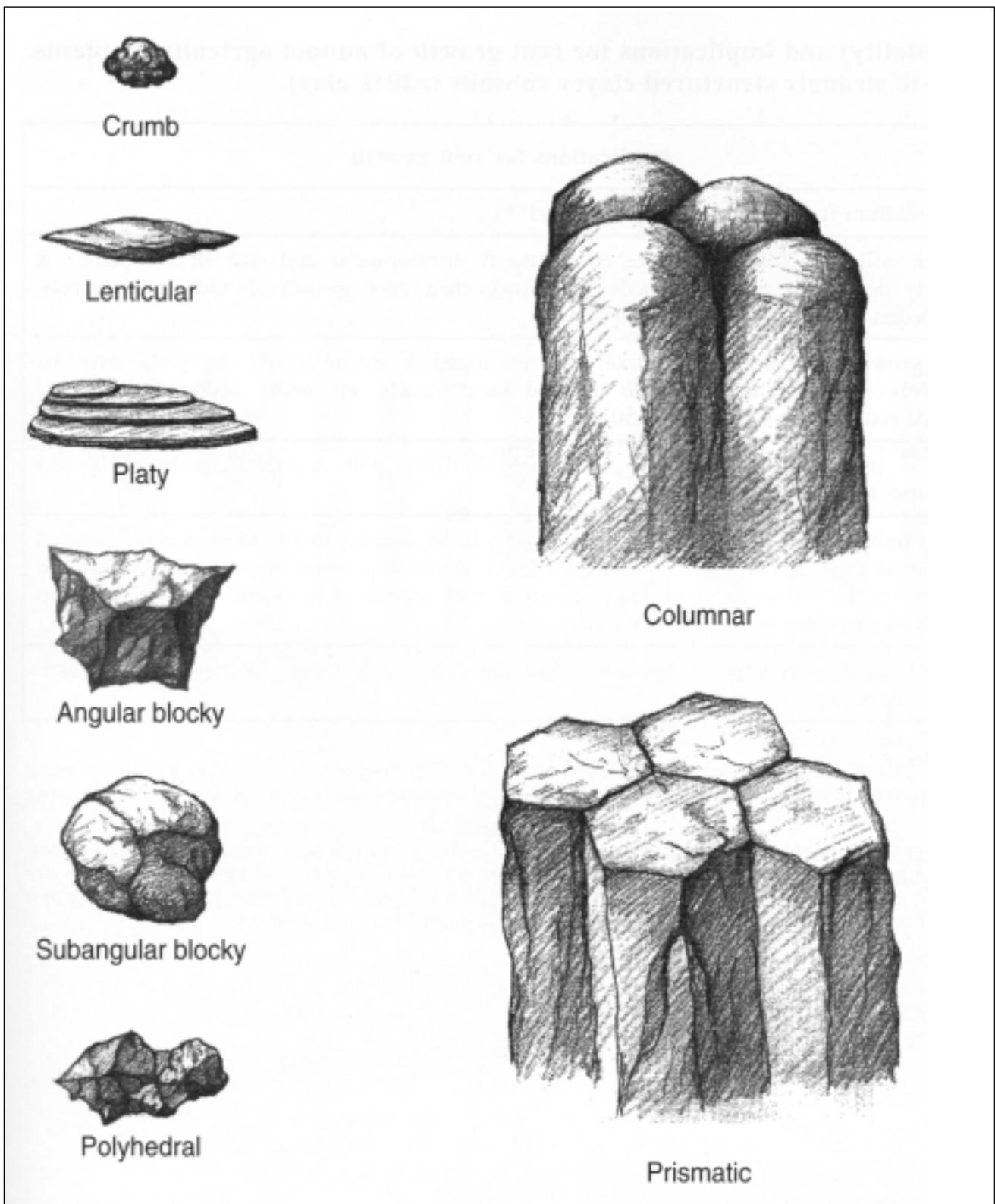


Figure 4.1. The different shape classes used to describe soil aggregates [by N.Schoknecht from Moore (1998)].

Size and abundance classes for description are listed in McDonald and Isbell (1990). Macropores can be important for drainage in heavy textured soil horizons which lack structure. In some cases the drainage

impediments of such layers may be overcome by numerous macropores created by earthworm activity, for example. Recording is optional, but recommended where a large number of macropores is a feature of a horizon.



Photo 4.41. The polished soil surface typical of a slickenside (Photo: R.W. Fitzpatrick, CSIRO)

**Record:**

- **Size and abundance of macropores** for each soil horizon

*Presence of cutans*

Cutans are modifications of the natural surfaces in soil materials. They arise from the concentration of particular soil constituents (Brewer 1964). This soil feature is more relevant to the understanding of soil forming processes than it is to soil management. For example the presence of a type of cutan called argillans (clay skins) on ped surfaces is an indicator of clay illuviation through the soil profile. Although, the preferential movement of illuviated clay through inter-ped spaces rather than through the soil fabric may be an indication of poor drainage through the soil. Refer to McDonald and Isbell (1990) for definitions for describing this feature. Recording is optional.

**Structural stability**

The very simple slaking and dispersion test developed by Emerson (1967) yields extremely valuable information on how a soil behaves structurally. The test involves placing a small dry half-pea-sized soil aggregate (i.e. 3 - 4 mm diameter) in a clear glass dish of distilled or

deionised water or rainwater (1 to 2 cm deep) and leaving it for at least 1 hour and then observing how it behaves. It may remain unchanged (stable), slake (breaking down into smaller particles indicating low organic matter), or partially or fully disperse (producing a cloud of clay around the aggregate indicating unstable clay chemistry and probable sodicity). If possible it is worth leaving the aggregate in the water for a period of 20 hours before taking the final observation to allow time for any dispersion to take its course (Photo 4.42 and Figure 4.2). The top row in Figure 4.2 is the most relevant for assessing a soil for structural limitations to crop growth as it tells you whether the soil aggregate is stable (class 7 or 8), low in organic matter only (slaking with no dispersion), or unstable due to soil chemistry (class 1 and some of class 2). Craze and Hamilton (1991) also recommend further subdivision of classes 2 and 3 into those showing (1) slight milkiness (dispersion immediately adjacent to aggregate), (2) obvious milkiness (< 50 % of aggregate dispersed) and (3) obvious milkiness (> 50 % of aggregate dispersed). These subdivisions are those originally suggested by Loveday and Pyle (1973). Under this classification a soil aggregate which only slightly dispersed would be classed as 2(1), while an aggregate which exhibited > 50 % dispersion would be classed as 2(3). A common practice is to place three

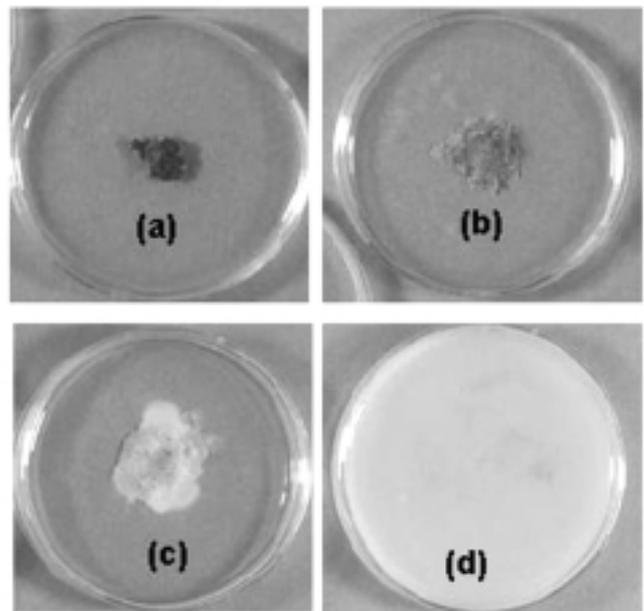


Photo 4.42. Four reactions of soil aggregates to the Emerson test: (a) stable intact, (b) slaked only, (c) slaked and partially dispersed, (d) slaked and completely dispersed. (Photo: Lowan Turton, NSW Agriculture)

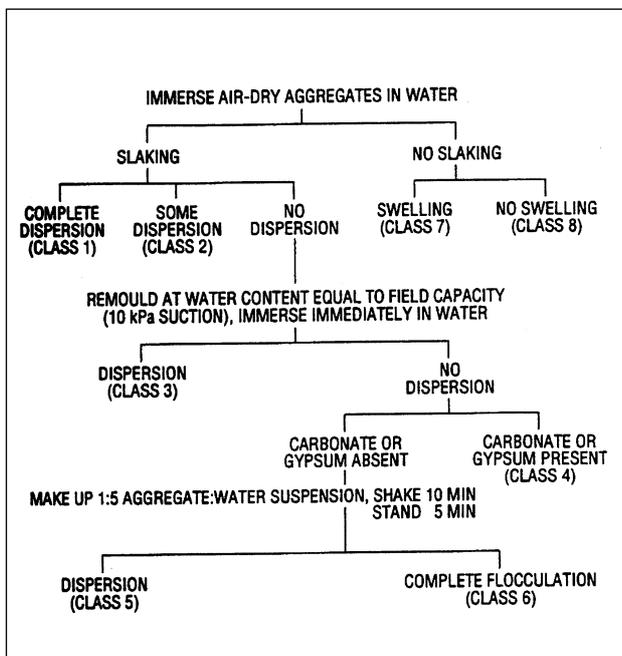


Figure 4.2. The Emerson aggregate test classes (from Murphy 1995, © CSIRO 1995).

small soil aggregates in the dish and record the most negative result out of the three. The remoulding of the soil in this test is meant to simulate the impact of ploughing on dispersion (Emerson 1967). Emerson (1991) recommends that classes 7 and 8 (the non-slaking aggregates) be remoulded as is done normally for the aggregates which slake but do not disperse. This is recommended on the basis that organic matter which stabilises dry aggregates can sometimes actually enhance the dispersion of wet sheared soil.

The relationship between the dispersion test scores of Nelson (2000) and the [Emerson (1967) - Loveday and Pyle (1973)] classes are as follows; Nelson (0) = Emerson classes 3,4,5,6,7, or 8; Nelson (1) = Emerson class 2(1); Nelson (2) = Emerson class 2(2); Nelson (3) = Emerson 2(3), Nelson (4) = Emerson 1.

If irrigating, it is recommended that this test be repeated using the irrigation water instead of rainwater as the presence of salt in irrigation water may retard clay dispersion. Refer to Murphy (1995) for an evaluation of the relationship between the Emerson aggregate test and soil exchangeable sodium percentage (ESP).

Note that dry soil aggregates are required to test for this property. In most cases the soil will be too moist and it is recommended that intact

soil aggregates be collected from the Ap1 and B2 horizons for later testing in the laboratory.

**Record:**

- Emerson class

**Soil consistence**

Examination: Consistence refers to the strength of cohesion and adhesion in a soil (McDonald and Isbell 1990). The most useful of these measurements is "strength". Strength will vary with soil moisture so soil water status must be recorded in conjunction with this determination. It is often best to determine soil strength on a dry piece of soil, so the best strategy is to collect a piece of soil in the field for determination of soil strength after it is dry. A piece of soil with a diameter around 20mm is recommended. It is important to try to adjust ratings for smaller pieces of soil, as a piece of soil half this size would require half the force to rupture it (Fitzpatrick *et al.* 1999). The soil strength classes and the methods of determination are outlined in McDonald and Isbell (1990, p139). All methods involve applying a force to a piece of soil until it ruptures or crushes. Classes range from loose to rigid.

**Record:**

- Soil strength rating
- Soil moisture rating for soil when soil strength was determined

**Segregations / pans**

Segregations are accumulations of distinct mineral particles such as iron or carbonate in the soil as a result of chemical or biological processes (McDonald and Isbell 1990). The most common segregations found in Australian sugarcane soils are manganiferous (manganese) and ferromanganiferous (iron and manganese) nodules and soft segregations. Carbonate nodules are also quite common in cane soils of the dry tropics areas such as the Burdekin. Carbonate segregations are generally not present in soils of the wet tropics or the humid subtropical coastal areas due to the leaching of soluble compounds under high rainfall.

**Examination:** Break open lumps of soil and look for accumulations of distinct mineral segregations within the soil fabric. Use McDonald and Isbell (1990) to describe the forms of segregations present, their size and nature, and estimate their abundance.

Abundance is usually determined by a visual estimate for soft segregations and by sieving some of the soil material through a 2mm mesh sieve for hard nodules. If the nodule is round, hit it with a hammer to open it up to see if concentric rings are present in the internal fabric.

Segregation form: The three most common forms encountered in cane soils are soft segregations, nodules and concretions. They are defined below. Further descriptors for segregations and pans are outlined in McDonald and Isbell (1990).

- *Soft segregations* - finely divided soft segregations (easily crumbled in hand).
- *Nodules* -hard irregular rounded mineral aggregates (not easily crumbled in hand). They have no concentric internal fabric.
- *Concretions* -hard spheroidal segregations with a concentric internal fabric (e.g. pisoliths).
- *Pans* - where nodules or concretions are cemented together to form an impermeable layer.

Segregation nature (mineral composition): The distinguishing features of the major segregation minerals that are most often present in cane soils are listed below:

- *Manganiferous* (manganese) - a distinctive black to purple black sheen on the mineral (Photos 4.9 and 4.11). Distinguishable from charcoal, which typically has a dull black appearance, is non rounded and often has remnant cell structure which is visible under a hand lens.
- *Ferruginous* (iron) - deep red to orange rust coloured mineral materials (Photo 4.1).
- *Ferromanganiferous* (iron - manganese) - black to purplish black mineral material combined with red or rust coloured mineral material in a segregation (Photos 4.9 and 4.11).

- *Carbonate* (usually calcium carbonate) - usually a white to grey coloured crystalline concretion. There is often a white powdery coating around carbonate nodules. Confirmed by evidence of fizzing on application of a couple of drops of dilute hydrochloric acid (HCl) to the nodule. Only present in alkaline soils with pH 8 or above.

**Record:**

- Segregation **abundance** (%)
- Segregation **nature** (e.g. carbonate, manganese)
- Segregation **form** (e.g. nodule, concretion)
- Segregation **size class**

**Soil coarse fraction**

The soil's gravel content or coarse fraction (particles >2mm diameter) is obtained by passing one or two handfuls of soil material through a 2mm sieve. The percentage gravel content (particles > 2mm) of the soil (by volume) is then estimated.

Separating out the gravel fraction in clayey materials in the field is usually difficult. Dry clay materials need to be broken down with a mortar and pestle before being sieved. Alternatively the dry clay lumps can be broken down by placing them in a cloth sample bag and bashing them with a hammer. For moist clay materials in the field, sieving is not a practical option. For these soil materials, the only option is to pick the gravels out by hand and roughly estimate the percentage. This will have to be done in any case for soil texturing.

The description classes for gravel content, abundance (%), size (mm) and shape, are provided in the 'coarse fragment' section of McDonald *et al.* (1990). The minerals and rock types of gravels can be determined with the aid of basic geology and mineralogy field handbooks. Such detailed descriptions are optional.

The <2mm particle size fraction of the soil which passed through the sieve is used to determine the soil texture grade.

**Record:**

- **Total gravel %** (proportion of soil particles > 2mm) for each soil horizon

## Soil texture

Soil texture is a measure of the relative proportions of sand, silt and clay in the soil. This can be measured by a particle size distribution analysis in the laboratory or by a field texture in the field. Field texture is a measure of the feel and behaviour of a small handful of soil (<2mm particle size fraction) when moistened and kneaded into a ball (bolus) and then pressed out between the thumb and forefinger to produce a diagnostic length of soil called a ribbon. Field texture is often used as an estimate of the particle size distribution of the soil (percentages of clay, silt and sand sized particles). Although the relationship between these two properties is generally consistent, it must be remembered that it is only approximate as factors other than clay, silt and sand contents influence field texture (McDonald and Isbell 1990).

Factors which can distort the field texture grade as an estimate of particle size distribution include: clay mineralogy, oxides, organic matter, carbonates, sodicity and strong fine structural aggregation (Northcote 1979). Smectite clay minerals (in cracking shrink-swell clays) and sodic clays (clays with >6 % sodium) tend to make the ribbons longer and cause an overestimation of the clay % by field texture. On the other hand, soils containing significant amounts of iron and aluminium oxides (Ferrosols) or organic matter or carbonates in the fine earth fraction (<2mm) or weathered kaolinite clay minerals (1:1 clays), may produce a shorter soil ribbon and a soil texture grade which underestimates the actual clay content in the soil (Northcote 1979).

### Field texturing procedure

#### *Forming a bolus (soil ball)*

The first step in determining the texture of a soil is to make a bolus or soil ball. This is formed by taking a handful of soil (<2mm fraction) and adding water bit by bit and kneading the soil continuously until the ball of soil formed is mixed and moist (around field capacity) but not sloppy, as described in McDonald and Isbell (1990). The bolus is then worked a further two minutes before it is ready for shearing manipulation and ribboning. Photo 4.43 shows soil being wetted up to form a soil bolus, while Photo 4.44 shows a soil



Photo 4.43. A soil being wetted up to form a soil bolus (Photo: Lowan Turton, NSW Agriculture).



Photo 4.44. A bolus ready to ribbon after two minutes of kneading (Photo: Lowan Turton, NSW Agriculture).

bolus ready to be ribboned.

#### *Ribboning (shear manipulation).*

Ribboning the soil bolus involves applying a shear force to the bolus by pressing it out between the thumb and forefinger. The resultant length of soil is called a ribbon and its length is diagnostic for texture grade determination. For clay soils, the degree of resistance of the soil material to ribboning is also important. It is used to supplement ribbon length in differentiating between the light, medium and heavy clay texture grades. Photo 4.45 shows a soil bolus being ribboned with the length of ribbon indicating the texture grade is a clay.



Photo 4.45. The soil bolus is ribboned by applying a shear force to the soil as it is pushed between the thumb and forefinger (Photo: Lowan Turton, NSW Agriculture).

### Feeling the bolus

The feel of the soil material when kneading the soil bolus provides important additional qualifying information which is used in conjunction with the ribbon length to determine the final texture grade.

- A gritty feel indicates the presence of sand.
- A slippery, silky feel indicates a significant amount of silt in the soil. Silty soils also often leave a distinctive white "floury" stain on the hands when texturing and may also exhibit flow behaviour when the bolus is shaken in the hand (Photo 4.46).
- A spongy feel is indicative of a loam soil material.
- Sodic soils often feel like a soapy lather when the soil bolus is kneaded.



Photo 4.46. A white coating of the hand often occurs when texturing silty loams and silty clay loams.

Quite often two of these diagnostic touch sensations will be present in the bolus. For example both the silkiness of silt and the grittiness of sand might be present. In this instance it is the touch sensation which is dominant that is the final texture qualifier. A soil material that had a dominantly silky feel with a minor feeling of grit would be described as silty.

Other important properties to note when forming the bolus are the soil's coherence and the presence of plastic behaviour. Soil textures lighter than sandy loam have slight to nil coherence, sandy loams and loams are coherent, while heavier textures are strongly coherent. Soil texture grades of clay loam and heavier exhibit plastic behaviour, dinting when pressed.

### Soil texture grade

Once the ribbon length has been determined

and the feel of the soil bolus noted, soil texture can be determined using the field texture grade table in McDonald and Isbell (1990, pp. 118 - 120). When using the table, first use ribbon length to find the texture grades which match, then use the feel characteristics of the bolus to hone in on the correct texture grade. An abbreviated version of this table is presented in Table 4.2.

### Subplasticity

Subplasticity is a property which is common in the Ferrosol (Krasnozems) soils of the tropics as it is often associated with iron oxides. To determine if a soil is subplastic, knead the soil bolus for an additional 10 minutes and then determine the soil texture. If the soil texture increases by at least one field texture group from that determined after the standard two minutes of kneading, then it is subplastic (McDonald and Isbell 1990).

#### Record:

- **Texture grade**
- Note the presence of **subplasticity**.

### Texture calibration for inexperienced practitioners

Note that since soil texturing is a skill it can take time to master. A fall back option for inexperienced assessors might be to have particle size analyses done on samples from some of the profiles described. These results would provide percentages of clay, silt and sand in the soil and would allow the texture to be determined from the texture triangle diagram over page (Figure 4.3). This would provide a reference which would allow the assessor to roughly calibrate their field allocated texture grades to these results.

### Soil pH

Soil pH influences many things such as availability of soil nutrients to plants and soil biological activity. It is also an important property for soil classification. Soil pH can be measured using either (i) Raupach indicator test kit or (ii) a portable pH electrode and a 1:5 soil / water suspension.

### Raupach indicator test kits

These test kits are based on the specifications of Raupach and Tucker (1959) and their estimate

**Table 4.2.** Field texture grades determined from moist soil bolus behaviour, with approximate estimates of the proportions of clay (< 0.002 mm) and silt (0.002 to 0.02mm) sized particles (adapted from McDonald and Isbell (1990))

| Field texture grade | Behaviour of moist bolus  | Approx. clay content (%) |
|---------------------|---|--------------------------|
| Sand                | Coherence nil to very slight; cannot be moulded; single sand grains adhere to fingers.  | usually < 5              |
| Loamy sand          | Slight coherence; ribbon of about 5mm.  | about 5                  |
| Clayey sand         | Slight coherence; sticky when wet; many grains stick to fingers; discolours fingers with a clay stain; ribbon of 5-15 mm.   | 5 to 10                  |
| Sandy loam          | Bolus coherent but very sandy to touch, ribbon of 15-25 mm.   | 10 to 20                 |
| Loam                | Bolus coherent and rather spongy; smooth feel when manipulated but with no obvious sandiness or 'silkeness'; may be greasy to touch if organic matter present; will form a ribbon of about 25 mm. | about 25                 |
| Silty loam          | Coherent bolus; very smooth to silky when manipulated; will form a ribbon of about 25 mm.   | about 25 with silt > 25  |
| Sandy clay loam     | Strongly coherent bolus; very sandy to touch; will form a ribbon of 25-40 mm.   | 20 to 30                 |
| Clay loam           | Coherent plastic bolus; smooth to manipulate; ribbon of 40-50 mm.   | 30 to 35                 |
| Silty clay loam     | As above, but silky to touch  | 30 to 35 with > 25 silt  |
| Clay loam, sandy    | As above, sandy to touch  | 30 to 35                 |
| Light clay*         | Plastic bolus; smooth to touch; slight resistance to shearing between thumb and fore-finger; will ribbon 50-75 mm.  | 35 to 40                 |
| Medium clay*        | Smooth plastic bolus; handles like plasticine; and can be moulded into rods of 3 mm diameter without fracture; moderate resistance to ribboning shear; ribbon of 75 mm or more                    | 45 to 55                 |
| Heavy clay*         | Smooth plastic bolus; handles like stiff plasticine; can be moulded into 3mm rods without fracture; firm resistance to resistance to ribboning shear; ribbon of 75 mm or more.                    | 50 or more               |

\* Add the prefix of sandy or silty to the clay texture grades if they also have a gritty or silky smooth feel.

of soil pH usually corresponds to within + or - 0.5 of a pH unit of laboratory pH (1:5 soil / water) value. An indicator dye is added to a small piece of soil and mixed in before being sprinkled with the inert barium sulfate white powder (as per kit directions) and then a colour chart is used to determine soil pH (Photo 4.47). This is by far the most common way of measuring soil pH for soil survey as it is very quick and easy. The only disadvantage is the slight coarseness of its accuracy which can be up to half a pH unit out. This can be important for soil classification e.g. pH > or < 5.5 in the B2 horizon is a major boundary between Kurosol and Chromosol soil orders in the Australian Soil Classification System. This can be overcome by taking samples for later pH testing using method (ii) back in the laboratory, when necessary.

It is important to be aware that the indicator

solutions in these test kits can deteriorate over time. To ensure that the test kit is reliable it is important to regularly check the quality of the indicator solution. The recommended way of testing the indicator is to add a few drops to the barium sulfate powder to make sure it gives a neutral pH 7 reaction. But it has proven essential in our experience to also test the solution against an alkaline material such as lime or an alkaline soil, which will turn a distinct purple colour if the solution is in good condition.

*Portable pH electrode on a 1:5 soil / water suspension.*

This method can provide a fairly accurate measurement of soil pH, but accuracy is dependent on good maintenance of the pH electrode. The main disadvantages of this method are the effort required to maintain the electrode, the time involved to carry out the

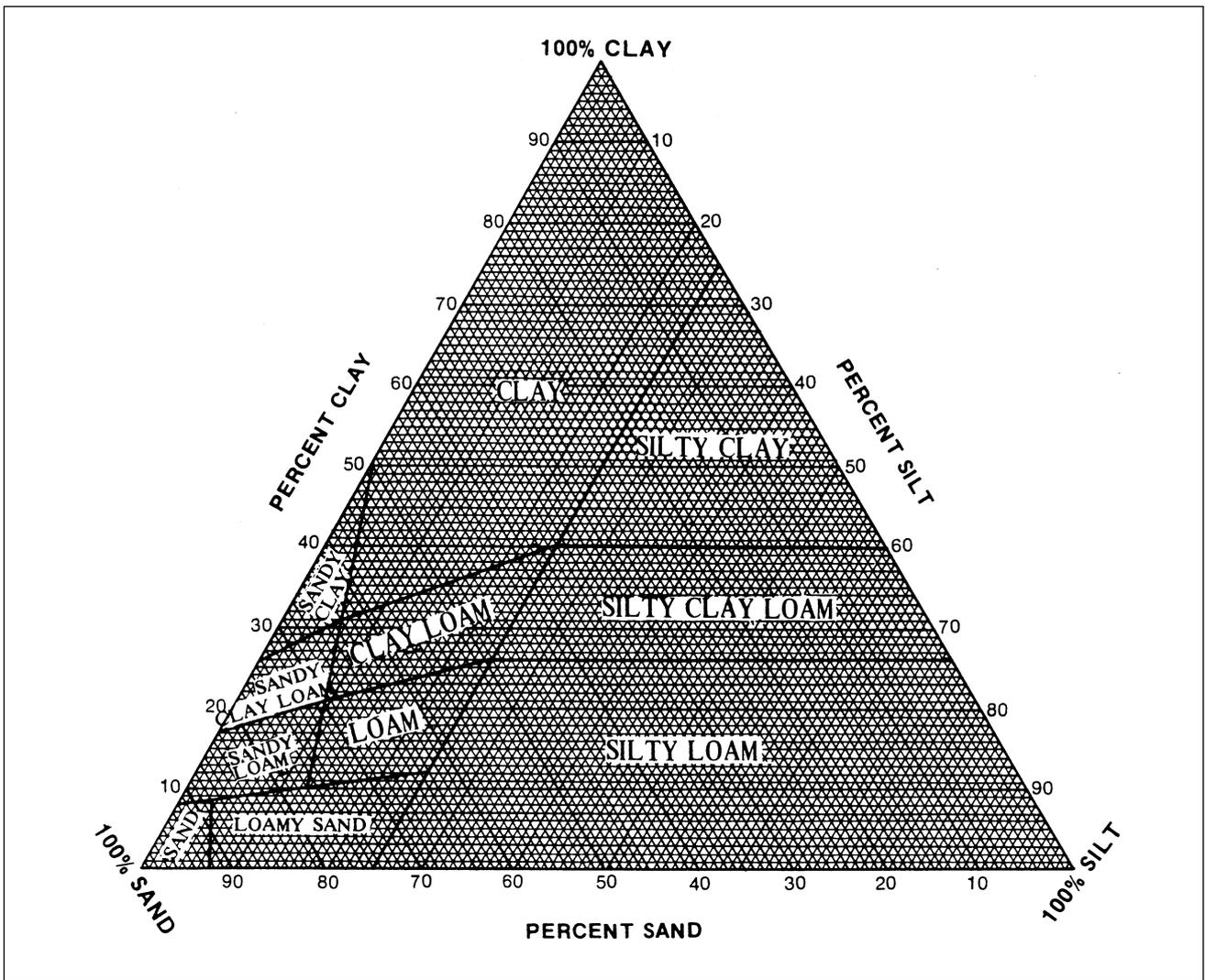


Figure 4.3. The soil texture triangle diagram (from McDonald and Isbell 1990, © CSIRO 1990)

measurement, and the fact that it is often difficult to prepare a 1: 5 soil / water suspension in the field for some soil materials such as heavy clays. For this reason it is often just as easy to collect small samples to take back to the laboratory or workplace to do later as it is to spend time carrying out the test in the field. The laboratory measurement also allows a more accurate 1:5 soil water suspension to be made by weighing out air dried soil.

A detailed field method for determining the pH of a 1: soil / water suspension using a portable pH electrode is outlined in Nelson (2000, p.22).



Photo 4.47. Testing a soil's pH using a pH test kit (Photo: Lowan Turton, NSW Agriculture)

- Record:**
- Soil pH
  - The method used to determine soil pH

## Electrical conductivity

Electrical conductivity (EC) of soil can be measured by placing an EC meter in a 1:5 soil / water suspension (prepared as for soil pH above). EC is a measure of soluble salts (chlorides, sulfates, and carbonates of mainly sodium, calcium and magnesium) in the soil solution and, as such, soil salinity. EC is one of the standard laboratory tests for detailed characterisations of representative soil profiles. However it is rarely done for routine soil profile descriptions in the field unless there is evidence to suggest salinity may be a problem at the site (e.g. evidence of salt scalds and bare patches on the soil surface, waterlogging, poor crop growth, salt tolerant ground cover species etc).

In the wet tropics, salinity is generally not a problem in the landscape above the tidal zone because of the flushing of salts from the soil by the very high rainfall. However salinity is present in the dry tropics and sub tropical regions of coastal Queensland where lower rainfall and an extended dry season are experienced. The Burdekin River catchment is an example of this. It is also important to note that sugarcane has a relatively low tolerance to salinity with yield reduction occurring when the ECe exceeds 1.7 dS/m (Ayers 1977).

### *EC units*

Soil electrical conductivity (EC) is usually expressed in decisiemens per metre (dS/m). However most portable EC meters used in the field read in either micro siemens per centimetre ( S/cm) or millisiemens per centimetre (mS/cm). One dS/m equals 1mS/cm which equals 1000 S/cm (Nelson 2000).

### *Converting EC to ECe*

To be able to interpret the significance of EC values for crop growth, they have to first be converted to ECe values using multiplier factors. A procedure for this is outlined in Section 5.5.2.

If salinity is to be measured, it is preferable to collect a small soil sample in the field to take back to the laboratory for later analysis, rather than do tests in the field. This is because it is hard to get the same level of accuracy in the field.

### **Record:**

- Soil EC (dS/m)

## Soil surface condition when dry

It is important to assess the condition of the soil surface as well. In the case of sugarcane fields assessments should be done on the row and interrow areas and recorded separately. The condition of the soil surface on the row is of most importance to crop growth. Assessing the soil surface involves a visual assessment as well as a subjective assessment based on the relative ease of pushing your forefinger through the soil. The classes for this property are defined in McDonald and Isbell (1990). They include cracking (Photo 4.48), self-mulching, loose, soft, firm, hard setting, surface crust and surface flake.



Photo 4.48 - Deep wide cracks in the soil surface indicating shrink-swell activity in the soil.

### **Record:**

- Soil surface condition

Water repellence is another important surface soil property (especially in sandy soils). It can be assessed with an ethanol or methylated spirits solution using the method outlined in McDonald and Isbell (1990). This is usually only ever done if water repellence is observed when wetting up the topsoil for texturing.

## 4.5 OTHER ESSENTIAL SITE AND SURVEY INFORMATION

Other site information that should be recorded for each soil description site is listed in data set 1 (Section 3.2.1). These are listed below. They include such things as information on the site location and the way the soil was sampled. Of all these pieces of information, the most

important is a map grid reference.

**Record:**

- **Australian Map Grid Reference** (GPS or topographic map - note geodatum)
- **Brief description of location** (e.g. top northern side of field, 20m from pump, Mann property, Rita Island)
- **Slope %** (estimate or clinometer reading)
- **Aspect** if any.
- **Landscape setting** (e.g. on footslope, hill crest, footslope - see Speight(1990) for terms)
- **Slope morphology** (i.e. waxing or waning etc)
- Soil profile **sampling method** (i.e. push tube core, hand augering, soil pit etc.)
- Soil profile described on the **row or interrow** area in field?
- **Date** of description

## 4.6 SAMPLING A SOIL PROFILE FOR LABORATORY ANALYSIS

The following section deals with sampling a soil profile as part of the process of characterising and classifying the site's representative soil profile. For composite sampling methods for fertiliser recommendations, APSIM modelling and environmental monitoring refer to the sampling section in Section 5 - soil chemistry.

### 4.6.1 Sampling depth intervals

#### Reasons for a 'soil horizon based' sampling approach

Soil horizon boundaries should be the basis for determining sampling depth intervals for a single soil profile for analysis. This is especially the case when sampling is associated with the characterisation of representative soil profiles. There are many reasons for this. Firstly, horizons are defined on the basis of observable features such as texture and colour which often directly relate to important measurable soil properties such as cation exchange capacity, organic matter, nutrient status, water holding capacity etc. Secondly, it is important that sampling intervals relate to soil horizons for soil classification. All indices used in soil classification relate to specific soil horizons and parts thereof. Any results from other parts of the profile or, even worse, from

depth intervals overlapping contrasting horizons (e.g. sand and clay) are not desirable.

However, fixed sampling depth intervals are the recommended approach when collecting composite samples from several deep soil cores across a field. This sampling approach is usually used to determine the average concentration of nutrients at certain depths across a field, and this procedure is outlined in Chapter 5 - soil chemistry.

#### How to subdivide the profile for sampling on the basis of soil horizons

There are two approaches to sampling the soil profile based on soil horizons. One approach is to collect soil samples as a series that covers the whole soil profile by continuously sampling down the profile. Soil horizon boundaries are used as the framework for the sampling intervals which further subdivide the horizons. This is the approach used in most of the CSIRO soil survey reports and is recommended by McKenzie and Cresswell (2002). The advantage of this approach is that it will provide a complete set of soil samples that will allow the chemistry of the whole soil profile as a continuum to be assessed if the budget is available now or some time in the future. One disadvantage is that additional soil samples have to be stored and may never be analysed. Another disadvantage is the relative cost benefit of assessing numerous soil samples from the one horizon.

An alternative soil sampling approach is to take a soil sample from only a selected depth interval or intervals in each soil horizon. This approach attempts to avoid any unnecessary sampling and ensure that the sample that is taken is not only representative of the soil horizon but is of particular use either in understanding the soil function or in the classification of the soil. Some key issues that need to be considered in deciding where to sample are addressed below. It should be noted that sampling increments chosen for this selective sampling approach should also be incorporated as sampling depth increments within the continual sampling approach in many cases, as they are the important areas of the soil profile.

### *General rules*

For the topsoil horizon, the sample should always include the surface of the mineral soil as this is where most of the nutrient cycling processes occur.

For subsoil layers, it is usually desirable to take the soil sample from the middle of the horizon, especially in horizons with gradual boundaries or transition zones to the soil layers above and below. B horizons are exceptions to this (see soil classification considerations). Also for very thick horizons (thicker than 75 cm) it may be preferable to take a sample from in the middle of the upper and lower halves of the horizon.

When sampling disturbed soil materials from hand augerings, which is not preferable, it is always advisable to sample from the middle of the subsoil horizons to ensure the sample is more likely to be representative.

### *Soil classification considerations*

Soil classification systems often have group divisions based on the chemistry of specific areas of the soil profile. Table 4.3 shows that many of the soil orders in the Australian Soil Classification have some finer subdivisions based on the chemistry of the top 20 cm of the B2 horizon. The table reveals that there are also some subdivisions based on the chemistry of the lower part of the B horizon. So if one of the intentions of sampling is to obtain laboratory results to help with soil classification according to the Australian soil classification system, it would definitely be advisable to sample the top 20 cm of the B2 horizon, and in some cases the lower B horizon as well.

### **How large or thick should the sampling depth interval be?**

As a general rule, it is better for the sampling depth interval to be smaller than to be too large, as it means there is less risk of diluting out critical information and also less risk of sampling across transitional boundary areas. McKenzie and Cresswell (2002) recommend a maximum sample depth interval of 10cm within the top 30 cm of the soil and a maximum sampling depth interval of 30 cm for the rest of the profile. This recommendation seems a reasonable default. A 10 cm sampling interval would even be acceptable for sampling

subsoil horizons in a soil pit, but preferably no smaller than this. But there are many factors to consider.

Firstly, the Australian Soil Classification requires information on the top 20 cm of the subsoil for many of its soil groups, so an economical option would be to take a single 20 cm sample of the B2 horizon.

Agronomic considerations such as cultivation practices are also important. For example, cultivation and land preparation for sugarcane crops usually disturbs the soil to a depth greater than 30cm, while cereal crop and pasture establishment may not disturb the soil below 10cm. Some argue that for sugarcane fields a sample interval of up to 20 cm may be appropriate for characterising a topsoil layer because of the extent of incorporation and mixing of the topsoil that occurs in land preparation for that crop.

Another consideration is the volume of soil material available to sample. In some instances with core samples it may be essential to increase the sampling interval to ensure that there is enough soil material for the planned analyses. The gouge auger which is used to collect soil samples from boggy areas collects a sample core which is only 2 cm in diameter, so the sample interval often has to be increased to 20 cm in order to ensure enough soil material.

When sampling soils for an investigation or research project, it is also important to relate the sampling strategy to the scale of the natural processes being investigated. For example investigations of cycling of organic matter and nutrients or movement of surface applied phosphorus in run off, may require very small sampling intervals (1 or 2cm) at the soil surface.

### **Composite surface sample**

When no soil test information is available for a field that is being characterised, it is sometimes worthwhile collecting a composite soil sample (0-10 cm) from within a 10 m radius of the sampled soil profile. This will provide a better estimate of the average soil nutrient status of the field's topsoil than a single sample taken from the top of the soil profile. This practice however is more common for sampling done in

## A Worked Example for Determining Sampling Depths

Examples of some acceptable sample depth intervals for a profile using (a) selective sampling strategy or (b) continuous sampling strategy.

### (a) Selective sampling strategy

| Soil profile          | Suggested sample intervals (cm)            |
|-----------------------|--|
| A1 horizon 0 - 28 cm  | → sampling interval 0 - 10 *               |
| A2 horizon 28 - 70 cm | → sampling interval 45 - 55                |
| B2 horizon 70 - 150cm | → sampling intervals 70 - 90 ,<br>120 -140 |

### (b) Continuous sampling strategy

\* It may be argued that for sugarcane, the top 20cm of soil is a more appropriate surface sample interval when soil management practices are taken into account. For example, this may be the case if the field was recently cultivated. 0 - 20cm is also the current recommended surface sampling depth interval for fertiliser recommendations in the sugar industry.

regional soil surveys. For crops it is better to collect this information as part of the routine assessment of a field's soil nutrient status for determining fertiliser application rates (see Section 5 for guidelines on this sampling).

## Which samples to test?

Once all of the soil samples are collected, decisions have to be made on which soil samples to test and what tests to do, within the allowed budget of the project. A rationale for deciding which soil tests to do and which soil samples to test is provided in Section 3.3.

Economics usually dictate that as few as one soil depth increment per horizon is actually tested.

## 4.6.2 Sampling equipment and procedure (soil pit)

### Loose bag samples for chemical analysis

To collect soil samples from a soil pit, it is

desirable to have the following equipment:

- Tape measure to locate the sampling depth intervals
- Knife or spatula to mark the sample depth intervals on the pit face
- Small trowel or spade to dig soil sample out of the soil pit face.
- Calico cloth sample bags or alternatively large plastic bags and elastic bands
- Paper tags and string or aluminium tags.

*Step 1:* Determine the sampling depth intervals from the horizon depths in the soil profile description, using the process outlined earlier.

*Step 2:* Mark sampling depth intervals on the picked back vertical face of the soil pit with a sharp knife or spatula.

*Step 3:* Use a trowel or spade to scoop out sufficient sample from this layer (usually 1.5kg to 2kg), removing soil uniformly throughout the chosen sampling depth interval.

*Step 4:* Write the horizon notation, layer number, depth interval of sample, site number, site name, location, and date on an aluminium or cardboard label. Tie the bag with string and attach the label.

*Step 5:* Collect composite surface soil sample as outlined above. This is usually only collected when no composite field sampling of the site has been done for planning fertiliser application.

*Step 6:* Put samples together in a crate / box and store in the shade whilst in the field or ideally place them in a refrigerated sample box if available. If nitrate is to be tested, samples should be placed in either a refrigerator or esky and kept below 4°C to reduce microbial N transformations.

### Intact core samples for bulk density and soil water properties

For guidelines on taking small core samples from soil pits for bulk density and soil water properties, see Section 6.6.

### Sampling a described 1.5m long push tube soil core for laboratory analysis

The following three points need to be

considered when taking soil samples from a push tube core for laboratory analysis.

#### *Reconstructing the soil core*

When sampling soil core samples, it is important that any unconsolidated soil material in the core is arranged on the sample table in a way that approximates its distribution when undisturbed. This can be done by ensuring the extracted soil core is the same length when laid out as the depth of the hole in the ground from where it came. This is done for the soil profile description which precedes sampling.

#### *Sampling a single soil core (1.5m long) for soil type characterisation*

For soil pedological characterisation, the profile should be sampled in the same manner as that outlined for soil pit profiles in Section 4.6.2.

#### *Mould oil as a potential contaminant*

The potential impact of using mould oil to lubricate the soil core sampling tubes needs to be considered when soil cores are to be sampled for laboratory analysis. Mould oil has been found to have the potential to significantly contaminate soil samples for organic carbon tests (Dowling *et al.* 1985). Ways to get around this are to: (1) not use mould oil; (2) use mould oil on the deep core sample and then re-sample the topsoil adjacent to this core using an alternative method; (3) use a silicon-based oil lubricant which has no risk of contaminating soil carbon results (but is usually more expensive); or (4) sample the soil profile in stages, sampling the topsoil without oil (0-50 cm) and then use oil for sampling the lower depths of the profile.

### **4.6.3 Storage, transport and processing of soil samples**

The storage and handling requirements for soil samples collected for chemical analysis depend on what properties the soil is to be tested for. There are basically three handling procedures: one procedure for most routine soil tests excluding mineral N and potential acid sulfate soils (PASS), one for soils to be tested for mineral N and another for acid sulfate soils. These procedures are outlined below.

### **Sample storage and handling for routine soil testing (minus mineral N and PASS)**

Soil samples destined for routine chemical analysis are usually placed in calico cloth bags and placed in the shade when in the field (Photo 4.49). They are then air dried at around 40 °C. This can be done in a fan force-draft oven or else by placing the samples on tables or hanging them on hooks in a well ventilated greenhouse or shed to dry in the cloth bags.



Photo 4.49. A haul of soil samples from the field. Loose soil samples collected in calico bags for routine analysis are in the background. A crate of intact soil cores sampled for soil water property testing is in the foreground.

Once air dry, the samples are ground or crushed before being passed through a 2mm sieve. Care must be taken to not crush up gravels or concretions during this process. Both the gravel fraction (>2mm size fraction) and the fines (<2mm size fraction) are weighed to determine the soil's gravel content (%). The fine <2mm size fraction is then sent to the laboratory for testing. The crushing and sieving equipment need to be adequately cleaned between samples in order to prevent cross-contamination.

If the Emerson aggregate test is to be done a few small pea sized aggregates will need to be subsampled from the soil sample before crushing begins.

### **Sample storage and handling for soils to be tested for mineral N**

Soil samples to be tested for mineral N require cold storage in the field to prevent the mineral N levels from changing significantly before the sample even reaches the laboratory. These

samples also have particular requirements in regard to their storage and preparation at the laboratory and these are outlined below.

When soil samples require routine analysis as well as mineral N testing, it is often convenient to take a subsample for mineral N testing which can be handled and stored as outlined in this section, while the bulk of the sample is handled as for routine analysis. This will help ensure that there is enough space in the portable fridge to store the mineral N samples.

#### *Sample handling and storage*

It is important that soil samples collected for mineral N testing, are placed in a portable refrigerator (or esky with ice bricks) as soon as possible after sampling (Photo 4.50). This is because slow drying and temperature will significantly affect ammonium N and, especially, nitrite N values. It is best to keep soil samples at  $-15^{\circ}\text{C}$  in sealed plastic bags where possible (Brown 1999) and as such soil samples should be frozen on return from the field. Samples are usually sent to the laboratory via express courier, frozen and packed in a small esky or cooler.



Photo 4.50 A portable fridge run off the car battery is ideal for storing mineral N and acid sulfate soil samples in the field.

#### *Sample analysis*

At the laboratory, analyses for nitrite N are usually carried out on field moist samples (Brown 1999). Rayment and Higginson (1992) warn against slow air drying mineral N soil samples as this can alter concentrations of nitrate nitrogen ( $\text{NO}_3^-$ -N) and ammonium

nitrogen ( $\text{NH}_4^+$ -N) and will totally invalidate results for nitrite nitrogen ( $\text{NO}_2^-$ -N). If sample drying is to be done, Rayment and Higginson (1992) recommend fast drying below  $55^{\circ}\text{C}$  (typically  $40^{\circ}\text{C}$ ) to minimise these affects. Soil samples oven dried at  $105^{\circ}\text{C}$  are definitely not suitable for mineral N analysis.

Both the field moist and rapidly dried soil sample preparations have pros and cons associated with them. Analysis of a field moist soil sample avoids the likelihood of N losses (especially nitrite) with drying. The advantage of the rapid drying approach is that it enables a more representative sub-sample to be taken for analysis, since the dried soil sample can be ground, sieved and well mixed before subsampling.

Samples should be analysed for all components of mineral N ( $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N, and  $\text{NO}_2^-$ -N). Methods for the determination of mineral N are outlined by Rayment and Higginson (1992).

### **Sample storage and handling for potential acid sulfate soil testing**

Acid sulfate soil profile samples require similar handling in the field to that outlined for the mineral N samples in that they need to be immediately placed in a portable refrigerator or esky (cooler) with ice bricks. In addition, for these samples extra efforts are normally made to ensure that all of the air is squeezed out of the plastic sample bags before tying off the samples. This is just another precautionary measure to help ensure that any chance of the pyrite oxidising is minimised. Once back from the field, these samples are typically frozen and express couriered to the laboratory for analysis.

## **4.7 SOIL CLASSIFICATION**

### **4.7.1 Why classify a soil?**

The main reason we classify soils is to provide a means of effectively communicating soils information to other scientists and the community. Classification does this by providing a standardised framework for organizing our knowledge of a soil (Isbell 1996).

However, for effective communication to growers, this same soils information will often need to be related to local soil names and be presented in a less technical way.

### 4.7.2 Soil classification systems

#### Australian soil classification systems

Up until recent times, there were two soil classification systems in use in Australia and these were the Great Soil Groups (Stace *et al.* 1968) and the Factual Key (Northcote 1979). Both of these classification systems had a number short comings associated with them and because of this the Australian Soil Classification (Isbell 1996) was developed.

The Australian Soil Classification (Isbell 1996) is now the official soil classification system for Australian soils, and as such this is the system which should be used for work on Australian soils.

#### International soil classification systems

For the communication of soil science ideas and information at international conferences and in international journals there needs to be a common reference soil classification system. As a standard, most international journals now require one of two soil classification systems to be referred to in submitted articles. One of these is the USDA classification, Soil Taxonomy (Soil Survey Staff 1998). The other accepted classification system has been the FAO Revised Legend of the Soil Map of the World (FAO 1988) and this has recently been superseded by the World Reference Base (WRB) (FAO-ISSS-ISRIC 1998).

### 4.7.3 Australian Soil Classification (ASC)

#### Properties important for the ASC

The soil morphological properties that are important for classifying a soil profile are listed in the soil classification data set (Section 3.2.1).

With increasing level of detail, the ASC goes from order to sub-order to great group to sub-group to family. The final classification is written in the following order: subgroup / great group / suborder / order/ family. An example of this would be: bleached, eutrophic,

red chromosol, thin, gravely, sandy/clayey, shallow (Isbell 1996). For conversation, such a soil would normally be referred to as a bleached red chromosol or red chromosol.

Figure 4.4 (Isbell 1996, p.10) demonstrates the properties that are important for the early 'order' stage of the Australian Soil Classification. These include soil colour, texture, structure, horizon notation, boundary distinctness between the B2t horizon and the overlying horizon (thicker than 0.03m), evidence of prolonged saturation (soil indicators and local knowledge), presence / absence of shrink-swell indicators (slickensides/surface cracks/lenticular peds), structure of the B horizon, pH of the B horizon, presence/absence of carbonate accumulations at or directly below the A1 horizon.

#### A Classification System for Australian Soils

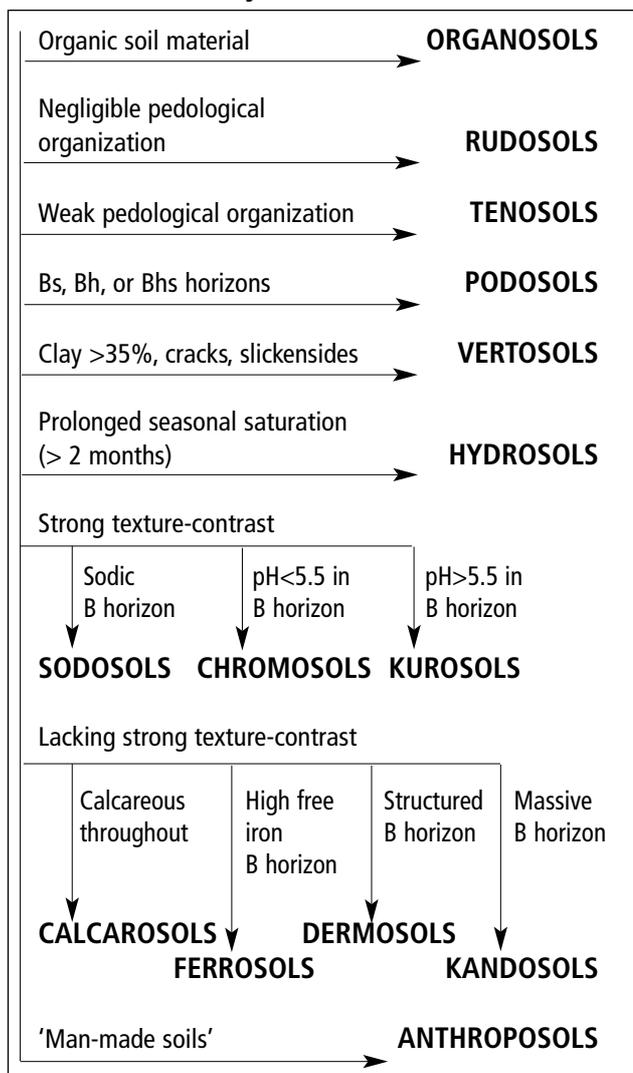


Figure 4.4. A schematic summary of the orders of the Australian Soil Classification. (Sourced from Isbell (1996), NOT to be used as a Key!)

### *A simplified overview*

The classification separates out soils resulting from man's activities such as excavation and burial etc (Anthrosols), soils with high organic matter (Organosols), some of the leached sandy soils of the coastal barrier dune areas (Podosols), the cracking clay soils (Vertosols), the soils that are wet for prolonged periods (Hydrosols). It includes the young soils which reveal little soil development beyond the accumulation of organic matter in the surface (Rudosols) and soils which have developed slightly more with the presence of a bleached layer or a colour B horizon (Tenosols). The texture contrast soils (e.g. sandy topsoil abruptly overlying a clay subsoil) are separated out and their orders subdivided on the basis of subsoil features such as sodicity (Sodosols), and acidity (Kurosols and Chromosols). The remaining soil profiles which lack texture contrast, being uniform or gradational in nature, are separated out into those which are calcareous throughout (Calcarosols), those which have a high free iron content in the B horizon (Ferrosols), and those which have a structured B horizon (Dermosols) or a massive B horizon (Kandosols).

### *Laboratory analyses*

Figure 4.4 reveals how two of the soil orders require laboratory verification and these are the Sodosols and the Ferrosols. For the Sodosol order the ESP (exchangeable Na as a % of CEC) needs to be determined for the upper 0.20m of the B2 horizon. For Ferrosols, free Fe % may be required if it is not certain that the soil in question is formed on basalt (Isbell 1996).

Laboratory analyses are also required to fully classify soils to the family level for several of the orders. The testing required is presented in Table 4.3 and this elaborated on by Isbell (1996).

Many of these tests will need to be routinely done for all soils but obviously some of these soil tests can be avoided by using common sense. For example the free iron test which only applies to Ferrosol soils would only be carried out on gradational structured red soils where it was uncertain whether they were formed on basalt or not. Other tests such as linear shrinkage for Vertosol soils are not really

necessary if diagnostic features such as surface cracking, slickensides and lenticular peds are observed present in the field. The CEC to clay ratio (CCR) can be used instead of this test to confirm a dominance of smectite clay minerals (high shrink-swell clays) in a subsoil (see Section 5.7.4).

Although the above tests are carried out on the soil profile to allow a full classification according to the Australian Soil Classification (Isbell 1996), they still allow a reasonably detailed Soil Taxonomy or FAO classification to be achieved in most cases.

### **Procedure for classifying a soil according to ASC**

Classifying a soil according to the ASC involves reading through the Key to Soil Orders section of the classification book from the beginning and working through the soil definitions until a description which matches your soil is found.

The order in which the soil orders are listed in the key (pages 15 to 17 in Isbell (1996)) is very important for getting the classification right. For example, a cracking clay soil which is wet for periods of more than 3 months is classified correctly as a Vertosol, but could easily be wrongly classified as a Hydrosol if the order was not meticulously followed.

Once the soil's order has been decided, one can then turn to the section of the text on that order and proceed through the key there for a more detailed classification.

The Glossary is a very important section of this classification as most of the terminology and all of the classification criteria are discussed in detail in this section. Classification always involves flicking back and forth between the glossary section and the classification key.

### **The Australian Soil Classification - An Interactive Key**

An interactive key that can be downloaded onto a computer has been developed to help people classify Australian soils according to ASC. The key has been developed by CSIRO (Jacquier *et al.* 2001) and includes many plain English definitions of soil properties and these definitions often include pictures as well.

**Table 4.3:** Laboratory analyses required to fully classify a soil for each soil order of the Australian Soil Classification (adapted from Isbell (1996))

| Soil tests  | Soil orders |    |    |    |    |    |    |    |    |    |    |    |    |   |
|---|-------------|----|----|----|----|----|----|----|----|----|----|----|----|---|
|   | OR          | RU | TE | PO | VE | HY | SO | CH | KU | CA | FE | DE | KA | A |
| Organic C or LOI for A1 horizon   | X           | X  | X  | X  | -  | X  | X  | X  | X  | X  | X  | X  | X  | - |
| pH (1: 5 soil/water) of A1 horizon  | X           | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | - |
| pH (1: 5 soil/water) of B2 horizon  | -           |    | X  | -  | X  | X  | X  | X  | X  | X  | X  | X  | X  | - |
| ESP <sup>1</sup> for the top 0.2m of the B2 horizon                             | -           | -  | -  | -  | -  | X  | X  | X  | X  | X  | X  | X  | X  | - |
| ESP for the lower part of B horizon   | -           | -  | -  | -  | -  | -  | -  | X  | X  | X  | X  | X  | X  | - |
| Cation exchange capacity (CEC) and cations for the major part of the B2 horizon | -           | -  | -  | -  | X  | X  | X  | X  | X  | -  | X  | X  | X  | - |
| ESP and cations for top 0.1m, upper 0.5m and lower 0.5m of profile              | -           | -  | -  | -  | X  | -  | -  | -  | -  | X  | -  | -  | -  | - |
| Free iron (Fe) for major part of B2 horizon*                                    | -           | -  | -  | -  | -  | -  | -  | -  | -  | -  | X  | -  | -  | - |
| EC (1:5 soil/water) of A1   | -           | X  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | - |
| EC of groundwater   | -           | -  | -  | -  | X  | X  | -  | -  | -  | -  | -  | -  | -  | - |
| Particle size analysis  | -           | -  | -  | -  | X  | -  | -  | -  | -  | -  | -  | -  | -  | - |
| Linear shrinkage <sup>2</sup>   |             |    |    |    | X  |    |    |    |    |    |    |    |    |   |

1 ESP is the exchangeable sodium percentage – need to test for CEC and exchangeable Na

2 Optional.

\* Citrate – dithionite extract (Rayment and Higginson (1992), Method 13C1).

OR = Organosol, RU = Rudosol, TE = Tenosol, PO = Podosol, VE = Vertosol, HY = Hydrosol, SO = Sodosol, CH = Chromosol, KU = Kurosol, CA = Calcarosol, FE = Ferrosol, DE = Dermosol, KA = Kandosol, A = Anthrosol.

#### 4.7.4 Soil Taxonomy

In Soil Taxonomy (Soil Survey Staff 1998) the order of division with increasing intensity of classification is: order, suborder, great group, subgroup, family, series.

The initial separation of soils into groups at the order level was developed on the basis of properties reflecting the major processes and pathways of soil formation (Ahrens and Arnold 2000).

#### Diagnostic horizons

The major differentiating criteria used in the classification are diagnostic horizons. These are defined in detail in the Keys to Soil Taxonomy (Soil Survey Staff 1998).

Epipedons are diagnostic horizons at or near the surface. There are currently eight recognised epipedons in soil taxonomy. These are the Anthropic, Folistic, Histic, Melanic, Mollic, Ochric, Plaggen, and Umbric epipedons.

There are 20 diagnostic subsurface horizons in soil taxonomy as well.

### Diagnostic pedological features

Many additional pedological features are used in the classification. These include 'slickensides', abrupt textural change, and waterlogged (aquic) conditions.

### Soil moisture and temperature regimes

Soil taxonomy also includes climatic zones in its classification system, with defined temperature and moisture regimes.

### Classifying a soil

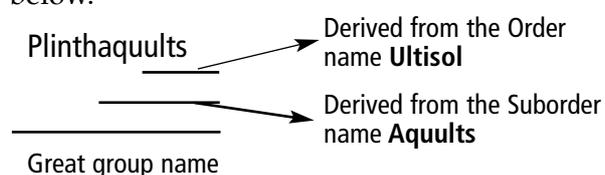
Most of the soils information noted above would be collected in a standard soil profile description in Australia. The main adjustment to be made when classifying an Australian soil using Soil Taxonomy involves converting local soil science terminology to that used in Soil Taxonomy. Thankfully the Soil Taxonomy terminology is defined in great detail, which makes the process easier. Many diagnostic horizons are defined according to the presence of particular soil features or materials (bleached soil, mottles etc). However, it is important to be aware that these features are also sometimes defined slightly differently to their Australian counterparts.

A simplified summary of how Australian sugarcane soils fit into Soil Taxonomy is presented in Table 4.4.

### Soil Taxonomy classification names

Soil Taxonomy classification names are not a simple collection of the names for the various classification levels as is the case with the Australian Soil Classification. Instead the final soil classification name is a word which is constructed from elements of the words used to name the order, suborder and great group.

For example the derivation of the great group Plinthaquults which belongs to the Aquults suborder of the Ultisol order is demonstrated below.



The Plinth component of the above classification comes from the presence of a mineral soil horizon in the top 150 cm of the soil which contains a high concentration of Plinthite.

A subgroup name is connected to the great group name in the following manner: Plinthaquults - Kandic.

A classification name which goes to the subgroup level such as this is often required for Journal articles.

### 4.7.5 World Reference Base (WRB)

The second international soil reference system that is accepted in most scientific Journals is the World Reference Base for Soil Resources (WRB) (FAO-ISRIC-ISSS 1998). This system has replaced the former Revised Legend of the Soil Map of the World (FAO 1988).

This classification is also based on soil properties defined in diagnostic horizons, with the reference base consisting of 30 reference soil groups plus a list of defined adjectives which can be used in combination with the group names to enable a more precise characterisation of a soil (Spaargaren 2000). The WRB is meant to serve as a link between existing national soils classification systems and to be a common denominator for international communication on soils (Spaargaren 2000).

Being somewhat more condensed than Soil Taxonomy, the WRB would probably be the easiest option for most people, especially those with limited experience in soil classification.

## 4.8 ACID SULFATE SOILS - A BRIEF OVERVIEW

Acid sulfate soils present a serious potential threat to the environment and agriculture if disturbed. For this reason, it is important to be aware of where they occur in the landscape and how to manage them. The best approach is to avoid disturbing these soils in the first place, as their remediation once drained can be very costly. This section only aims to provide a brief overview about what acid sulfate soils are, why they are a problem, and how to identify them. For a more detailed coverage of acid sulfate

**Table 4.4.** A simplified summary of how Australian sugarcane soils relate to Soil Taxonomy order groupings (correlations with ASC adapted from Isbell 1996)

| Soil Taxonomy (USDA 1998) orders present in sugarcane lands   |
|---|
| <p><b>Alfisols:</b> - soils from a wide range of ASC soil orders fall within this classification. Soils with an ochric epipedon, an argillic horizon, moderate to high base saturation of 35% or more (at designated critical subsoil depths).</p>  |
| <p><b>Entisols:</b> = some Tenosol, Rudosol and Hydrosol soils(ASC)<br/>SOILS with little or no evidence of diagnostic soil horizons, other than an ochric epipedon<sup>1</sup>.<br/>e.g. Some soils in floodplain , dune, or actively eroding slope environments</p>   |
| <p><b>Inceptisols:</b> = some Tenosols and some Hydrosols (ASC).<br/>Soils with one or more pedogenic horizons of alteration or concentration with little accumulation of translocated materials other than carbonates or amorphous silica. Soils with a cambic horizon and an ochric epipedon<sup>1</sup>. Includes a wide variety of soils from soils with minimal development to soils with diagnostic horizons which fail the criteria of other orders. Soils range from very poorly drained to excessively drained.</p>  |
| <p><b>Mollisols:</b> = some Dermosol soils (ASC)<br/>SOILS with a very dark brown to black surface horizon (mollic epipedon) that accounts for more than 1/3 of the combined thickness of the A and B horizons or that is &gt;25cm thick and has structure or is not hard when dry; a dominance of Ca<sup>2+</sup> among exchangeable cations in the A and B horizons; and &lt; 30% clay in some horizon above 50cm if the soils have deep wide cracks (&gt;1 cm) above this depth at some season.</p>  |
| <p><b>Oxisols:</b> = some Ferrosol soils (ASC) in the tropics.<br/>Soils which have experienced extreme weathering of minerals other than quartz to kaolin and free oxides, and have very low activity of the clay fraction (i.e. low CEC, low shrink/swell), and a loamy or clayey texture (sandy loam or finer).</p>  |
| <p><b>Spodosols:</b> = Podosols (ASC)<br/>Soils characterized by a 'spodic' B horizon consisting of an accumulation of black or reddish amorphous materials with a high cation exchange capacity. The dominant process is the translocation of humus and aluminium, or humus, aluminium and iron. The CEC is more often related to the organic carbon levels than to the clay%.</p>   |
| <p><b>Ultisols:</b> - soils from a wide range of ASC soil orders fall within this classification.<br/>Ultisols, like alfisols have markers of clay translocation, but they also have markers of intense leaching which are absent in Alfisols. The CEC is mostly moderate or low. They have a kandic<sup>3</sup> or argillic horizon<sup>2</sup> with low base saturation (&lt;35%). In natural sites, the base saturation is highest in the top few cm of soil at the surface and decreases with depth. Require fertilizer additions to be made highly productive.</p>   |
| <p><b>Vertisols:</b> = Vertosols (ASC)</p>  |
| Orders generally absent from sugarcane land   |
| <p><b>Andisols:</b> soils on volcanic ejecta exhibiting little evidence of translocation. Dominated by short-range-order-minerals or Al-humus complexes, low bulk density, high P sorption.</p>   |
| <p><b>Aridisols:</b> soils of arid areas – aridic(torric) soil moisture regime.</p>   |
| <p><b>Gelisols:</b> freeze / thaw soil features and the presence of permafrost.</p>   |
| <p><b>Histosols:</b> = Organosols (ASC) i.e. peats</p>  |
| <p>1 Ochric epipedon – covers all those surface horizons which don't fit into the definitions of the other 7 epipedons.<br/>2 Argillic horizon – a subsurface horizon with a significantly higher phyllosilicate clay content than the overlying horizon, with evidence of clay illuviation being present.<br/>3 Kandic horizon – a subsurface horizon with a significantly higher clay content than the overlying horizon, where the dominant clay mineralogy is low activity (1:1) clays with a low CEC. Common in Ultisols and Oxisols.<br/>4 Cambic horizon – a subsoil horizon identified by structure, and a higher clay content, redder hue or higher chroma than the overlying horizon.</p> |

soils and their management refer to Stone *et al.* (1998) and Hey *et al.* (1999).

#### 4.8.1 What are acid sulfate soils?

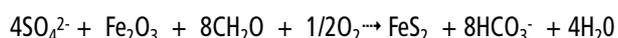
An acid sulfate soil is a soil which contains iron sulfides.

## 4.8.2 Where do they occur?

Acid sulfate soils are generally found in coastal lowland plain or swamp / lagoon environments in areas that are less than 5m above mean sea level. Sugarcane is grown in and adjacent to these environments along the Queensland coastline and the north coast of NSW. The management of acid sulfate soils presented a considerable challenge to the cane growers on the NSW north coast. The efforts of the sugar industry in tackling this problem have resulted in the industry being granted self regulation by the NSW Government for drain works in these sensitive areas (Beattie *et al.* 2001).

## 4.8.3 How do they form?

In tidal or brackish waters with a high amount of organic matter present, anaerobic bacteria use iron from the sediments and reduce sulfate present in the ocean water to produce iron sulfides. The most common iron sulfide product is pyrite (FeS<sub>2</sub>).



sulfate + iron oxide + organic matter + oxygen → pyrite + bicarbonate + water

## 4.8.4 What do they look like?

Soils containing pyrite material in an unoxidised form are called potential acid sulfate soils (PASS). This material is still in its reduced form due to it being found in anaerobic waterlogged conditions. PASS soils typically have a dark grey appearance associated with the organic matter which is present and they also tend to have a swampy sour smell. They can be either clayey or sandy in texture.

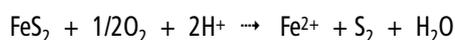
When PASS soils are exposed to the air as a result of drainage, they oxidise to form actual acid sulfate soils. Actual acid sulfate soils are easily identified by the presence of a bright yellow butter coloured mottle produced by the mineral jarosite [KFe<sub>3</sub>(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>], which is a by-product of the oxidisation of pyrite in the soil (Photo 4.13). Other indicators of the presence of actual acid sulfate soil include soil pH < 4, bare scalded areas on the soil surface in the area and the presence of rust coloured iron

stains around drains in the area. Black monosulfide mineral muds may also be present in the bottom of drains.

## 4.8.5 Why are they a problem?

Actual acid sulfate soils are a problem because the oxidation of pyrite in the soil produces sulfuric acid. This lowers soil pH to less than 4 and as low as 2 and causes large quantities of Fe and Al to become soluble in the soil and wash into waterways. The resultant soil conditions impede vegetation growth on the surface and produce bare scalded areas. The soluble Al washed into the estuaries is toxic to fish, resulting in disease and fish kills. The soluble ferrous Fe<sup>2+</sup> iron washed out of the soil and into the estuaries removes dissolved oxygen (DO) from the water and this can also cause fish kills. The acid attacks and weakens steel and concrete infrastructure such as the foundations of buildings and the buttresses of bridges, resulting in very expensive repair bills. Ahern and McElnea (1999) present the following equations to explain this oxidation process:

(1) Oxidation of pyrite to elemental sulphur and ferrous iron (Fe<sup>2+</sup>)



(2) Sulphur is then oxidized to sulfate and acid (sulphuric acid).



(3) Oxidation of ferrous iron (Fe<sup>2+</sup>) to ferric iron (Fe<sup>3+</sup>) producing extra acidity and the potential to remove DO from waterways.



## 4.8.6 Assessing a site suspected of having acid sulfate soil

### Step 1: Consult the relevant state government department

When a site is suspected of having acid sulfate soils, the first thing to do is consult the relevant state government department for any information they may have on the soils in that area. In Queensland, the Department of Natural Resources and Mines (NR&M) is the appropriate agency. NR&M has its own acid

sulfate soil investigation team (QASSIT) based at its Indooroopilly office. They have advisory staff as well as maps on the distribution of acid sulfate soils which are available for much of the Queensland coastline. In NSW the appropriate agency is the Department of Infrastructure, Planning and Natural Resources (DIPNR), formerly DLWC. They also have maps of the location of potential acid sulfate soil areas for much of the NSW coastline. As a result of a CRC Sugar and NSW Sugar Milling Co-operative joint project, which investigated almost all NSW sugarcane farms for the presence of ASS, there is now fairly detailed information on the presence of ASS in these areas.



Photo 4.51. The NR&M acid sulfate soil sampling rig taking samples in the Ingham area.

### Step 2: Initial sampling of a suspected acid sulfate soil area for laboratory analysis

For an initial assessment of a suspected area, it is advisable to sample a soil core near any suspect bare or scalded areas if they are present. If not, a soil core should be taken in a low spot in the landscape. Hand augering with a Jarret auger or alternatively a standard soil sampling rig can be used to sample the soil to the watertable with a thin walled steel push tube (Photo 4.24). Soil below the water table can then be sampled with a gouge auger which is pushed into the soil by hand, twisted 180 °C and pulled out (Photo 4.29). Extensions allow the soil to be sampled down to a few metres. For deeper investigations the QASSIT specialized vacuum sampler can be used (Figure 4.51)

### Step 3: Field test for acid sulfate soil

A pH test result of 4 or less using either a

Raupach pH kit or a pH electrode on a soil paste is usually a good indicator of the presence of a possible actual acid sulfate soil. If low pH is accompanied by the presence of jarosite mottles (bright butter yellow coloured) in the soil horizon, it is confirmed (jarosite can be seen in the soil profile in Figure 4.13).

The presence of dark grey material below this, which reacts strongly with peroxide, confirms the presence of a potential acid sulfate soil (PASS) layer (Photo 4.13). The reaction of inorganic sulphide to a few drops of a 17% peroxide solution is typically very vigorous bubbling accompanied by the release of a cloudy smoke-like gas (sulphur dioxide) (Photo 4.52). Once experienced, it is hard to confuse this reaction with the more benign reaction of peroxide with organic matter. The organic matter reaction is typically a lot gentler, producing milkshake-like froth, lacking any emissions of smokey sulphur dioxide gas (Photo 4.53) and generating very little heat. It is important to allow enough time for the peroxide reaction to take place as sometimes it can take a while because of such factors as temperature and particle size. Allowing 20 minutes with regular stirring should be sufficient.



Photo 4.52. Vigorous reaction of PASS with peroxide reagent, accompanied by a smokey gas - sulphur dioxide (Photo courtesy of NSW Agriculture).

Usually a small piece of soil (pea sized) is sampled at 10cm intervals down the soil profile for testing with peroxide. Photo 4.54 shows a soil core laid out for sampling and testing with peroxide.

The soil profile is described as usual, noting especially the depth at the top of the jarosite mottles and the top of the PASS layer,



Photo 4.53. A more benign froth reaction indicative of the presence of organic matter. (Photo courtesy of NSW Agriculture)



Photo 4.54. A soil core laid out for testing with peroxide. (Photo courtesy of NSW Agriculture)

determined by the depth where the soil first had the diagnostic reaction to the peroxide test (usually corresponds with a darkening in soil colour).

Note that a 17% peroxide solution is a highly corrosive chemical and potentially hazardous. OH and S issues need to be addressed for its use. Such provision should include protective eye wear and rubber gloves, as well as adequate first aid including eye wash and a water supply to wash hands.

#### **Step 4: Sampling and diagnostic laboratory tests for acid sulfate soils**

##### *Soil samples*

Soil sampling and handling approaches should follow all of the proper protocols outlined in the Acid Sulfate Soil Manual (Stone *et al.* 1998). Soils are typically sampled in 10cm depth increments. Samples should be placed in a plastic bag, have all the air squeezed out of the

bag before being tied off, labelled and placed in a portable refrigerator. An esky with ice bricks is an alternative. Soil samples are frozen and placed in a portable esky for express courier to a suitable laboratory.

The soil tests outlined in the acid sulfate soil data set (Section 3.2.6) will yield valuable additional information for those soils which react positively to the peroxide test in the field.

Note that it is advisable to check with QASSIT, NR&M, for advice on the latest information on suitable laboratory tests, as tests are continually being refined and developed.

##### *Groundwater samples*

Groundwater samples are sometimes collected for analysis from the holes where the suspect soil cores were taken. Water samples are handled in the same way as soil samples, being stored in a refrigerator before being frozen for the trip to the laboratory. Water samples are commonly tested for pH, EC, chloride and sulfate.

Groundwater pH often reflects the extent of sulphide oxidation that has occurred in the profile, while EC reflects the influence on groundwater salinity of saltwater inputs from king tides and the oxidation of PASS material in the sediments. Chloride and sulfate concentrations in the groundwater indicate the relative influences of tidal processes and acid sulfate soil processes on groundwater salinity.

The chloride to sulfate ratio in the groundwater is another diagnostic indicator of the presence of an acid sulfate soil (Mulvey 1993). It is based on the ratio of  $\text{Cl}^-$  to  $\text{SO}_4^{2-}$  in sea water on a mass basis being 7.2. A ratio of less than 4 and certainly less than 2 is considered a strong indication that there is a source of sulfate other than sea water contributing to the water chemistry (i.e. oxidation of pyrite in the soil).

## **4.9 EXAMPLE OF A SOIL PROFILE DESCRIPTION**

**Site 10 - Terrace silty loam** (CSR mapping unit - Herbert catchment)

**Profile photo** - Photo 4.8.

## Soil Profile Description:

| Horizon                    | Description   |
|----------------------------|---|
| <b>Ap1</b><br>0 - 0.31m    | Very dark greyish brown(10YR 3/2), fine sandy clay loam; massive; hardsetting; <2% fine (2-6mm) angular quartz gravels - dispersed; 2-10% medium sized (2-6mm) ferromanganiferous nodules; field pH 5.5; Abrupt change to;  |
| <b>A2e</b><br>0.31- 0.60m  | Brown (10YR 5/3), conspicuously bleached (10YR 8/2-dry), 2-10% distinct fine (<5mm) dark yellowish brown (10YR 4/6) mottles, silty clay loam; weak pedality - 5-10mm rough faced polyhedral peds; 20-50% coarse (6-20mm) manganiferous and ferruginous nodules, field pH 4.5; Abrupt change to; |
| <b>B1</b><br>0.60 - 0.80m  | Greyish brown (10YR 5/2), 2-10% distinct fine (<5mm) yellowish brown (10YR 5/8) mottles, silty light clay; weak pedality - 5-10mm smooth faced angular blocky and polyhedral peds; 20-50% coarse (6-20mm) manganiferous and ferruginous nodules, field pH 6.0; Abrupt change to;                |
| <b>B21</b><br>0.80 - 1.24m | Greyish brown (2.5Y 5/2), 10-20% prominent fine (<5mm) red (10R 5/8) mottles, silty medium clay; moderate pedality - 5-10mm angular blocky peds; 10-20% medium sized (2-6mm) manganiferous nodules; field pH 7.0; Abrupt change to;   |
| <b>B22</b><br>1.24 - 1.47m | Grey (2.5Y 5/1), 10-20% distinct fine (<5mm) yellowish brown (10YR 5/6) mottles, silty medium clay; moderate pedality - 10-20mm smooth faced angular blocky peds; field pH 7.0; Layer continues;  |

## Site details:

**Nature of exposure:** Soil Pit

**Location:** (Grid Reference: 0404 414E 7941 651N), Ingham area

**Landform pattern:** Alluvial plain

**Landform element:** Terrace

## Soil classification:

CSR mapping unit: Terrace silty loam

A.S.C<sup>1</sup>: Dermosolic Redoxic Hydrosol

GSG<sup>2</sup>: Affinity with a Gleyed Podzolic

SPC<sup>3</sup>: Closest to 'Ingham' and 'Midway'

S.T.<sup>4</sup>: Kandiaqualf

1 - Australian Soil Classification (Isbell 1996)

2 - Great soil group (Stace *et al.* 1968)

3 - Soil profile class from DPI mapping (Wilson and Baker 1990)

4 - Soil Taxonomy (Soil Survey Staff 1998)

## Australian Soil Classification in detail:

ASC: Melacic-Bleached, Dermosolic, Redoxic Hydrosol, thick, non-gravelly, clay loamy / clayey, deep. [Symbol abbreviation = HY/ED/FQ/EZ - C,E,M / O,W]

ASC soil concept: " A soil which is saturated in the greater part of the profile for 2 to 3 months in most years (Hydrosol), has a mottled subsoil (Redoxic), " lacking texture contrast with a structured B horizon (Dermosolic), ) with a Dark organic A horizon with < 4% Organic Carbon/ black moist colour/ pH < 5.5 and a conspicuously bleached A2 horizon(Melacic-bleached)".

Note: This soil in a less tropical climate would be classified as a poorly drained Dermosol. It is the very high rainfall concentrated in the wet season that ensures that the profile is saturated for 2-3 months each year. Many of the texture contrast soils are also classified as Hydrosols in the wet tropics due to the concentration of rainfall. Note also that although this soil does have an abrupt boundary between the A and B horizons, it does not rate as an abrupt texture contrast boundary according to Isbell (1996) because the texture change between the horizons is only slight.

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# Section 5. Soil chemistry

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## 5.1 INTRODUCTION

The chemistry of soil not only provides a measure of a soil's nutrient store and its ability to supply nutrients to plants but also has implications for the physical behaviour of the soil and its biology. This section deals with the soil chemistry tests recommended in soil characterisation data sets (Section 3). Preferred standard soil tests are listed for each soil chemistry attribute in Table 1. These preferences are based largely on the book by Peverill *et al.* (1999), which should be referred to for further information. Variable charge, which is an important feature of tropical soils, is discussed in detail in this Section and its relevance is noted. A number of useful indices, which are components of the major soil classification systems and are useful in their own right for interpreting soil chemistry data, are also presented.

A large proportion of this Section is focused on the soil chemistry information that is important for characterising the representative soil profile of a site. It is the change in soil properties in a vertical direction down the profile which is of prime importance for this purpose. The aim is to gain a better understanding of the soil in a holistic sense as a functioning unit, as well as to provide the necessary information to classify the soil.

The average soil fertility status of a field is another important aspect of characterising the chemistry of the soil. A brief section on soil sampling procedures and tests for field scale fertility assessments is provided later in this Section. Soil fertility assessments for fertiliser recommendations based on soil test results are briefly covered. For a more detailed treatment of this topic, readers are referred to Bruce (2000), Calcino (1994) and Peverill *et al.* (1999). For coverage of the fundamentals of soil chemistry refer to Brady and Weil (2002) or White (1997).

## 5.2 RECOMMENDED TESTS FOR EACH SOIL PROPERTY

Preferred soil tests for the soil chemical properties listed in characterisation data sets (Section 3) are displayed in Table 1. In most cases a test reference is given from the 'Australian laboratory handbook of soil and water chemical methods' (Rayment and Higginson 1992). Where this is not possible, a reference is provided for the test. However, it is often hard to find a laboratory that offers all of these tests. So some ways of overcoming less appropriate tests are also mentioned in the following section. The soil tests listed are general ones commonly used in soil characterisation. No attempt is made to include the wider variety of tests which are used in various specific soil research investigations. The latest literature will need to be consulted for this.

## 5.3 USING THE DATA SETS

Soil data sets in Section 3 assist decisions regarding which soil chemical properties to have measured for particular applications. There are seven data sets presented for a number of applications and most of these have a soil chemistry segment. Data sets provide information on the chemistry data necessary for soil classification (data set 1), basic characterisation (data set 2), an input file for the APSIM model (data set 4 or 5), and for the assessment of potential acid sulfate soil (data set 6). Data set 7 contains a list of soil properties that can be entered into the SUGARBAG database, which is a valuable information resource for the sugar industry.

Data set 2 in Section 3 extends the important soil tests (pH, EC, CEC, exchangeable cations) to both subsoil and topsoil horizons and also includes some tests useful for agronomy (available P, P sorption, total N, plant available Si). This data set is designed to provide very basic characterisation of a soil's nutrient status in addition to its classification and is the

**Table 5.1.** List of preferred soil test methods for each soil chemical attribute. Method reference numbers are from Rayment and Higginson (1992)

| Soil attribute   | Method reference | Preferred method  |
|--|------------------|---|
| Air dry moisture (40° C)   | 2A1              | Air dry moisture content  |
| Particle size analysis   |                  | Bruce and Rayment (1982)  |
| Soil pH  | 4A1              | pH in 1:5 soil : water suspension   |
| Soil pH  | 4B1 or 4B2       | pH in 1:5 soil : 0.01M CaCl <sub>2</sub> suspension   |
| Electrical conductivity (EC)   | 3A1              | EC 1:5 soil : water extract   |
| CaCO <sub>3</sub> %  | 19A1             | CaCO <sub>3</sub> equivalent  |
| Organic carbon   | 6B3              | Total organic carbon, Leco CR12 analyser  |
| Cation exchange capacity (CEC), anion exchange capacity (AEC) and exchangeable basic sum cations (Ca, Mg, K, Na) | 15E1 or 15E2     | Compulsive exchange methods for neutral and acid soils, including those with variable surface charge. Use 15E1 for non-saline soils and 15E2 for saline soils.<br>An alternative method for CEC is effective CEC (ECEC) which is the of exchangeable basic cations measured with another extractant and exchange acidity. |
| Exchange acidity (Al + H)  | 15G1             | Exchangeable H and Al by 1M KCl   |
| Free iron oxide  | 13C1             | Citrate / dithionite extractable Fe and Al  |
| Plant available silica   |                  | Extraction with 0.01M CaCl <sub>2</sub> for 16hrs (Berthelsen <i>et al.</i> (2001a). Outlined in Haysom and Chapman (1975).   |
| Total phosphorus   | 9A1              | Total P – X-ray fluorescence  |
| Total potassium  | 17A1             | Total K – X-ray fluorescence.   |
| Total sulphur  | 10A1             | Total S – X-ray fluorescence  |
| Total nitrogen   | 7A1-3            | Kjeldahl digest   |
| Available phosphorus   |                  | BSES (acid extractable) P (Kerr and von Stieglitz 1938) for acidic sugarcane soils. Colwell P for alkaline soils (see Section 5.5.2). Check industry guidelines for other crops.  |
| P sorption   | 9I1              | Phosphate sorption index – single point.  |
| Nitrate N  | 7B1              | Water soluble nitrate   |
| Mineral N (NH <sub>4</sub> -N, NO <sub>3</sub> -N and NO <sub>2</sub> -N)  | 7C1              | 2M KCl – steam distillation.  |
| Sulfate S  | 10B1             | Calcium phosphate extractable S (soluble + adsorbed)  |
| Potential acid sulfate soils (PASS)  |                  | Refer to data set 6 in Section 3 for suitable methods   |

recommended option for sites of longer term research (i.e. more than one season).

Data set 3A, Australian soil reference data set, is that proposed by ACLEP (McKenzie *et al.* 1995) and is recommended only for soil reference sites of regional significance. It includes additional chemistry data such as total P and total K, the P and K reserves that are largely unavailable to plants in the short and medium term.

## 5.4 WHICH SOIL SAMPLES TO TEST, WHICH TESTS TO DO?

Refer to Section 3.3 Rationalising the soil testing to be done.

## 5.5 NOTES ON SOME KEY SOIL TESTS

### 5.5.1 Soil pH

There are two standard methods of determining soil pH and these are pH<sub>w</sub> and

pH<sub>Ca</sub>. The pH<sub>w</sub> is measured in water at a soil: solution ratio of 1:5 while pH<sub>Ca</sub> is measured in 0.01M CaCl<sub>2</sub> at a soil: solution ratio of 1: 5 (Slattery *et al.* 1999). The pH<sub>Ca</sub> is often preferred for diagnostic purposes because it is considered a more robust test and is less affected by seasonal variations in soil moisture and ionic concentration of the soil solution. On the other hand, pH<sub>w</sub> is thought to more accurately represent the conditions experienced by plant roots in the rhizosphere, but it can vary up to 0.6 of a pH unit with the seasons for a given soil in any one year (Slattery *et al.* 1999). The pH<sub>Ca</sub> values are approximately 0.5 to 1.0 pH units less than the pH<sub>w</sub> measurements, but the difference varies with soil type and conditions (Hazelton and Murphy 1992). Isbell (1996) uses the regressions of Ahern *et al.* (1995) to suggest the important soil classification cut off value of pH<sub>w</sub> 5.5 is approximately equivalent to pH<sub>Ca</sub> 4.6. But Isbell (1996) states that pH<sub>w</sub> is the preferred test for the Australian Soil Classification and it is for this reason that it is recommended that the pH<sub>w</sub> test always be done for soil characterisation samples. Another argument for the pH<sub>w</sub> test is the fact that BSES bases its fertiliser recommendations for the sugar industry on pH<sub>w</sub>. There is however a good case for also carrying out the pH<sub>Ca</sub> test, especially when other agricultural crops are involved.

### 5.5.2 Soil salinity

Electrical conductivity (EC) is widely used to measure the salinity of a soil. It is carried out on a 1:5 soil : water suspension. Soil EC is usually expressed in decisiemens per metre (dS/m). Sometimes EC is reported in microsiemens per centimetre (µS/cm) or millisiemens per centimetre (mS/cm). One dS/m equals 1mS/cm which equals 1000 µS/cm (Nelson 2000).

A previously popular way of expressing salinity was as total soluble salts (TSS). The following formula converts EC 1:5 to TSS in mg / kg (ppm) units. The approximate relationship (Hazelton and Murphy 1990) between the two is:

$$EC\ 1:5\ (dS/m) = \frac{TSS\ (mg/kg)}{3200}$$

### Converting EC to ECe

Traditionally the EC of saturated soil extracts (ECe) was the method of measuring soil salinity and most crop response research related to this. However, the EC of a 1:5 soil water suspension is the preferred measurement as it is a much quicker, easier and cheaper test than ECe. But for EC measurements to be interpreted for crop response, they first have to be converted to ECe. A number of multiplier factors based on soil texture have been empirically determined to convert EC to an approximate value of ECe and these are given in Table 5.2.

**Table 5.2.** Multiplier factors for converting EC (1:5 soil : water suspension) values to ECe values from the Salinity Management Handbook (QDNR 1997)

| Soil texture   | Approx. (%) clay content | Multiplier factor |
|--|--------------------------|-------------------|
| Sand, loamy sand, clayey sand  | < 10                     | 15                |
| Sandy loam, fine sandy loam, light sandy clay loam   | 10-20                    | 13                |
| Loam, loam – fine sandy, silty loam, sandy clay loam   | 20-30                    | 11                |
| Clay loam, silty clay loam, fine sandy clay loam, sandy clay, silty clay, light clay, light medium clay. | 30-45                    | 9                 |
| Medium clay  | 45-55                    | 8                 |
| Heavy clay   | > 55                     | 6                 |

Note that Shaw (1999) proposed another method of conversion that is slightly more complex than this approach. For the sake of simplicity, the conversion factors of the Salinity Management Handbook (QDNR 1997) presented in Table 5.2 are recommended. These are the standard conversion multiplier factors used in soils work in Queensland and are recommended for soils work in Queensland sugarcane fields. It is however important to be aware that there is a degree of coarseness about such conversion factors, as these are only the mid range conversion factor values for these groupings of textures. Slavich and Petterson (1993) found there was quite a large variation in these values across the individual texture grades within each group, especially with the sandier textures (refer to Table 5.3). For example, they found conversion factors to range from 9.9 to 17.6 for the texture grades in

**Table 5.3.** Multiplier factors of Slavich and Petterson (1993) for converting EC (1:5 soil : water suspension) values to E<sub>Ce</sub> values

| Soil texture   | Approx. clay content (%) | Range of conversion factor (f) | Mid range conversion factor (f) |
|--|--------------------------|--------------------------------|---------------------------------|
| Sand, loamy sand, clayey sand  | < 10                     | > 17.6                         | 22.7                            |
| Sandy loam, fine sandy loam, light sandy clay loam   | 10-20                    | 17.6 – 9.9                     | 13.8                            |
| Loam, loam – fine sandy, silty loam, sandy clay loam   | 20-30                    | 9.9 – 9.0                      | 9.5                             |
| Clay loam, silty clay loam, fine sandy clay loam, sandy clay, silty clay, light clay, light medium clay. | 30-45                    | 9.0 – 8.2                      | 8.6                             |
| Medium clay  | 45-55                    | 8.2 – 6.7                      | 7.5                             |
| Heavy clay   | > 55                     | < 6.7                          | 5.8                             |

the sandy loam to light sandy clay loam texture grade grouping in Table 5.3. Slavich and Petterson (1993) concluded that the error in these conversions is likely to be greater in the sandier textured soils and actually recommended the direct measurement of E<sub>Ce</sub> in preference to EC1:5 for these textures.

When assessing soil salinity it is also important to be aware that sugarcane has been found to have a relatively low tolerance to salinity, with yield reduction occurring when E<sub>Ce</sub> exceeds 1.7 dS/m (Ayers 1977).

provided accurate measures of inorganic carbon can be obtained. They also recommend that loss on ignition (LOI) procedures for soil organic matter (SOM) (Ball 1964, Lowther *et al.* 1980) should only be used when alternative methods 6B3 and 6B1 cannot be utilised and should be restricted to soils of low clay content where loss of hygroscopic water on heating is minimal.

Most commercial laboratories at present offer only a wet oxidation method such as the Walkley and Black (1934) method (method

**Table 5.4.** Growth restrictions to sugarcane due to salinity (Nelson *et al.* 2000)

| Soil type  | EC 1:5 values (dS/m)         |             |             |        |
|------------|------------------------------|-------------|-------------|--------|
|            | Degree of growth restriction |             |             |        |
|            | None                         | Slight      | Moderate    | Severe |
| Organic    | < 0.32                       | 0.32 - 0.65 | 0.65 – 0.97 | > 0.97 |
| Clay       | < 0.28                       | 0.28 – 0.55 | 0.55 – 0.83 | > 0.83 |
| Clay loam  | < 0.21                       | 0.21 – 0.42 | 0.42 – 0.62 | > 0.62 |
| Loam       | < 0.19                       | 0.19 – 0.39 | 0.39 – 0.58 | > 0.58 |
| Sandy loam | < 0.19                       | 0.19 – 0.37 | 0.37 – 0.55 | > 0.55 |
| Sand       | < 0.14                       | 0.14 – 0.28 | 0.28 – 0.42 | > 0.42 |

Table 5.4 overcomes the need for conversion of salinity values from EC 1:5 soil water to E<sub>Ce</sub> by providing critical EC 1:5 soil water values for sugarcane for different texture grades. These data show again just how sensitive sugarcane is to soil salinity.

### 5.5.3 Soil organic matter

Baldock and Skjemstad (1999) note that dry combustion methods that measure carbon dioxide with an infra-red sensor such as method 6B3 are the best methods of determining soil organic carbon (SOC)

6A1). The problem with the Walkley and Black method is that it underestimates SOC as recoveries are usually only around 75 to 80% (Rayment and Higginson 1992). Nelson and Sommers (1996) suggested a general correction factor of 1.3 for this test in the absence of any other information.

Rayment and Higginson (1992) advise against the use of a correction factor, stating that Walkley and Black results should be reported as OC - W&B without any attempt to convert values to total OC as the rate of recovery varies

with soil type. Rayment and Higginson (1992) advise that the method of Heanes (1984) (method 6B1) is a preferable wet oxidation method as it incorporates an external heating step to ensure complete oxidation of OC. The Heanes method (6B1) should be requested in preference to the Walkley and Black method (6A1) if wet oxidation methods are the only tests offered. Both of these methods require correction for soluble chloride present in the soil (Rayment and Higginson 1992).

To convert SOC to SOM, traditionally a multiplication factor of 1.72 has been used (Baldock and Skjemstad 1999).

$$\text{SOM (g/kg)} = \text{SOC (g C/kg soil)} \times 1.72$$

The argument that measured values of soil organic carbon (SOC) should simply be reported as such and not converted to SOM seems the most sensible approach. Baldock and Skjemstad (1999) argue that this is preferable as it avoids all the problems and assumptions associated with conversion factors.

For conversions of LOI values to SOM, Isbell (1996) refers to the work of Spain *et al.* (1982) who found the relationship to be influenced by clay content. Consequently, Isbell (1996) recommends multiplication factors of 2.0, 2.3, and 2.7 for soils with <20, 20-60 and >60% clay respectively.

Nitrogen mineralisation potential is a property of agronomic significance that is related to soil organic matter.

#### 5.5.4 Available phosphorus

For a soil P test to be useful as a diagnostic tool, it must be correlated with crop yield and growth responses to increasing soil P availability (Moody and Bolland 1999). All of the soil P test calibration work for sugarcane has used BSES P, but this acidic extractant may be less suitable for alkaline soils such as those that occur in the Burdekin (Phil Moody pers. com. 2003). The BSES P test should be used for all sugarcane soils except for alkaline soils where Colwell P could be used as a substitute for BSES P but interpreted in the same manner (except in the Bundaberg region where it would need to be multiplied by 1.5 to give it some sort of equivalence with the BSES P, Phil

Moody pers. com. 2003).

#### 5.5.5 P sorption

For P sorption, either a P sorption curve or a P sorption index can be used as a suitable measure. The P sorption curve, which plots adsorbed P versus the concentration of P remaining in solution after the addition of several rates of soluble P, is probably the most useful for soil nutrient management decisions. But for simplicity and practicality, the P sorption index of Rayment and Higginson (1992) is recommended at present for the purpose of characterising soils as it can effectively group them into meaningful P sorption categories (Moody and Bolland 1999). In a recent study, the phosphorus buffering index of Burkitt *et al.* (2002), which utilises a single point P sorption index with an addition of 1000mg P/kg, was found to be capable of accurately predicting the phosphorus buffering capacity (PBC) for a range of soils, especially high P sorbing ones.

#### 5.5.6 Plant available silicon

This test has been included in the lists of recommended soil tests because recent work by Berthelsen *et al.* (2001a) has demonstrated that there are sub-optimal levels of plant available Si (PA-Si) for sugarcane in many of the soils on the wet tropical coast of north Queensland. The importance of this deficiency to sugarcane production has since been demonstrated with the recording of sugarcane yield increases of up to 58% in response to Si product fertiliser applications (Berthelsen *et al.* 2001b). Berthelsen *et al.* (2001a) classed soils as suboptimal with PA-Si levels <10 mg/kg, and marginal with PA-Si levels 10 - 20 mg/kg. They based these suggestions on Chapman *et al.* (1981), and noted that further calibration work may be necessary.

#### 5.5.7 Soil mineral nitrogen

Soil mineral nitrogen includes ammonium N ( $\text{NH}_4^+$ ) and nitrate N ( $\text{NO}_3^-$ ). Soil nitrate is not held strongly by the soil. Its movement through soil and into groundwaters and rivers is of environmental concern. Ammonium N, being a cation, is more firmly held and less mobile than nitrate N. Soil nitrate is rated as an optional test for standard characterisations

because it really only provides a "snapshot in time" due to the dynamic nature of the soil's N supply and how freely nitrates move through the soil. The concentration of mineral N with depth through the soil profile at a specific point in time is however a required input for the APSIM crop simulation model. This information is collected by sampling a large number (usually > 15) of deep soil cores (1.5 m deep). Composite soil samples are collected from all of these cores at set depth intervals. The resultant mineral N concentrations and soil depths are entered into APSIM for that sampling date (see Section 5.10 for information on composite soil sampling and Section 8 - modelling).

### 5.5.8 Free iron oxides

This soil test is only necessary for those soils suspected of being Ferrosols. It is used to verify whether a soil belongs to the Ferrosol order by confirming that the fine earth (<2mm) fraction of the B2 horizon has a free iron oxide content of > 5 % (Isbell 1996). Usually such soils occur on basic or ultrabasic igneous rocks such as basalt, their metamorphic equivalents or alluvium derived therefrom. Soils are suspected of being Ferrosols if they are strongly structured (10-15mm polyhedral shaped compound peds breaking down to a very fine granular structure) with a red or brown coloured B2 horizon.

## 5.6 SOIL EXCHANGE PROPERTIES

### 5.6.1 Exchangeable cations

Exchangeable soil cations are the positively charged ions that are held by negatively charged surfaces of the soil.

### 5.6.2 Exchangeable basic cations

The major exchangeable basic cations (sometimes called exchangeable bases) are sodium (Na<sup>+</sup>), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>) and potassium (K<sup>+</sup>).

### 5.6.3 Exchange acidity

There are also the important exchangeable acidic cations aluminium (Al<sup>3+</sup>) and hydrogen (H<sup>+</sup>) which are often present in the soil when

pH is below 6. Exchange acidity is calculated by summing the exchangeable Al and H extracted from the soil using method 15G1 of Rayment and Higginson (1992).

### 5.6.4 Cation exchange capacity

Cation exchange capacity (CEC) is a measure of the soil's capacity to hold exchangeable cations. Three main methods of measurement of CEC are presented below.

#### Total cation exchange capacity (CEC<sub>T</sub>)

CEC<sub>T</sub> is a direct measure of the total capacity of a soil to hold exchangeable cations and represents the negative charge present per unit mass of soil. It is expressed as centimoles of positive charge per kilogram of soil (cmol(+)/kg), which is a unit numerically equal to the previous standard unit of mequiv / 100g (Rengasamy and Churchman 1999). The expression of CEC units as positive charge (cmol(+)/kg) relates to the amount of positive charge from the test cation solution (commonly NH<sub>4</sub><sup>+</sup>) that the negatively charged soil surface could hold under the conditions imposed by the method.

#### Effective cation exchange capacity (ECEC)

ECEC is an estimate of the total amount of exchangeable cations held by a soil. For an acidic soil it includes exchange acidity (exchangeable Al and H). The formula (Rangasamy and Churchman 1999) for calculating ECEC is:

$$ECEC = \sum_{\text{exch}} (\text{Ca} + \text{Mg} + \text{Na} + \text{K} + \text{Al} + \text{H})$$

ECEC differs from CEC<sub>T</sub> by being calculated from the addition of exchangeable bases and exchange acidity, rather than being determined directly from a single measurement or test.

#### Cation exchange capacity by compulsive exchange (CEC<sub>CE</sub>)

CEC<sub>CE</sub> is the capacity of the soil to retain exchangeable basic cations (Ca, Mg, Na, K) under field conditions and is measured by the compulsive exchange method. The main advantage of this method is that it provides a more accurate direct measurement of CEC for

variable charge soils than the conventional methods used for directly measuring  $CEC_T$  (Section 5.8).

ECEC and  $CEC_T$  differ from  $CEC_{CE}$  in the fact that they both include exchange acidity in their determination. Since the compulsive exchange method ( $CEC_{CE}$ ) does not include the measurement of exchangeable acidic cations (Al and H) it cannot directly substitute for CEC in the calculations of indices such as ESP and base saturation percentage for acid soils with  $pH < 6$ . Instead, ECEC will need to be determined by adding exchangeable acidity (Al + H) to  $CEC_{CE}$ . This ECEC value can then be used in these formulae.

The following rating for CEC values (cmol (+) / kg soil) is sourced from Hazelton and Murphy (1992): < 6 (very low), 6-12 (low), 12-25 (moderate), 25-40 (high), > 40 (very high).

A browse through soil survey reports shows that very low ECEC values (<6) are typical for most of the weathered tropical soils in north Queensland. The main exception to this are the cracking clay soils such as occur in the Burdekin. Our results for topsoils of sites in that district were typically around 20 - 25 cmol (+) / kg.

### 5.6.5 Anion exchange capacity

Anion exchange capacity (AEC) is the capacity of a soil to hold anions and is often present in variable charge soils of the tropics. AEC can be measured by the compulsive exchange method of determining CEC.

CEC and AEC are complicated in the tropics by the common presence of soil components with variable surface charge. Some implications of this are discussed further in Section 5.8.

## 5.7 OTHER IMPORTANT CATION EXCHANGE INDICES

### 5.7.1 Base saturation

Rayment and Higginson (1992) define base saturation percentage (BSP) as the portion of the soil CEC accounted for by exchangeable bases. It is calculated from the following equation where cations and CEC are expressed

as cmol (+) / kg on an oven-dry basis. ECEC values can substitute for  $CEC_T$  in this formula.

$$BSP = \frac{\sum_{\text{exch}} (\text{Ca} + \text{Mg} + \text{Na} + \text{K}) \times 100}{CEC}$$

BSP is commonly used as a coarse indicator of soil fertility. Values of < 20, 20 - 60, and > 60% are rated as low, medium, and high respectively (Landon 1984). Base saturation becomes irrelevant in soils with  $pH > 6$ , as basic cations dominate the CEC giving a BSP of 100. BSP is really just an inverse way of presenting exchange acidity status.

Base saturation has some importance in the Soil Taxonomy classification system where it is important in distinguishing between Alfisols and Ultisols. Ultisols are defined as soils with an argillic horizon and base saturation <35% in the lower subsoil horizons.

### 5.7.2 Base status

Base status is the sum of exchangeable basic cations expressed in cmol (+)  $kg^{-1}$  of clay (Isbell 1996). The formula is:

$$\text{Base status} = \frac{\sum_{\text{exch.}} (\text{Ca} + \text{Mg} + \text{Na} + \text{K}) \times 100}{\text{clay\% of fine earth fraction (<2mm)}}$$

Base status is used as a classification criterion for the great group level of some soil orders in the Australian Soil Classification. The classes are:

*Dystrophic*: base status < 5

*Mesotrophic*: base status 5 to 15 inclusive

*Eutrophic*: base status > 15.

Base status is therefore a measure of soil fertility which takes into account the capacity of the soil to hold nutrients (CEC and clay mineralogy) as well as the current stores of nutrients (exchangeable basic cations).

### 5.7.3 Exchangeable sodium percentage

The formula for exchangeable sodium percentage (ESP) (Rengasamy and Churchman 1999) is:

$$ESP = \frac{100 \times \text{exch. Na}}{CEC_T}$$

It can also be calculated as:

$$ESP = \frac{100 \times \text{exch. Na}}{\sum_{\text{exch.}} (\text{Ca} + \text{Mg} + \text{Na} + \text{K} + \text{Al} + \text{H})}$$

The acidic cations  $\text{Al}^{3+}$  and  $\text{H}^+$  were included in the second formula because soils which are both sodic and acidic occur in the tropics (Nelson pers. comm. 2000). For variable charge soils either ECEC or  $(\text{CEC}_{\text{CE}} + \text{exchange acidity})$  should be used in the place of  $\text{CEC}_{\text{T}}$  in the first formula.

Rayment and Higginson (1992) stress that the method to determine CEC and exchangeable Na are optional as long as the method to determine CEC is an extension of the same method used for exchangeable sodium.

### Sodicity and ESP

Sodic behaviour is the dispersion of soil clay particles leading to the deterioration of the physical condition of soils. Northcote and Skene (1972) defined sodic soils as soils with  $\text{ESP} > 6$  in the top metre of the profile and this is the measure that has been most commonly adopted in Australia. More recent investigations have shown that dispersive behaviour is more complex than this, being affected by the interaction between soils and aqueous solutions and especially salinity (Rengasamy and Churchman 1999).

The Australian Soil Classification defines soils in the Sodosol order as those texture contrast soils with an ESP of 6 or greater in the top 0.2 m of the B2 horizon.

The Emerson aggregate test (Emerson 1967) is useful for screening sodic soils. It has been found to work very well for screening highly sodic soils and moderately well on slightly sodic soils (Murphy 1995). Refer to Section 4.4.4 for the Emerson aggregate test method.

A sodic soils kit (Nelson 2000, Nelson 2001) has been specifically developed for diagnosing sodic soils in Australian sugarcane areas. This kit allows sodic soils to be diagnosed in the field.

### 5.7.4 CEC to clay ratio and clay mineralogy

The CEC to clay ratio (CCR) is used as an index of clay mineralogy on the basis of the relationship between CEC and clay content and clay activity. It is used in place of the standard X-ray diffraction measurement of clay

mineralogy which is expensive and is not a routine laboratory test. It is sometimes also referred to as the clay activity ratio, CAR (Wilson and Baker 1990). The CEC / clay ratio is expressed as  $\text{cmol}(+)/\text{kg}$  clay and it is determined by dividing the soil's CEC ( $\text{cmol}(+)/\text{kg}$ ) by the clay content (%) of the  $<2\text{mm}$  particle size fraction (Shaw *et al.* 1998). The formula is:

$$\text{CCR} = \text{CEC} [\text{cmol}(+) \text{ kg soil}] \div \text{Clay } \%$$

The approximate relationship between CCR and clay mineralogy is presented in Table 5.5. This was determined from correlations between CEC and clay content with clay mineralogy, based on an extensive data set.

**Table 5.5.** Relationship between CCR and clay mineral composition of a soil (based on Shaw *et al.* 1998)

| CCR         | Clay minerals indicated                       |
|-------------|---|
| < 0.20      | kaolinite                                     |
| 0.20 – 0.35 | illite and kaolinite                          |
| 0.35 – 0.55 | mixture of clay minerals                      |
| 0.55 – 0.75 | mixture with a higher proportion of smectites |
| > 0.75      | dominantly smectite                           |

\* Note smectite clays were formerly referred to as montmorillonite.

The main outside factor that can affect the reliability of this index to predict clay mineralogy is the presence of organic matter in the soil. For this reason it is advisable to use this index only on subsoil layers where organic matter content is negligible.

Clay mineralogy is important because it can allow the prediction of shrink swell behaviour in a soil which is encountered in a moist uncracked state in the field and it helps us explain other soil properties such as CEC and soil water storage.

## 5.8 VARIABLE CHARGE SOILS AND CEC

### 5.8.1 What is a variable charge soil?

Variable charge refers to the characteristic of some soil particles to carry charges that may be

positive or negative, depending on soil pH and ionic strength of the soil solution. Variable charge is associated with organic matter, Fe and Al oxides and the edges of clay minerals, especially kaolinite. Variable charge is a feature of many tropical soils since kaolinite is usually the dominant clay mineral in tropical soils, while Fe and Al oxides are also common in highly weathered soils. Fe and Al oxides occur in very high concentrations (>5% and often >10%) in Ferrosol soils which are common in areas with basalt (or other basic igneous rock) geology. The Andisol soil group (Soil Survey Staff 1999) formed on volcanic ejecta and relatively high in Al oxides are another soil type affected by variable charge but they are not common in Australia. The contribution of organic matter to variable charge is usually less significant than that from Fe and Al oxides for soils in the tropics.

Soil particles with variable charge are negatively charged at high pH and positive at low pH. The point of zero net charge (pzc) for a material is the soil pH at which the amount of positive charge equals the amount of negative charge. At this point there is no net total particle charge to be neutralized by ions in the diffuse layer and all the adsorbed ions are immobilized in surface complexes (Sposito 2000). This occurs at around pH 4 for organic matter, around pH 7-9 for Fe and Al oxides and hydroxides (Uehara and Gilman 1982) and pH 4-5 for the clay mineral kaolinite (Sposito 1989). Therefore at field conditions in the tropics (field pH of 5.5), the net charge contribution to CEC from organic matter and kaolinite clay minerals is negative charge, but from Fe and Al oxides it is positive charge (i.e. anion exchange capacity).

### 5.8.2 Clay minerals

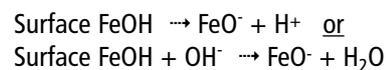
Variable charge associated with clay mineral edges is the major source of CEC for kaolinite as it has little or no permanent charge (Bloom 2000). However, even though it does not represent a large CEC value on its own, it is very important for that soil material as it accounts for a high proportion of its total CEC. This variable charge in silicate clays arises from the exposed hydroxyl groups of the AlOH layer that can adsorb or desorb protons. Variable edge charge is still present on the highly

charged smectite and vermiculite clays, but it is less important as it is very small compared to the permanent charge. For example, one investigation found the variable charge present in a smectite clay at pH 7 accounted for less than a tenth of the CEC value for that material (McBride 1994).

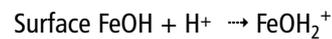
### 5.8.3 Iron and aluminium oxides

The variable charge nature of these oxides is due to their containing strongly bound OH groups on their hydrated surfaces which can act as both proton donors and acceptors. In the example of the hydrated surface of the iron oxide haematite [Fe(III) or 2Fe(OH)<sub>3</sub>], the strong bonding of the O atom to Fe(III) weakens the bond of the proton to the O atom to the extent that the metal bound hydroxide groups can donate protons at high pH creating negative surface charges. Then at low pH these OH groups can also accept protons to become positively charged (Bloom 2000). This is illustrated in the following equations;

*At high pH*



*At low pH*



### 5.8.4 Why is it important?

The variable charge characteristic is important for the following two reasons:

#### Overestimation of CEC

Firstly, soil variable charge results in an overestimation of CEC by the standard laboratory methods, which measure CEC at ionic strengths and pH that are much higher than those in the natural field conditions. In the tropics, the field pH of the topsoil (A1 horizon) is commonly around 5.0 to 5.5. However, the most commonly used methods for determining CEC by commercial laboratories are done at pH 7.0 (method 15B-NH<sub>4</sub>Cl extract, method 15D-NH<sub>4</sub>OAc extract). Raising soil pH to measure CEC results in an over estimation of CEC present in field

conditions by making the variable surface charge (a major contributor to CEC in tropical soils) more negative and less positive. For example in the case of Fe oxides (p<sub>znc</sub> 7 to 9), at pH 5 they contribute a substantial +ve charge to the soil, lowering its overall net CEC. But at pH7 for the laboratory measurement they contribute very little +ve charge, thus resulting in the laboratory measurement drastically overestimating the CEC of that soil in the field.

It must be stressed however that these problems associated with measuring CEC at a pH above field condition relate only to the measurement of CEC<sub>T</sub> as a single measurement. It does not relate to determinations of effective cation exchange capacity (ECEC) where the individual displaced exchangeable cations are measured and summed. So methods of using ammonium chloride or ammonium acetate at an elevated pH are still valid for determining ECEC.

Table 5.6 shows the extent of this overestimation, with the CEC value determined at a higher pH being on average a minimum of three times higher than values obtained by the methods that measure the CEC at field pH (silver thiourea and compulsive exchange). This tendency of the high pH CEC methods to drastically overestimate the CEC of the soil is

also very evident in the analytical data in most of the CSIRO soil survey reports for tropical Qld (Murtha 1986, Laffan 1988, Cannon *et al.* 1992). These reports provide a great opportunity to see the effect of raising the pH on the measurement of CEC as they have had the CEC determined by ammonium acetate at pH 7, ECEC, and compulsive exchange for most soil samples. It is also interesting to note that this discrepancy is evident in the data for a number of different soil types.

### Soil anion exchange capacity

The second important implication of variable charge is the anion exchange capacity which can develop in tropical Ferrosol soils due to +ve charge associated with iron oxides when the soil pH is below the p<sub>znc</sub> for the iron oxides (<7 to 9). This can have some important environmental implications such as a higher retention of nitrates below the root zone with less nitrate reaching the groundwater reserves.

### 5.8.5 Implications for analysis of soil CEC

#### Deciding if a soil is or isn't a variable charge soil

As stated above, variable charge is largely associated with Fe and Al oxides, organic

**Table 5.6.** CEC (cmol(+)/ kg) of 10 different Queensland soils determined by five different methods (adapted from Gillman *et al.* 1983)

| Sample | Laboratory methods  |   |                 |                            |                                  |
|--------|---|---|-----------------|----------------------------|----------------------------------|
|        | 1M NH <sub>4</sub> +OAc<br>pH 7.0<br>Leaching tube<br>(15D1*) | 1M NH <sub>4</sub> +Cl<br>pH 8.5<br>(15C1*) | ECEC<br>(15J1*) | Silver thiourea<br>(15F3*) | Compulsive<br>exchange<br>(15E*) |
| 2v     | 20.1  | 29.0  | 7.5             | 6.0                        | 7.6                              |
| 6v     | 25.6  | 30.2  | 15.3            | 15.4                       | 14.9                             |
| 7v     | 8.9   | 14.6  | 2.9             | 2.5                        | 3.0                              |
| 8v     | 3.4   | 2.3   | 1.2             | 2.3                        | 2.1                              |
| 9v     | 16.8  | 24.7  | 5.5             | 6.2                        | 4.8                              |
| 10v    | 3.6   | 0.6   | 0.8             | 2.4                        | 1.9                              |
| 1p     | 38.4  | 34.0  | 38.9            | 37.7                       | 34.8                             |
| 3p     | 21.7  | 21.2  | 18.6            | 18.2                       | 16.1                             |
| 4p     | 11.1  | 11.7  | 6.9             | 7.0                        | 7.4                              |
| 5p     | 18.1  | 17.9  | 15.0            | 14.6                       | 14.6                             |

\* denotes a Rayment & Higginson (1992) method; v = variable charge soil; p= permanent charge soil

matter and the clay mineral kaolinite. As such, one can immediately include Ferrosols in the grouping of soils with a high variable charge CEC component because of their high iron oxide content. Equally, all Vertosol soils (cracking clays) which are dominated by permanent charge CEC can be ruled out straight away. For the rest of the soil types it is not quite as obvious. It is however fairly safe to assume that the clay fraction of most other soils in the tropics is likely to be dominated by kaolinite type minerals because of the tropical environment which is conducive to weathering. As such these soils are likely to have a component of variable charge in their CEC. In the absence of contrary information, all sugarcane soils apart from Vertosols should be assumed to have a component of their CEC that is variable.

### Which CEC test method to use?

Table 5.6. illustrates the large inaccuracies associated with the ammonium acetate and ammonium chloride tests done at raised pH levels for the CEC of soils with a substantial variable charge component. It also shows the comparable accuracy of the compulsive exchange and silver thiourea CEC methods carried out at field pH for both variable and permanent charge soils. This is validated by how close these CEC results are to the sum of cations (ECEC).

With this in mind, the recommended option for the direct measurement of  $CEC_T$  in tropical soils is to use the compulsive exchange method (method 15E) or alternatively the silver thiourea method (method 15F) for all soil types except Vertosols. For the Vertosols the standard ammonium chloride (methods 15B or, if calcareous, 15C) is an acceptable option.

However, none of the above methods are currently in widespread use in commercial laboratories in Queensland, with the most popular currently being the ammonium acetate (15D) or ammonium chloride methods (15B). Consequently, probably the best approach when using commercial laboratories is not to get  $CEC_T$  measured at all but to have ECEC determined instead. This will avoid the complications associated with variable charge. In this case the ECEC value should be used in

place of CEC in all of the soil chemistry indices and formulae discussed in the previous section.

### Soil CEC and soil classification

Note that soil CEC at pH 8.2, the sum of the exchangeable basic cations plus  $BaCl_2$ /triethanolamine exchange acidity, is a component of a criterion in soil taxonomy for separating Alfisols and Ultisols (Rayment and Higginson 1992, p.138).

$CEC_{CE}$  values from the compulsive exchange method can be used for soil classification directly for soils with pH >6, but for more acid soils this value will need to be first added to exchangeable Al +H to give an ECEC value that can then be used in soil classification.

It is best to avoid any method which makes a direct measurement of  $CEC_T$  at a pH level above field condition in tropical soils. It is better to use only methods that estimate the ECEC by summing the cations.

## 5.9 CEC AND SOIL SOLUBLE SALT LEVELS

A significant number of commercial laboratories currently determine soil ECEC using the ammonium acetate method (15D1) without prewash for salts (Nelson 2001). This presents a problem as the presence of significant amounts of salts such as NaCl in the soil sample ( $EC > 0.3$  dS / m) will result in an overestimation of exchangeable Na, ECEC and ESP with such methods. This occurs because an  $NH_4^+$  salt solution is used to displace the cations including sodium (Na) from the soil's exchange sites and then these cations are measured in the extract solution and added together to give the ECEC value. If soluble salts in the soil are not washed out before carrying out this test the Na from the salt (NaCl) will be measured with the Na that was displaced off the exchange complex, thus causing an overestimation of the ECEC and ESP.

However, one way to overcome this use of an inappropriate method is to request soluble chloride (Cl-) be measured on the soil samples as well. With a value for soluble chloride, and

knowing that the samples were not washed for salts, the ECEC and ESP values for a soil can then be corrected (Nelson 2001) using the following formulae:

$$\text{corrected ECEC} = \frac{c - (a / 355)}{\text{corrected ECEC}}$$

$$\text{corrected ESP (\%)} = 100 \frac{[b - (a / 355)]}{\text{corrected ECEC}}$$

Where:

a = chloride content in mg / kg (or ppm)

b = exchangeable sodium content in cmol (+)/kg

c = laboratory measured value for ECEC in cmol(+)/kg

## 5.10 COMPOSITE SAMPLING A FIELD SOIL

When the objective of soil sampling is to estimate the average nutrient concentration (or other soil attribute) for a field as a whole at a specified soil depth, a composite sampling approach is required. This involves taking a large number of cores from a field (usually more than 10 and sometimes more than 30), subsampling each core at set depth intervals and bulking these subsamples together as a composite sample for each depth interval. This bulked composite sample is usually mixed well in a bucket before a smaller subsample is taken for laboratory analysis.

Three common situations where an estimate of the average soil nutrient levels for a field is desirable are (i) estimating required fertiliser application rates, (ii) monitoring environmental impacts of agricultural practices, and (iii) as an input for agricultural production simulation modelling (e.g. mineral N profile for modelling with APSIM).

### 5.10.1 Composite samples

The main reason for composite sampling is to reduce the analytical costs associated with establishing the average value of a soil chemical property for a field as a whole (Brown 1999).

Four conditions for a composite sample to be considered valid (Brown 1999, Cline 1944) are:

- sampling volume is representative of a homogenous population

- equal amounts of each sample unit contribute to the subsample tested
- the integrity of the sample is preserved
- an unbiased estimate of the mean is the only goal of sampling

### 5.10.2 Reasons for using fixed depth sampling intervals

Fixed depth sampling intervals are used when taking composite samples from many soil profiles to determine the average concentration of nutrients at those depths for a field as a whole. For composite sampling of several cores from a field, horizon based sampling is generally not a practical option as horizon depths and thicknesses commonly vary across a field and the horizons themselves may be absent from parts of a field. Statistical considerations also favour the use of fixed depth sampling intervals for field composite samples.

Situations where fixed depth intervals for soil sampling are not appropriate involve scenarios where soil profile morphology is important, such as when sampling a representative single soil profile for classification (Section 4.6) or sampling a soil profile that is stratified or duplex (abrupt horizon boundaries and contrasting texture) for soil water storage or bulk density properties (Section 6.9). Where soil properties are largely controlled by management actions at the surface, such as fertiliser applications, fixed depths are appropriate. Where soil profile features have an important controlling influence (e.g. soil water storage, infiltration) the soil horizons are a more appropriate sampling basis.

### 5.10.3 Sampling designs

A review of sampling designs and strategies is outlined in Brown (1999). Webster and Oliver (1990) also provide a comprehensive coverage of soil sampling designs and strategies and all of the associated statistical issues. These texts should be consulted when planning a sampling strategy for an experiment site or field.

Three important statistical principles of soil sampling outlined originally in Cline (1944) were re-emphasized by Brown (1999) as being

just as critical to sampling today. These are that:

- A sample composed of few sampling units scattered at random throughout a homogenous population contains information up to the limits of its size, but even a large sample, confined to a part of the population, contains no information about the excluded parts
- An unbiased estimate of the mean requires that every sampling unit has an equal chance of being selected, and
- An unbiased estimate of significance and confidence limits requires that every sample of n sampling units has an equal chance of being selected.

Brown (1999) however, notes that despite the truth of the first two principles above, there are situations where a biased sample is more appropriate. The most notable example of this is the need to deliberately avoid abnormal high fertility areas when sampling a field for a soil nutrient assessment. This is the judgement (random with bias) type of sampling design which is most commonly used to assess the average soil nutrient status of a field and is discussed below.

Some soil sampling designs of relevance to sugarcane investigations are a (i) judgement (random with bias) sampling design, (ii) a systematic grid (non-random, no bias), and (iii) a simple random grid sampling design. These are illustrated in Figure 5.1 (overpage).

#### **Judgement sampling design** (see Figure 5.1a)

A judgement (random with bias) design involves selecting typical spots for sampling and avoiding unusual spots (unusually excessive or poor growth, disturbed areas) and typically employs a zigzag, loop or figure 8 type sampling pattern which the person sampling will try to follow walking through the field. In sugarcane fields when the cane is tall, the zigzag tends to become a little bit more linear for practical reasons. This is the most common method of sampling a soil for fertility assessment and is thought to be the best method for diagnostic work (Brown 1999).

#### **Proportional sampling design** (see Figure 5.1c)

This approach involves judgement sampling as above but with a mathematically derived proportion of cores being taken from the rows and interrows to account for the affect of fertiliser bands in the rows and to gain a possibly more realistic representation of the nutrients available to the crop (Brown 1999). This approach may have some potential for sampling sugarcane fields with a row mound - interrow layout that have received banded fertiliser applications.

#### **Systematic grid sampling** (see Figure 5.1e)

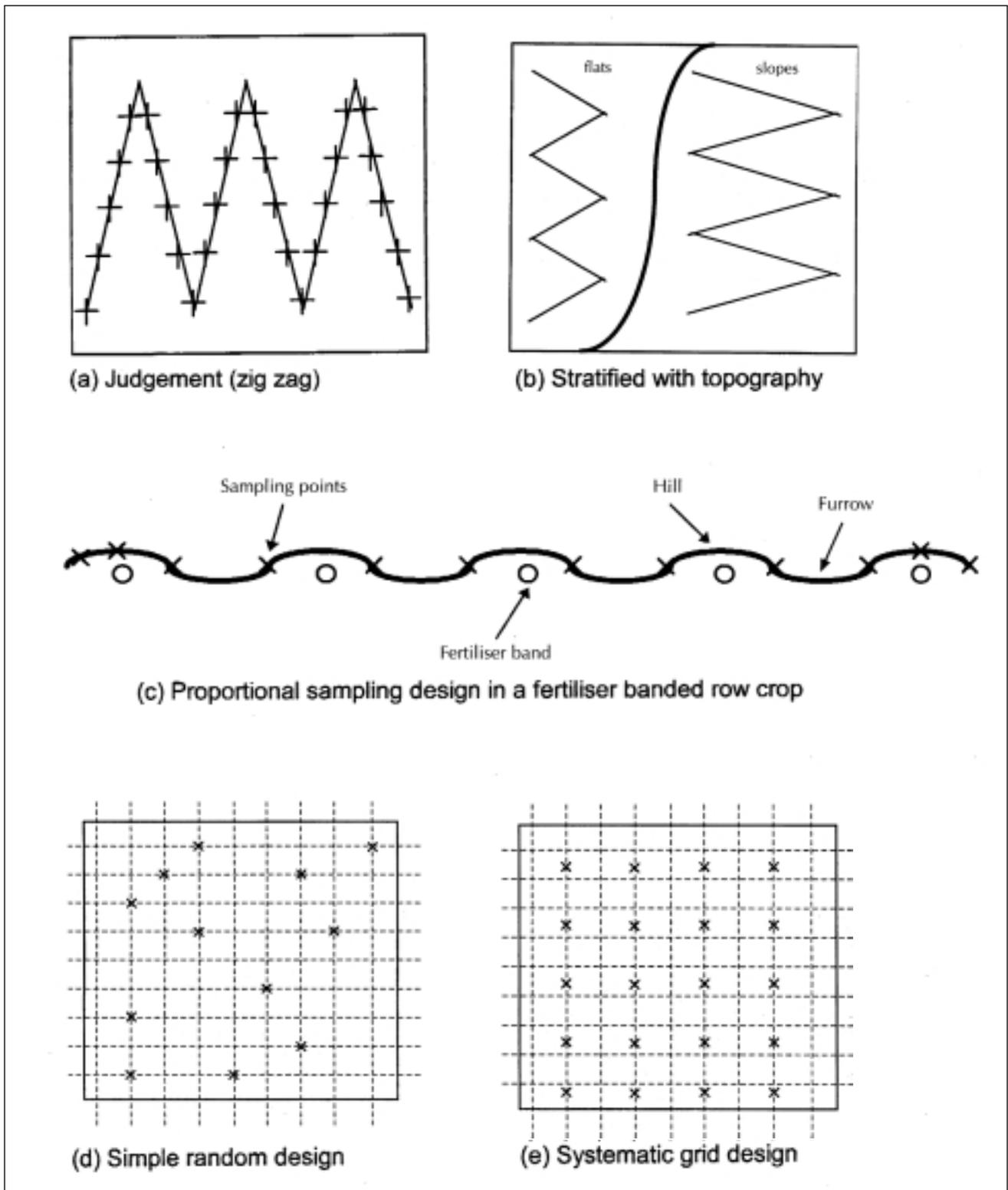
A systematic grid sampling design (non random) involves taking soil samples at the intersections of a uniform grid pattern. It is useful when there is interest in the spatial distribution of soil properties within a field such as in a soil spatial variability survey (Section 2). A version of this approach is often used to acquire information on the distribution of mineral nitrogen across a field for APSIM modelling, where there is some interest in the variability across the field (Section 5.10.6). Sugarcane fields with regularly spaced planting rows lend themselves to a grid pattern of sampling. Another type of systematic style of sampling involves regularly spaced sampling along a transect line.

#### **Simple random sampling design** (see Figure 5.1d)

For simple random sampling, the sampling locations are decided by two randomly selected distances (e.g. 2.5 m north: 4.8 m west) on a fixed co-ordinate grid system. It provides unbiased sampling and is most commonly used in research experiments. Brown (1999) notes that large numbers of samples are needed for this approach since it does include unusual sampling spots which may affect the final analysis.

#### **Non-stratified / stratified / multistage sampling**

Selected sampling areas are most often sampled as a whole (non-stratified), but these areas can also be subdivided into smaller areas (stratified sampling) as well (Brown 1999). A stratified sampling approach (Figure 5.1b) is useful for situations where there is some obvious landform variation or crop growth differences



**Figure 5.1.** Standard soil sampling designs; (a) judgement - zig zag, (b) stratified - according to topography, (c) proportional sampling-fertiliser banded row crop, (d) simple random, (e) systematic grid (sourced from Brown 1999, © CSIRO 1999).

across the site to be sampled. In other situations it is sometimes desirable to select a number of smaller plots representative of the field as a whole for monitoring (multistage sampling) to reduce the need to sample the whole field (Brown 1999). Multistage sampling is a popular soil sampling approach for

environmental monitoring work.

#### 5.10.4 Where to sample? The row or the interrow?

The current practice in composite sampling for fertility assessment of sugarcane fields is to

sample in the interrow area to avoid fertiliser bands (Schroeder *et al.* 2002). This issue of where to take soil samples in landformed fields is quite complex as there are many aspects to consider. There is the importance of getting a soil sample which is representative of the average fertility in the soil root zone. Then there is the need to obtain a composite sample which is not contaminated by any atypical high nutrient soil samples from fertiliser bands. The standard approach of delaying soil sampling until a few months after fertiliser applications will at least allow time for the more mobile nutrients such as nitrate to disperse. For the row - interrow sugarcane field layout, compaction in the interrow is common and hence the crop tends not to have the same amount of root development in this zone of the field. As a consequence soil nutrients in interrow areas may be less accessible to the crop than those in row areas which tend to have good soil structure. So in addition to not receiving the same fertiliser inputs in some cases (no fertiliser band applications) these areas may not experience the same extent of nutrient uptake by the crop.

For fields adopting controlled traffic permanent bed layouts, there is little choice but to sample on the crop beds. For no tillage systems, there may also be an argument for sampling on the crop row or bed as there is little mixing of the topsoil to allow for any homogenisation of the soil between these zones. A proportional sampling design as outlined above may have potential for sampling such fields with spaced cane rows (mounds). Although this may take care of the differences in fertiliser distribution due to narrow band applications, it still does not deal with differences in the accessibility of nutrients if the interrow area is more compacted.

In the case of soil sampling for standard assessments of field nutrient status, it is important to follow the industry recommendations. When deciding what sampling approach is most appropriate the following factors will need to be considered: the time since the last fertiliser application; tillage practices; site condition; field layout (row / interrow or permanent bed layout - controlled traffic or 'tram lining'); as well as how the results are going to be used or applied.

## Research site soil fertility characterisation

For field nutrient assessments that are done as part of the characterisation of a research site, it would be desirable to sample the row area (planted mounds) and the interrow area separately. Results for both areas in the field would provide a more complete and useful characterisation. The differences between these areas will depend on factors such as the time since the crop was established; the extent of fertiliser applications on the row as bands; the extent of tillage practices to mix soils; and the extent of compaction.

### 5.10.5 Determining fertiliser application rates

As mentioned earlier, agronomic response and fertiliser recommendations have been determined from past field trials based on soil samples from fixed depth intervals. For the sugar industry, sampling depth intervals are 0-20 and 40-60 cm (Schroeder *et al.* 2000) and these should be adhered to when sampling for that purpose. These samples can be collected with a soil auger by hand (jarret or Dutch - see Section 4). When the cane has been harvested, a sampling rig can be used. Schroeder *et al.* (2000) also recommend sampling in the interrow area to avoid fertiliser bands in the rows. If fertilisers have been applied to the soil surface, they could affect the results for up to 3 months after spreading. Refer to Schroeder *et al.* (2000) and Calcino (1994) for advice on soil sampling and soil testing for sugarcane soils. Generally when sampling a field for fertiliser recommendations, a composite of about 30 samples is taken for each depth sampled. Brown (1999) recommends 30-40 samples from paddocks that receive regular fertiliser inputs.

Field sampling strategies are presented in Brown (1999). The meandering, zigzagging judgement-based sampling approach that avoids abnormal spots in the field is the most commonly used sampling approach. It is important to ensure that the area sampled is uniform in terms of both its soil type and the management it receives and that locating sampling spots within the field is as unbiased and random as possible, but avoids any atypical areas.

For fields under fallow pastures or a break crops, it may be more appropriate to sample the soil at 0-10 cm which is the common sampling depth for assessing soils for pasture systems. These samples can be taken with standard push in sampling tubes often supplied by fertiliser companies. It is usually advisable to use tests that the crop response has been calibrated against.

### 5.10.6 An average nutrient profile for the field

An average nutrient profile for mineral N ( $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N, and  $\text{NO}_2^-$ -N) is often required. Sampling a field for a mineral N profile involves a large number of samples as  $\text{NO}_3^-$  is highly mobile and its distribution through the soil is a transient phenomenon. Sampling  $\text{NO}_3^-$  for modelling applications with APSIM is done to provide a reasonably realistic starting input for the model. At the moment mineral N is the dominant nutrient input for the model but over time as research continues other nutrients are likely to be included. For this reason, it is important to store soil samples for the possibility of later analyses for other nutrients and re-running of the model. The following are some important factors to consider for  $\text{NO}_3^-$  sampling for modelling sugar production with APSIM®.

#### How deep to sample?

Profiles up to 180 cm deep are required for sampling as this depth is often used as a default maximum effective rooting depth for sugarcane crop modelling (Mazzucchelli *et al.* 1997). Sometimes however soil conditions or sampling equipment do not allow this depth of soil core to be collected and it is compromised. Often 150 cm has to be the limit as many soil sampling rigs are equipped to take cores only to 150 cm.

#### How to sample?

Thin walled steel sampling tubes driven in by either a truck-mounted hydraulic rig or else a jackhammer sampler are the preferred option as they provide an intact soil core for subsampling. When the samples are to be tested for organic C, steps will need to be made to avoid sample contamination from sampling

tube lubricants (see comments in Section 4.4.1). Also avoid using any galvanised equipment for sampling if the soil sample is to be tested for zinc levels.

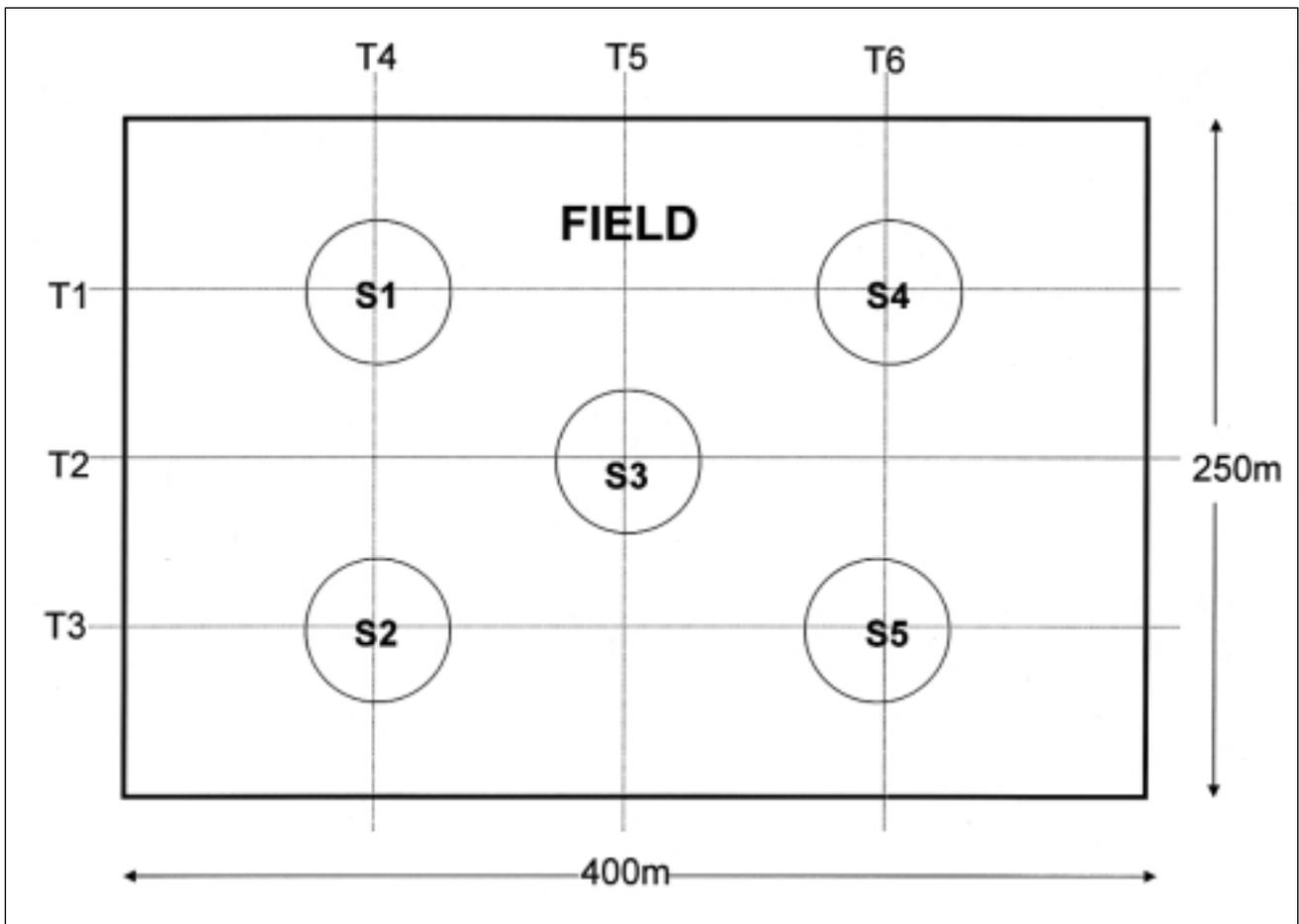
#### How many samples are required?

Foale *et al.* (1999) noted that research had found that on Vertosol soils in sub-tropical Australia, 11 soil cores are needed to achieve accuracy in the measurement of mineral nitrogen of +/- 10% in 4 out of 5 samplings. Our research group however tended to take more soil cores than this, on the basis that most sugarcane soils tended to be much more variable in their morphology than Vertosols. We would normally take a minimum of 15 soil cores and quite often 20 for a field size that rarely exceeded 5 ha.

#### Locating the sampling points

If there is no interest in measuring the spatial variability in soil mineral N, the field soil could be sampled by using random judgement based, simple random or a systematic grid sampling design. If there is interest in any broad trends in spatial variation in mineral N levels across the field, a systematic grid approach may be a more appropriate sampling strategy.

In our investigations there was often interest in broad spatial variations in soil mineral N across the field in addition to the average distribution of mineral N with depth for the field as a whole. To sample for this we would first divide the field up with three traverse lines running in each direction across the field in such a way as to create 16 equal areas of cane in the field. The intersections of these traverse lines would then be used to locate five sampling locations within the paddock (Figure 5.2). Each of these five sampling areas would consist of a circular area with a diameter of 20 m. We would take three to four soil cores in the interrow areas, located in a random fashion within each 20m diameter circular sampling zone. Each soil core would be sectioned according to set sampling depth intervals in each sampling area. For each sampling area, the soil material from each corresponding soil sampling depth increment of each core would be bulked together and mixed together in a clean bucket or bag. A subsample of this bulked soil would then be taken for laboratory



**Figure 5.2.** Determining five sampling area locations (S1 to S5) for soil nitrogen, based on traverse line divisions of a field. Traverse lines T1, T2 and T3 are parallel to the row orientation. The sampling vehicle is driven along these traverses to get the sampling sites. A GPS can be used to locate sampling sites

analyses. By the end of sampling there would be a composite subsample of soil for each sampling depth, for each sampling area (Photo 5.1).

This sampling approach provides a better appreciation of spatial variability of mineral nitrogen profiles across the field. The results for each sampling area would then be added together and averaged to give an average mineral nitrogen profile to a depth of 180cm for the field as a whole. This average profile was then used for the modelling work with APSIM.

**What depths to subsample cores?**

Each core is sampled at predetermined fixed depth intervals to provide a field composite sample for each depth interval. The SUGARBAG minimum data set manual (Mazzucchelli *et al.* 1997) recommends the following

sampling depth intervals: 0-15, 15-30, 30-45, 45-60, 60-90, 90-120, 120-150 and 150-180 cm. In the absence of a reason to sample differently it is probably desirable to conform to this as a standard. But there is no reason why this can not be altered on the basis of economic,



**Photo 5.1** Three soil cores ready to be composite sampled at set depth increments for mineral N testing.

agronomic or soil grounds. For example it may be argued that if the topsoil / subsoil horizon boundary was consistently around 25cm in a previous soil survey of the site. Then it would make sense to sample at 0-10cm and then 10-25cm for the topsoil section of the profile. Some might consider that finer sampling intervals are required in the top 20 cm to better capture the dynamics of the mineral nitrogen distribution.

### Other sampling considerations

If there have been any banded applications of fertiliser on the sugarcane rows in recent times (e.g. in the last 2 months), it would be best to take cores for mineral N from interrow areas in the field. Otherwise sampling on the row area where the plant roots are actually interacting with the soil would seem to be the more sensible option for obtaining a soil data input for modelling.

### Sample storage

It is important that soil samples collected for mineral N are placed in a portable refrigerator (or esky with ice bricks) as soon as possible after sampling to avoid significant changes occurring in the soil mineral N levels. It is best to keep soil samples at -15°C in sealed plastic bags, keeping them frozen until they are sent to the laboratory for analysis (see Section 4.6.3-storage, transport, and processing of soil samples).

## 5.11 INTERPRETATION OF SOIL CHEMISTRY RESULTS

When interpreting soil chemistry it is important to be able to relate the results to management for each soil type and crop variety. Soil profile chemistry taken from just one site to characterise the representative soil profile allows some general interpretations on the soil behaviour in addition to providing the chemical data needed to classify the soil. The soil chemistry results for samples taken down the length of the soil profile provide a valuable snapshot of change in soil chemistry in the vertical direction which is important for understanding how the soil functions in the field. Many of the indices required to classify a soil have been outlined in this section already

and in many cases critical values for interpretation have been provided. Other publications for interpreting soil analyses include Bruce and Rayment (1982), Baker (1991) and Peverill *et al.* (1999).

It is unwise to give too much weight to soil nutrient levels from the chemical data of one topsoil sample from the single soil profile in the soil type characterisation. Composite samples from across a field (ideally from 30+ randomly collected samples) allow such interpretations to be made. For fertility recommendations, crop specific guidelines developed from field trials need to be consulted. For sugarcane refer to Calcino (1994) and Bruce (2000). The interpretation guide for the standard soil nutrient tests done for sugarcane fertiliser recommendations is presented in Table 5.7. These guidelines are generic for the industry as a whole and not soil type specific. Soil specific guidelines are currently being developed for sugarcane in some regions in north Queensland (Wood *et al.* 2003, Schroeder and Wood 2001) and these refinements in the guidelines are likely to produce significant environmental and economic benefits. New soil tests are continually being developed and fertiliser recommendation guidelines are continually being refined, and as such it is important to always consult the latest industry guidelines for this application.

In addition to this table, many of the interpretation guidelines provided in this Section can be used for additional help in the interpretation of these and other soil test results. The sections on phosphorus, salinity and ESP are particularly relevant. Some of the standard soil tests which are not presented in Table 5.7 are EC, ECEC, pH and exchangeable aluminium (Al). This may be due to sugarcane being very tolerant of high exchangeable Al levels and low pH. Liming recommendations for sugarcane in recent times have been based solely on the levels of calcium and magnesium in the soil and not related to soil pH because of sugarcane's tolerance of acid soils and high exchangeable Al levels (Schroeder *et al.* 2000). Aitken (2000) put forward a strong argument for the need for liming to maintain soil pH around 5.5. The basis for this argument was that even though sugarcane can tolerate highly acidic soils, acidic conditions still have a

significant affect on nutrient availability to the crop and can also cause difficulties when needing to grow a fallow crop or an alternative crop. The cost of lime to increase soil pH from a very low value to 5.5 in one hit can be significant. Aitken (2000) presented the following formula for calculating the lime requirement in tonnes of lime per ha per 10cm of soil to raise the current soil pH (pHi) to pH 5.5 (LR<sub>5.5</sub>) in Queensland soils.

$$LR_{5.5} = 16.3 + 0.485 (OC\%) - 3.05 (pHi)$$

This formula is based on field trial work in south east Queensland and assumes good quality lime (NV 98, 39% Ca, 97% < 0.25mm) is used. It is based on OC being the major contributor to soil pH buffering capacity and as

such may be less relevant to areas with cracking clay soils.

Soil testing for soil micronutrients (Zn, Cu, Bo) is less useful (Schroeder *et al.* 2000) for sugarcane. Leaf tissue testing and deficiency diagnoses by crop and leaf inspection is more effective. Records and local knowledge in regard to the susceptibility of different soil types are also helpful.

## 5.12 SOME VALUABLE NON-STANDARD SOIL CHEMICAL TESTS

Potential tests to determine the following soil properties are presently being evaluated for the sugar industry (Phil Moody pers. com. 2003):

**Table 5.7.** BSES soil test interpretation guide (Schroeder *et al.* 2000)

| Nutrient  | Critical value                               | Rating                                       |            |
|---|--|--|------------|
| Phosphorus<br>(mg / kg)<br>(0.005M H <sub>2</sub> SO <sub>4</sub> )               | < 6  | Extremely low                                |            |
|   | 6-10   | Very low                                     |            |
|   | 11-20  | Low  |            |
|   | 21-40  | Medium                                       |            |
|   | > 40   | High   |            |
| Potassium<br>(cmol (+) / kg)  | Exch K<br>(1M NH <sub>4</sub> OAc)<br>< 0.24 | Nitric K<br>(1M HNO <sub>3</sub> )<br>< 0.24 | Low        |
|   |  | 0.24 – 0.70                                  | Medium/low |
|   |  | > 0.70                                       | Medium     |
|   | > 0.24                                       | < 0.70                                       | Medium     |
|   | > 0.24                                       | > 0.70                                       | High       |
| Sulfur (mg / kg)<br>(0.01M Ca<br>(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub> ) | < 3  | Low  |            |
|   | 3-7  | Medium                                       |            |
|   | > 7  | High   |            |
| Calcium<br>(cmol (+) / kg)<br>(1M NH <sub>4</sub> OAc)                            | <0.55  | Low  |            |
|   | 0.55-1.25                                    | Medium                                       |            |
|   | > 1.25                                       | High   |            |
| Magnesium<br>(cmol (+) / kg)<br>(1M NH <sub>4</sub> OAc)                          | < 0.1  | Low  |            |
|   | 0.1-0.25                                     | Medium                                       |            |
|   | > 0.25                                       | High   |            |
| Copper<br>(mg/kg)<br>(DTPA)   | < 0.2  | Low  |            |
|   | > 0.2  | High   |            |
| Zinc<br>(mg/kg)<br>(HCl)  | < 0.6  | Low  |            |
|   | > 0.6  | High   |            |

- Nitrogen mineralisation potential
- Soil capability to replenish exchangeable K

### Nitrogen mineralisation

Organic nitrogen is progressively converted to inorganic (mineral) nitrogen (ammonium plus nitrate N) during the crop cycle and as such the pre-plant levels may not reflect the availability of N to the crop over this period. Two laboratory methods are presently being evaluated by BSES, CSR and NR&M for their usefulness in estimating the amount of nitrogen mineralisation, so as to allow the standard nitrogen fertiliser recommendations to be modified accordingly. Both methods involve incubating the soil for a period of 1 to 2 weeks, with one method incubating the soil under aerobic conditions (Keeney 1982) and the other under anaerobic conditions (Lober and Reeder 1993). The amount of mineral N released over the incubation period gives an indication of the potential release of mineral N that could occur during the crop cycle (Phil Moody pers.com. 2003).

### Soil capacity to replenish exchangeable K

Current soil tests for assessing potassium availability measure the readily available 'exchangeable' potassium. However, as this store of potassium is depleted by crop uptake, some soils have potassium in less available forms which can replenish the exchangeable form and thereby maintain potassium supply to the crop. Just determining the exchangeable potassium levels in such soils does not reflect the ability of these soils to continue to supply potassium. A soil test (tetra phenyl borate extractable potassium (Cox *et al.* 1996)) that assesses the ability of a soil to replenish exchangeable potassium is currently being investigated for Queensland sugar cane soils (Phil Moody pers.com. 2003).

## 5.13 STORING SOIL SAMPLES FOR THE FUTURE

Once all of the tests have been carried out on the soil samples, it is worthwhile storing a small subsample (200g) of each tested sample in a sealed container for future reference. Such archives of soil samples are useful as they

allow the soil sample to be revisited in the future if there are any queries about the results or if new tests that may shed some light on research results are developed. Such collections of soil samples, when combined with good records, can provide a valuable resource for soil research as they are a snapshot in time.

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# Section 6. Soil porosity and water storage properties

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## 6.1 INTRODUCTION

Soil porosity and water storage properties provide valuable information on soil water interactions that are important for understanding the dynamics of a cropping system in terms of both productivity and environmental impacts. Such information can tell us how well water moves through the soil, how effectively soil water is stored for crop use, and the ease with which crop roots can grow through and explore the soil to access stored nutrients and water. This information is important for practical applications such as irrigation scheduling and the design of irrigation and drainage systems. It is also important as input parameters for modelling crop production and profile drainage (with the APSIM, SWIM, and Hydrus models). The following chapter provides a brief outline of some of the more important soil water and porosity properties as well as some practical guidelines for measuring them in the field and sampling soils for later laboratory measurements. For further details on the laboratory methods for determining soil water retention and bulk density properties refer to Cresswell (2002) and Cresswell and Hamilton (2002). For additional guidance on sampling soils for these properties refer to McKenzie and Cresswell (2002), McIntyre (1974a, 1974b), McIntyre and Loveday (1974), and Dalgliesh and Foale (1998). In sugarcane fields, agronomic factors such as differences between plant row and interrow areas, the ratoon stage of the crop and cultivation history can all have a very significant bearing on the measured values for these soil physical properties. This section also deals with some issues specific to sugarcane production that need to be taken into account when characterising properties of soils under sugar cane production (see Section 6.5).

## 6.2 BASIC SOIL WATER AND POROSITY PARAMETERS

A brief outline of some important basic soil porosity and water storage properties is provided below. Texts such as Marshall *et al.* (1996) can be referred to for a more detailed treatment of this topic and associated theory.

### Soil water potential energy and units of measurements

The component of soil water potential energy associated with mutual attraction between water and soil particles due to capillarity and adhesion is referred to as the matric potential ( $\psi_m$ ). A matric potential of zero is associated with wet soil while the drier the soil, the more negative the matric potential value. The drier the soil and the more negative the matric potential value, the greater the suction force that is exerted on the soil water by the dry soil. Units used to denote soil matric potential or suction in the following discussions are principally the SI unit, kilopascal (kPa). The unit, metres of water, has been added in brackets due to its common usage (Cresswell 2002). An acceptable approximate conversion relationship between the soil water energy units (Cresswell 2002) used in this Chapter is as follows:

$$-1.0 \text{ m (water at } 20^\circ \text{ C)} = -10 \text{ kPa} = -0.1 \text{ bar}$$

### Gravimetric water content

Gravimetric water content is the soil water content expressed as a percentage of the dry soil mass. The formula is expressed as:

$$\text{gravimetric water content (g g}^{-1}\text{)} = \frac{[\text{mass of soil sample at time of sampling (g)} - \text{oven dry mass of soil sample(g)}]}{\text{oven dry mass of soil sample(g)}} \quad (6.1)$$

Gravimetric water content can also be expressed as a percentage of oven dry soil weight by multiplying the value from formula 6.1 by 100.

## Bulk density

The bulk density (BD) of a soil is "the oven dry (105 °C) mass of a soil per unit volume of bulk soil volume" (Cass 1999). The soil volume includes all pore spaces within the soil as well as the soil matter itself. In plain English, it is the oven dry mass of a core sample of intact soil per unit volume. The unit of bulk density is  $\text{g cm}^{-3}$ , which is identical to  $\text{Mg m}^{-3}$ .

$$\text{bulk density (g / cm}^3\text{)} = \text{oven dry soil mass (g) / total volume of soil (cm}^3\text{)} \quad (6.2)$$

Bulk density is a reflection of soil structure. It is also needed to convert gravimetric measures of soil moisture and nutrient levels to volumetric ones. Values range from 0.8 to 2  $\text{g / cm}^3$  (Cass 1999).

Determining bulk density for most soil types is usually fairly straightforward. It normally involves collecting a sample of intact soil from the field with a metal ring (of known dimensions) and then drying the sample in an oven at 105°C and weighing it.

The only exceptions to the above method are soils with vertic properties (i.e. the high shrink swell or cracking soils). Bulk density of these soils varies with moisture content. Consequently it is especially important that the small steel ring core sample is taken when the soil is close to field capacity as shrinkage cracks can greatly affect bulk density results. Method 503.02 outlined by Cresswell and Hamilton (2002) is recommended for determining the bulk density of vertic soils. According to their method the soil core is saturated and then equilibrated on a tension plate at a matric potential of -10 kPa (-1.0 m). At this point, callipers are used to measure the dimensions of the core to calculate its volume, before weighing and oven drying it (Cresswell and Hamilton 2002). Reporting the bulk density value of a high shrink-swell soil should be accompanied by its gravimetric moisture content at -10 kPa (-1.0 m) matric potential (the matric potential at which the bulk density was determined).

## Volumetric soil water content

Volumetric soil water (VWC) is the soil water content expressed on a volume of water to volume of soil basis ( $\text{mm}^3 \text{mm}^{-3}$  or  $\text{m}^3 \text{m}^{-3}$ ).

This value is sometimes multiplied by 100 to express VWC in percentage (%) terms.

$$\text{VWC (mm}^3 \text{mm}^{-3}\text{)} = \text{gravimetric water content (g/g) x bulk density (g / cm}^3\text{)} \quad (6.3)$$

## Total porosity

Total porosity (PO) is the volume of air or pore space per unit volume of bulk soil when the soil is dry.

$$\text{PO (mm}^3 \text{mm}^{-3}\text{)} = 1 - (\text{BD} / 2.65) \quad (6.4)$$

Here  $\text{BD} / 2.65$  is the proportion of the soil volume occupied by solid particles based on an assumed density of  $2.65 \text{g / cm}^3$  for the solid matter in the soil. This holds true for most soils except for organic soils (where it is lower) and Ferrosols (where it is higher) (Dalglish & Foale 1998).

## Air filled porosity

Air filled porosity ( $\epsilon_a$ ) is the air filled pore space per unit volume of soil for any given soil volumetric water content.

$$\text{air filled porosity (}\epsilon_a\text{)} = \text{PO} - \text{VWC} \quad (6.5)$$

## Air filled porosity at field capacity or DUL

Air filled porosity at field capacity (AFPFC) is the minimum volume of air in the soil that is available to plants at the wettest drained condition (Cass 1999). It is calculated as the difference between total porosity and field capacity with the formula:

$$\text{AFP}_{\text{FC}} (\text{mm}^3 \text{mm}^{-3}\text{)} = \text{PO} - \text{DUL} \quad (6.6)$$

Sometimes this air filled porosity at field capacity value is multiplied by 100 to express it as an air filled porosity percentage (%) value.

## Saturation

The water content of soil at saturation (SAT) is the maximum amount of water able to be held in the soil before drainage takes place. But even when the soil is considered to be at saturation some of the pore space will contain entrapped air (e) and this property, which varies with soil type, is factored into the equation.

$$\text{SAT (mm}^3 \text{mm}^{-3}\text{)} = \text{PO} - e \quad (6.7)$$

The value of e varies from  $0.03 \text{mm}^3 \text{mm}^{-3}$  (heavy clays) to  $0.07 \text{mm}^3 \text{mm}^{-3}$  (sand)

(Dalglish and Foale 1998).

This property is important for models that employ a 'tipping bucket' approach to modelling water movement through the soil, such as the SoilWat2 component of the APSIM model.

### Field capacity or drained upper limit

Field capacity (FC), or drained upper limit (DUL), is the amount of water held in a soil after it has been saturated and then allowed to drain. It is more specifically defined as the amount of soil water (volumetric soil water) remaining in the soil profile 2 to 3 days after having been saturated with water and after free drainage is negligible (Anon. 2001). Negligible drainage can be taken to mean  $<1\text{mm} / \text{day}$ , according to Cassel and Nielson (1986) and Dalglish and Foale (1998). This point can be determined accurately in the field using a neutron probe or other methods that allow the soil water content to be measured as a function of depth. Cass (1999) notes the importance of excluding evapotranspiration processes as part of his definition.

This soil property, which is a field measured property by definition, can be estimated or approximated in the laboratory by applying a  $-10\text{ kPa}$  ( $-1.0\text{m}$  or  $0.1\text{bar}$ ) suction or matric potential to a saturated soil core on a tension plate (Photos 6.1 and 6.2) until it reaches equilibrium (Cresswell 2002). The tension of  $-10\text{ kPa}$  is based on the fact that many of the reported in situ measurements of soil water matric potential values at field capacity were found to be near the  $-10\text{ kPa}$  value (Cassel and Nielson 1986). The use of loose, ground soil material ( $<2\text{ mm}$ ) is not recommended for laboratory assessment of DUL. This is because grinding destroys most of the soil structure, and soil structure has an important influence on soil water storage between the matric potentials of  $0$  and  $30\text{ kPa}$  ( $-3.0\text{ m}$ ) (Cresswell and Hamilton 2002).

Values range from  $<0.1$  to  $0.4\text{ mm}^3\text{ mm}^{-3}$  ( $<10$  to  $40\%$  or  $<100$  to  $400\text{mm/m}$ ) (Cass 1999).

### Permanent wilting point

Permanent wilting point (PWP) is "the volumetric water content of a soil when indicator plants growing in that soil wilt and



Photo 6.1. Laboratory tension plate setup for determining soil water retention at matric potentials up to  $-2.0\text{m}$ , including field capacity at  $-1.0\text{m}$ .

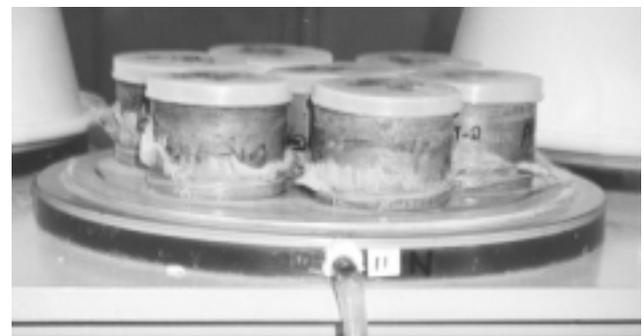


Photo 6.2. A close up of soil cores sitting on porous ceramic tension plates

fail to recover when placed in a humid chamber" (Anon. 1984). It is a crop specific property.

Early determinations of PWP used the dwarf sunflower (*Helianthus annuus* L.) and it was found that the soil water potential at this plant's PWP was approximately  $1500\text{ kPa}$  ( $-150\text{ m}$  or  $15\text{ bar}$ ) (Richards and Weaver 1943). This is the basis of  $1500\text{ kPa}$  pressure being adopted as the standard for laboratory approximations of PWP using pressure plates (Photos 6.3 and 6.4).



Photo 6.3. A laboratory pressure chamber setup to determine soil water retention for matric potentials up to 1500 kPa.

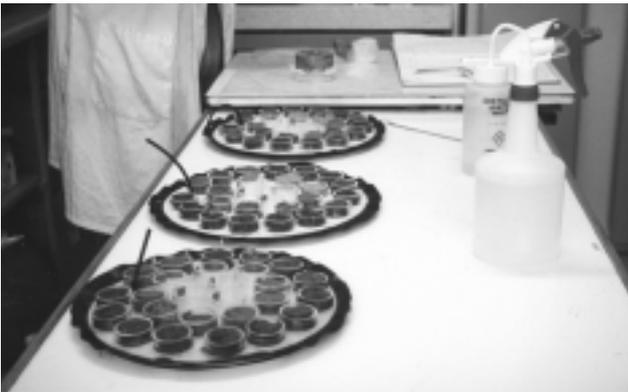


Photo 6.4. Sub samples of soil cores on ceramic pressure plates awaiting transfer to pressure chambers for the determination of PWP or LL (1500kPa)

As such, the -1500 kPa estimate of PWP will vary in accuracy for different crops. For sugarcane it is believed to be a fairly good estimate (Inman-Bamber pers.com. 2001), while for other crops such as cotton it is less accurate, especially deeper in the soil profile (Williams 1983, Dalgliesh and Foale 1998). For cotton, the laboratory measurement at -1500 kPa tends to overestimate PAWC at depth.

Values range from  $<0.05$  to  $0.2 \text{ mm}^3 \text{ mm}^{-3}$  ( $<5$  to 20% volume or  $<50$  to 200 mm/m) (Cass 1999).

#### *PWP and modelling terminology*

The volumetric water content of a saturated soil sample equilibrated at 1500 kPa suction on a pressure plate in the laboratory (PWP) is referred to as LL15 in the SoilWat module of the APSIM model (Dalgliesh and Foale 1998).

The volumetric soil water content in a soil at the PWP for a specific crop when induced in the field (via a rain shelter) is referred to as the lower limit (LL) in the SoilWat module of the APSIM model. Dalgliesh and Foale (1998) refer to this as the crop lower limit (CLL).

Bringing on permanent wilting and death in a crop via water deprivation (rain shelter) can sometimes prove difficult for crops such as sugarcane which are resilient and sometimes able to access groundwater in the typical alluvial settings where they are grown. The height of advanced sugarcane crops also makes the use of rainfall shelters in the field very difficult, if not impractical.

Given the difficulty in inducing PWP for sugarcane plants in the field, it may be an acceptable fall back option in the absence of this measurement to use the LL15 value as a surrogate for LL in the data inputs for SoilWat2 module of APSIM.

#### **Plant available water capacity**

Plant available water capacity (PAWC) is the maximum amount of soil water available to a crop. It is the amount of water held in the soil between field capacity (FC) and the crop's lower extracting limit (PWP) over the depth of rooting (Dalgliesh and Foale 1998). It therefore varies with soil type and crop. The formula, using VWC ( $\text{mm}^3 \text{ mm}^{-3}$ ) values of FC and PWP, is:

$$\text{PAWC} (\text{mm mm}^{-1}) = [\text{FC} - \text{PWP}] \quad (6.8)$$

Or, in hydrology modelling terminology, it is expressed as:

$$\text{PAWC} (\text{mm mm}^{-1}) = [\text{DUL} - \text{LL}] \quad (6.9)$$

Note that PAWC is commonly expressed as mm of water / mm of soil, and this is factored into the following calculations:

#### *PAWC for a depth interval or soil horizon*

To calculate the PAWC in mm of water for one soil horizon or sample depth interval:

$$\text{PAWC} (\text{mm of water}) = [\text{DUL} - \text{LL}] \times \text{horizon thickness or sample depth interval (mm)} \quad (6.10)$$

Volumetric water contents ( $\text{mm}^3 \text{ mm}^{-3}$ ) are entered for DUL and LL.

#### *PAWC for a whole soil profile*

To calculate the PAWC (mm) for the whole soil profile, first calculate the PAWC for each depth interval and then sum these values. This will give a profile PAWC in mm of water.

#### *Conversions for expressing PAWC in different units*

The calculations in this text have focused on expressing PAWC values in  $\text{mm mm}^{-1}$  units, as this is the most commonly used unit in soil water modelling applications. But PAWC is often also expressed as a percentage (water to soil volume) and as  $\text{mm / m}$ . The  $\text{mm / m}$  unit is commonly used with irrigators as they tend to find these numbers easier to visualise and work with.

To convert from  $\text{mm mm}^{-1}$  values to percentage (%) values simply multiply the PAWC  $\text{mm mm}^{-1}$  values by 100.

To convert from  $\text{mm mm}^{-1}$  values to  $\text{mm per metre}$  values ( $\text{mm m}^{-1}$ ) simply multiply PAWC  $\text{mm mm}^{-1}$  values by 1000.

For example, a PAWC value of  $0.42 \text{ mm mm}^{-1}$  could be expressed as 42% or  $420 \text{ mm m}^{-1}$ .

PAWC values range from 0.05 to  $0.40 \text{ mm mm}^{-1}$  (5 to 40% or 50–400  $\text{mm / m}$ ) (Cass 1999).

#### PAWC and PAW

It is important to be aware of the difference between PAWC and PAW. Plant available water capacity (PAWC) is the maximum amount of plant available water that the soil can store and as such is a fixed value for a given soil and crop. Plant available water (PAW) on the other hand is merely the amount of plant available water stored in the soil at any point in time, and as such is constantly changing.

## 6.3 CALCULATION OF SOIL WATER PROPERTIES

A worked example of soil water and porosity calculations is presented below to illustrate the calculation steps further.

### SITE DETAILS

Site 1 – Clay loam soil (CSR map unit)  
 Location: Seymour's Rd, Herbert.  
 Horizon: Layer 7 (3B22) 101-121cm  
 Core sample depth: 110-115cm  
 Texture: Silty medium clay

### RAW LABORATORY DATA

Sampling ring cylinder dimensions: 7 cm internal diameter (3.5 cm radius) and 5 cm high.  
 Oven dry mass of soil from core = 315.5 g  
 Gravimetric water content of wetted soil at -10 kPa =

23.78% or  $0.2378 \text{ g g}^{-1}$   
 Gravimetric water content of wetted soil at -1500 kPa =  
 14.15% or  $0.1415 \text{ g g}^{-1}$

### CALCULATIONS

#### Bulk density

Volume of core sample:

Ring cylinder has an internal diameter of 7 cm (3.5 cm radius) and is 5 cm high.

Volume of core =  $\pi r^2 \times h = 3.14 \times (3.5)^2 \times 5 = 192.4 \text{ cm}^3$

Oven dry mass of soil from core:

Weight of core = 315.5 g

Soil bulk density = oven dry weight (g) / total volume of soil core ( $\text{cm}^3$ )  
 $= 315.5 \text{ g} / 192.4 \text{ cm}^3 = 1.64 \text{ g/cm}^3$

#### Total porosity

Total porosity (PO) ( $\text{mm}^3 \text{ mm}^{-3}$ ) =  $1 - (\text{BD} / 2.65)$   
 $= [1 - (1.64 / 2.65)] = 0.381 \text{ mm}^3 \text{ mm}^{-3}$

#### Saturation (SAT)

SAT ( $\text{mm}^3 \text{ mm}^{-3}$ ) = PO - e where e = 0.03 (heavy clays) to 0.07 (sand)  
 $= 0.381 - 0.035 = 0.346 \text{ mm}^3 \text{ mm}^{-3}$

#### Drained upper limit (DUL) or field capacity

Gravimetric water content of wetted soil at -10 kPa =  $0.2378 \text{ g g}^{-1}$

Soil volumetric water content ( $\text{mm}^3 \text{ mm}^{-3}$ ) = gravimetric water content ( $\text{g g}^{-1}$ )  $\times$  BD ( $\text{g/cm}^3$ )

DUL = WVC at -10 kPa =  $0.2378 \times 1.64 = 0.390 \text{ mm}^3 \text{ mm}^{-3}$

#### Crop lower limit (LL)\*

Gravimetric water content of wetted soil at -1500kPa =  $0.1415 \text{ g g}^{-1}$

Soil volumetric water content ( $\text{mm}^3 \text{ mm}^{-3}$ ) = gravimetric water content ( $\text{g g}^{-1}$ )  $\times$  BD ( $\text{g/cm}^3$ )

LL = WVC at -1500 kPa =  $0.1415 \times 1.64 = 0.232 \text{ mm}^3 \text{ mm}^{-3}$

\* Note in this case the laboratory estimate of PWP (LL15) is used as a substitute for field determined crop lower limit (LL).

#### Plant available water capacity (PAWC)

PAWC ( $\text{mm mm}^{-1}$ ) = [DUL - LL] =  $0.390 - 0.232 = 0.158 \text{ mm mm}^{-1}$  or 158  $\text{mm/m}$  of soil

PAWC (mm) for horizon = [DUL - LL]  $\times$  [depth interval (mm)]

$= [0.390 - 0.232] \times [200] = 31.6 \text{ mm}$  of water for this 200mm thick horizon.

The PAWC for the soil profile can be estimated by adding up the PAWC values in mm for each horizon down to the bottom of the crop's rooting depth.

## 6.4 THE SOIL WATER CHARACTERISTIC

The soil water characteristic  $\theta(\Psi)$  is the relationship between volumetric water content and matric potential (tension due to adhesion and capillarity of the soil). It is also known as the water release characteristic (in a drying soil), water retention function, soil water retention characteristic, or pF curve (Cresswell 2002).

The soil water characteristic has many practical applications for both irrigation and modelling. It can be used in conjunction with hydraulic conductivity to predict the wetting front area for drip irrigation (Cook 1995), while water retention data at matric potentials closer to saturation are important in the design of irrigation and drainage systems. The slope of the soil water characteristic is used to calculate the soil water diffusivity which is often used in modelling plant water uptake (Cresswell 2002). It is also an important input parameter for soil water balance models such as SWIMv2.

Water balance models which use a storage-flow system (or tipping bucket) such as the SoilWat module of the APSIM model require soil volumetric moisture content values for only the -10 kPa (-1.0 m) or -1500 kPa (-150.0 m) matric potentials, which approximate drained upper limit and lower limit respectively (Cresswell 2002). Models like SWIMv2 and Hydrus on the other hand, which utilise flow equations to simulate soil water balance, require the full soil water characteristic as a soil property input.

To determine the soil water characteristic, a soil core collected from a soil horizon in the field is first saturated and then equilibrated to a sequence of increasing matric potentials on tension plate and pressure plate apparatus. The soil core is weighed at each equilibration point to later calculate its volumetric water content at that point. A ceramic suction plate (Photos 6.1 and 6.2) is used to equilibrate a soil core sample for potentials less than -80 kPa (-8.0 m), while a pressure plate apparatus (Photos 6.3 and 6.4) is used to equilibrate a smaller soil sub sample for potentials between -80 kPa (-8.0 m) and -1500 kPa (-150 m) (Cresswell 2002).

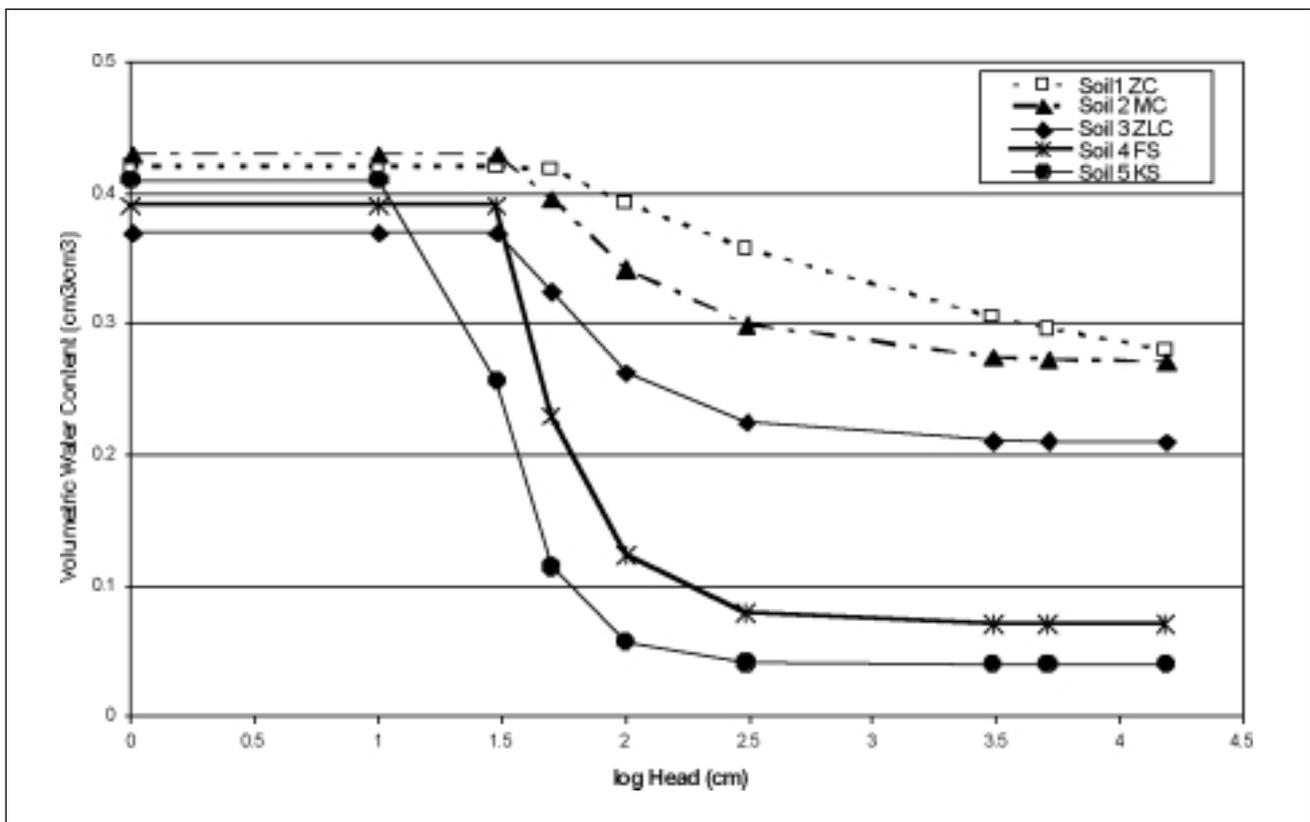
A suitable range of matric potentials for plotting a full soil water characteristic on a logarithmic scale includes 1 kPa (-0.10 m), -3 kPa (-0.30 m), -6 kPa (-0.60 m), -10 kPa (-1.0 m), -33 kPa (-3.3 m), -60 kPa (-6.0 m), -100 kPa (-10.0 m), -300 kPa (-30.0 m), -500 kPa (-50.0 m), and -1500 kPa (-150.0 m). However, this work could take several months (Cresswell 2002) so is often reduced to five points spread across this range. Cresswell and Paydar (1996) present a method which enables functions of the form given by Hutson and Cass (1987) to be fitted to only two measured points (either -1500 kPa or -500 kPa together with one of -3 kPa, -5 kPa, or -10 kPa) to describe the complete soil water characteristic. This method is explained clearly in McKenzie and Cresswell (2002).

Usually bulk density is determined for all core samples collected for soil water retention measurements as a matter of procedure, as it requires little extra effort. At the completion of soil water retention and bulk density measurements, it is also worthwhile carrying out a particle size analysis on a composite sample of soil from replicate cores for each soil layer sampled. Particle size and texture are important influences on soil water retention, especially at the more negative soil matric potentials (higher suction).

Once a soil's volumetric water content has been determined for each matric potential measured (usually at least five points), VWC can be graphed against the log of matric potential to give a soil water retention curve for that soil.

A smoothed continuous soil water retention function can be created with the RetC® (Van Genuchten *et al.* 1991) software package which applies the curve fitting equation of Brooks and Corey (1966) to volumetric water content / matric potential data pairs. The RETC package also can produce hydraulic conductivity functions for unsaturated soils with the addition of one K value for the soil material. Demonstrations of RETC can currently be downloaded from the USDA Salinity Laboratory internet site ([www.ussl.ars.usda.gov/MODELS/retc.htm](http://www.ussl.ars.usda.gov/MODELS/retc.htm)).

An example of a soil water retention curve from a sugarcane soil from the Burdekin catchment is presented in Figure 6.1.



**Figure 6.1.** The full soil water characteristic for five soil horizons of a soil profile from Kalamia in the Burdekin catchment. [Note that soil 1 is a silty clay, soil 2 is a medium clay, soil 3 is a silty light clay, soil 4 is a fine sand, and soil 5 is a coarse sand. A negative log head of 4.2 on this graph equates to PWP (-15000 cm), while a negative log head of 2 equates to field capacity (-100 cm).]

## 6.5 FIELD WORK IN SUGARCANE FIELDS – FACTORS TO CONSIDER

When investigating soil water properties at a site, it is important to be aware of that site's recent history of agricultural practices and their potential impacts on the soil properties of interest. It is also important that field measurements and sampling are done when field and soil conditions are suitable and that the final results are representative. Every effort needs to be made to ensure that all sampling is carried out in a way that provides samples that are representative of the area being characterised. Some of the more critical matters to consider are outlined below.

### 6.5.1 Row (mound) and interrow areas

Row and interrow areas of cane fields need to be treated as separate soil entities when sampling soil cores for analysis and when carrying out field measurements of soil physical / hydraulic properties, as these two areas receive very different management (Photo 6.5). The interrow area tends to become

heavily compacted from tractor and harvester wheels during the cane's life cycle. In contrast, the row area receives a zero tillage treatment and a high organic matter input from trash, which encourages earthworm activity. Earthworm activity and cane root growth in the row result in a considerable number of large macropores (> 2mm) in this area. These pores ensure a much higher infiltration rate, higher PAWC and lower bulk density on the row than in the interrow area.



Photo 6.5. The row and interrow areas in a cane field

### 6.5.2 Crop class (plant or ratoon stage)

Is the field newly planted (a plant cane crop) or is it growing a 6th ratoon crop. This will make a difference to porosity and infiltration in the surface soil layers. If it is a newly planted cane crop, then it is likely, given current practice, that the surface soil horizons would have been pulverized to a fine dust and had all soil structure destroyed as part of the land preparation (especially if laser levelling was involved). This results in a lower than normal porosity on the cane row (due the destruction of macropores) and a higher than normal porosity in the interrow area due to the loosening up of compacted soil. The same is true for infiltration. At the newly planted stage, row and interrow differences are minimal. The later the ratoon stage of the crop, the greater the differences will be between row and interrow areas. By the last ratoon stage of the crop cycle, the infiltration rate on the row is usually at its fastest and porosity at its highest due to macropore development, while for the interrow area infiltration is at its slowest and porosity at its lowest due to compaction.

The hard question is when is the best time in the plant-to-plough-out crop cycle to sample a soil for soil water storage and porosity properties, and to measure infiltration rates. Perhaps the middle of the planted crop's life (3rd ratoon) could be argued to be representative of the average soil condition for the life of the crop. But having any say in the timing of these measurements is a rare luxury. So it is therefore especially important to ensure that the ratoon number for the cane crop at the time of measurement is recorded. This will at least allow these measurements to be put in context. However, measurements in newly planted crops should be avoided if possible as they miss the very important row / interrow differences that develop for infiltration, bulk density and soil water storage properties.

### 6.5.3 Cultivation history

It is important to be aware of any cultivation practices that may impact on the validity and representativeness of any measurements. Such practices include tillage, deep ripping and the use of cane splitters in fertiliser applications.

### 6.5.4 Soil moisture conditions

The soil moisture condition is an important consideration when planning to do small core (e.g. 7 cm diameter x 5 cm deep cores) sampling for either soil water retention or hydraulic conductivity laboratory work. It is probably somewhat less important for bulk density determinations, the exception being cracking clays or Vertisol soils (see bulk density Section 6.2). Ideally small soil core sampling should be done at soil moisture conditions approaching but not exceeding the plastic limit of the soil (McKenzie and Cresswell 2002).

## 6.6 COLLECTING SMALL INTACT SOIL CORES IN THE FIELD

Small intact soil cores (e.g. 70 mm diameter x 50 mm high) are collected from the field for laboratory measurements of bulk density, soil water retention (storage) characteristics, and, in some cases, hydraulic conductivity.

The soil sampling strategy or design for soil water and porosity properties will vary depending on the objectives of the work as well as sampling practicalities. For example the main focus of this chapter is on the characterisation of the soil water and bulk density properties of a representative soil profile.

It is generally adequate to limit subsoil core samples and measurements to those taken from the representative soil profile pit site (for selection of this area see Section 2), and surface core samples to an area within a 20 metre diameter of this pit. If care is taken in the handling, storage, and transport of small cores (Section 6.6.3 step 5), they can be used to assess water retention or infiltration properties.

Small intact cores are usually sampled from each horizon at a soil pit site as part of a full characterisation of the soil, which includes a soil profile description and bag sampling of loose soil for basic soil chemistry testing. The methodology for the selection of the pit site location, the description of the soil profile and horizon identification has been outlined in Sections 2.2 and 4.4. Detailed guidelines on

field sampling of small soil cores are provided by McKenzie and Cresswell (2002). Guidelines on the laboratory assessment of soil water properties and bulk density can be found in Cresswell and Hamilton (2002) and Cresswell (2002) respectively.

### 6.6.1 How many samples?

#### Approximations for characterisation and modelling applications

For characterising a representative soil profile, a minimum of four small intact soil core samples (70 mm diameter x 50 mm deep rings) should be taken from each soil horizon for the laboratory determination of DUL, LL, and bulk density.

If soil horizons are very similar in texture and structure, one horizon can legitimately be used as a surrogate for the other, thus saving time, effort and laboratory costs. This approach is especially relevant to alluvial soils which often have many sequences of alternating coarse and fine textured soil layers due to depositions of sediment during flood events in the past. In such highly stratified soils it would be very expensive to sample every layer for characterising soil water retention. But it may be worthwhile to sample every layer for an assessment of bulk density as this test is simple and cheap.

When sampling has to be limited to just two or three layers due to expense, it is advisable to select those soil horizons which exert the most control over the soil's physical environment. These are usually the A1 horizon (topsoil) and the top of the B horizon, if it is impeding infiltration (McKenzie and Cresswell 2002).

#### Very accurate estimates of the mean values for a field

When sampling surface soil, it is possible to acquire an unbiased and highly accurate estimate of the mean value of a soil property. The only restrictions are the expense and time involved. McKenzie and Cresswell (2002b) presented typical sample numbers for bulk density and soil water retention characterisations as being 3 to 5 replicates and 2 to 4 replicates respectively.

For a more accurate assessment of the surface soil, a design based probabilistic sampling approach is required to ensure an unbiased sample. This is discussed further by McKenzie and Cresswell (2002b), while Webster and Oliver (1990) provide a detailed coverage of such sampling designs and the computation of statistics.

To achieve a high level of accuracy it is important to ensure that sufficient samples are collected. To determine the number of replicate samples required the following procedure outlined in Peterson and Calvin (1965) and McBratney (1991) is recommended.

First, an initial sampling of the soil is required to allow an estimate of the population sample variance ( $s^2$ ) to be made. Once this is known, the sample size ( $n$ ) required to estimate the mean ( $\bar{X}$ ) of a soil entity within defined limits ( $D$ ) at the 95% probability level can be made using the following formula;

$$n = \frac{t_{\alpha}^2 s^2}{D^2} \quad (6.11)$$

where  $t_{\alpha}^2$  is the Student's t at the level of probability  $\alpha$  and  $s^2$  is the variance determined on the initial preliminary sampling. A preliminary sampling of 10 samples would probably be sufficient in most cases to provide an initial estimate of  $s^2$  for the above formula.

*Example;* Bulk density results ( $\text{g cm}^{-3}$ ) from an initial sample size of 10 are:

1.60, 1.65, 1.43, 1.75, 1.64, 1.82, 1.55, 1.62, 1.45, 1.35

#### Step 1 – Calculate the sample mean average

$$\bar{X} = \frac{\sum X_i}{n} = \frac{(1.60 + 1.65 + \dots + 1.59)}{10} = 1.586$$

#### Step 2 – Calculate the sample variance ( $S^2$ )

$$s^2 = \frac{\sum (X_i - \bar{X})^2}{n - 1} = \frac{\sum (X_i - 1.586)^2}{9} = 0.021093$$

#### Step 3 – Calculate the variance of the mean $V(\bar{X})$

$$V(\bar{X}) = \frac{s^2}{n} = 0.021093 / 10 = 0.002109$$

#### Step 4 – Calculate the 95% confidence limits for the initial sampling

$L = \bar{X} \pm t_{\alpha} [S^2 / n]^{1/2}$  where  $t_{\alpha}$  is the student's  $t$  with  $(n-1)$  degrees of freedom at the  $\alpha$  probability (usually 0.05).

$$L = 1.59 \pm 1.833 [0.002109]^{1/2} = 1.59 \pm 0.084$$

This means that the probability is 0.95 that the mean lies between 1.506 and 1.674.

#### Step 5 – Decide on a specified limit (D) and calculate the required number of samples to estimate the mean value within the specified limit with a 95% probability.

For example in this case, we have chosen to estimate the mean within  $\pm 0.05 \text{ g / cm}^3$ , at the 95% probability level.

$$n = \frac{t_{\alpha}^2 s^2}{D^2}$$

where  $t_{\alpha}$  is 1.833 (from  $t$  distribution table) for 95% probability and 9 degrees of freedom (i.e.  $n - 1$  for initial sample of 10).

$$n = (1.833)^2 \times (0.021093) / (0.05)^2 = 28.3 \text{ samples.}$$

i.e. To obtain the desired level of precision in estimating the mean (i.e.  $0.05 \text{ g / cm}^3$ ) the sample number will need to be increased from 10 to 29 samples. To be able to estimate the mean within  $0.01 \text{ g}$ , the required number of samples would be 707 (i.e. this is obtained by substituting 0.01 for 0.05 in the above formula). This level of accuracy would certainly not be economical in this instance. So an accuracy of  $0.05 \text{ g / cm}^3$  would be the chosen level of accuracy in this case.

This procedure is essential for field research experiments evaluating treatment effects on soil porosity, and possibly for some modelling applications where a higher level of accuracy is specifically required. For most other practical applications, the previously suggested sampling numbers should suffice.

The cost of some tests, for example the laboratory determination of field capacity and wilting point by pressure plates, will often limit sample numbers to the minimum in any case. Bulk density on the other hand is a cheaper test and the only limiting factor on sample numbers for the soil surface is the time available to sample.

## 6.6.2 Sampling equipment

The following is a list of necessary gear for sampling intact small soil cores for the determination of soil water retention and bulk density. The small core sampling field kit is also pictured in Photo 6.6.

#### *Preparation of sampling surface*

- Wet up gear (for wetting up a dry soil surface overnight)
- Garden spade
- Shovel
- Mattock
- Cane knife

#### *Sampling phase*

- "Tanner sampler guide" or alternatively a "slide hammer" setup
- Hammer
- Brass or stainless steel cylinder rings (70 - 100 mm diameter), cutting edge sharpened to a 5 degree angle
- A blank cylinder ring (as above but not sharpened).
- Pedology or trenching shovel (sample excavation)
- Trowel (sample excavation)
- Sharp knife (trimming soil)
- Sharp scissors

#### *Storage and transport*

- Plastic lids to fit rings
- Electrical tape
- Permanent marker pen
- Milk crate

Note that details of suitable samplers and sampling techniques are provided in McIntyre (1974a, b), as well as McKenzie and Cresswell (2002), and Dalglish and Foale (1998).

#### *Sampling ring (cylinder)*

The integrity of the soil core sample collected is dependant on the amount of compression and shattering from the sampling process, which is in turn largely dependant on the size of the sample and the soil water content (Chan 2002). Dealing with the soil water content issue is outlined in 6.6.3 step 1. The influence of sample size can be addressed by using as large a diameter sampling ring cylinder as practical. A diameter between 75mm and 100mm is thought to be a good compromise (McIntyre and Loveday 1974). The sampling ring should

## Small core sampling kit

- 1 Milk crate
- 2 Sampling cylinder rings
- 3 A collected soil core packaged ready for transport
- 4 Pedologists spade
- 5 Plastic lids
- 6 Electric tape
- 7 Marker pens
- 8 Tanner small core sampler (guide section)
- 9 Tanner sampler (inner section)
- 10 Hammer
- 11 Scissors
- 12 Sharp knives
- 13 Blank ring cylinder (no cutting edge)
- 14 Trowel



Photo 6.6. Field kit for sampling small intact soil cores for bulk density and soil water properties (Photo: J.Kemei, CSIRO).

ideally be of similar length to its diameter, but there are advantages associated with a shorter length if soil water retention work is planned for the cores (Cresswell 2002). A shorter length will mean a more rapid equilibration time for the soil core at each pressure plate tension. Sampling rings (cylinders) can be made from brass, aluminium or steel (mild, hardened, or stainless) tubing pipe which is cut to length before the cutting edge is sharpened to a half-angle of approximately  $5^\circ$  (McKenzie and Cresswell 2002).

The sampling ring cylinders used by CSIRO in Townsville for the CRC Sugar work had a

70mm diameter and were 50mm long. In this case the diameter was chosen to match the laboratory disc permeameters and therefore allow the option of this measurement for all cores collected. The shorter 50mm sampling ring length was chosen to help hasten soil core equilibration for soil water retention measurements.

### 6.6.3 Sampling procedure

#### Step 1 – Assessing topsoil moisture condition (wetting up the soil)

Once the representative pit location has been chosen (ideally based on a soil variability survey), the first task is to assess surface soil moisture at this site on the evening before the work begins. If it is dry, the surface will need to be wet up overnight using trickle irrigation as outlined in McKenzie and Cresswell (2002) and pictured in Photos 6.7 and 6.8 or 6.16.

The soil moisture condition is an important consideration when planning to do small core (7 cm x 5 cm) sampling for either soil water retention or hydraulic conductivity measurements in the laboratory. Ideally, small soil core sampling should be done at soil moisture conditions approaching but not exceeding the plastic limit of the soil (McKenzie and Cresswell 2002). Sampling at this moisture level will help minimise soil disturbance and shattering which can affect soil water retention or hydraulic conductivity measurements made on the cores. Soil moisture is considered adequate for soil core sampling when there is enough moisture in the soil for it to hold itself together when squeezed in the hand in the case of loams and clay loams or to be dented from applied pressure in the case of clays. If the soil is dry, it will need to be wetted up overnight. This is an option when characterising a small representative area such as a soil pit site, but it is not an option when there are plans to sample across a whole field area. In this instance the only option is to delay fieldwork until a later more opportunistic time after a rainfall event, ensuring a satisfactory moisture content for sampling.

The trickle irrigation setup pictured can be set to deliver 150 L of water over a 1.5 m x 1.5 m area (covering both the row and interrow areas in a cane field) over a 6 hour period. In our



Photo 6.7. A trickle irrigation setup designed to wet up dry surface soil overnight for small core sampling the following day. Trash is gently brushed away and the setup is placed over an area covering a section of both row and interrow.

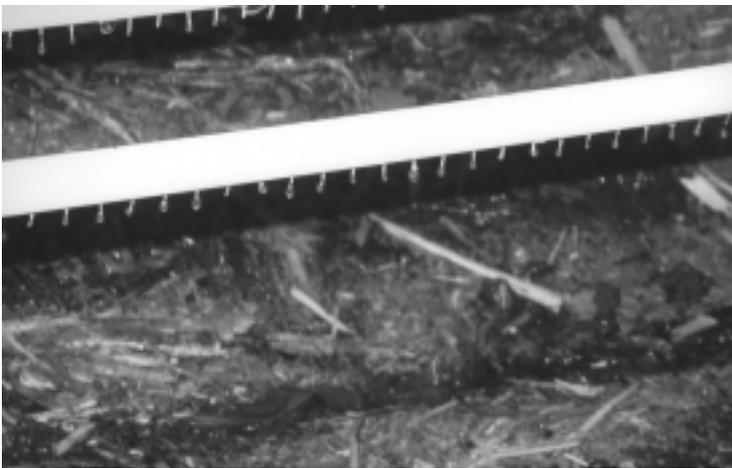


Photo 6.8. A close up of the micro-tubes on the trickle irrigation setup which allow water to be delivered to the soil as fine droplets, minimising any impact of wetting up on surface soil structure.

experience if the irrigation setup was started at 5pm, the surface would usually be ready for sampling (i.e. at the soil's plastic limit) by 3pm the following day after 16 hours drainage.

In our experience this approach is suitable for all soils except for cracking clays or Vertosols. For Vertosols, we found that the best sampling approach during dry times was to simply put the sampling off until a later date when the moisture conditions were right (i.e. following an extended period of rainfall). An alternative to this setup, which may well be even easier to fabricate, is that outlined by McKenzie and Cresswell (2002) where a drum of water gravity feeds a rectangular grid of dripper lines pegged onto the soil surface.

Subsoil layers below 20 cm in cane fields of Queensland always had enough moisture

content for core sampling in our investigations for CRC Sugar, so there was never any requirement for them to be wet up.

### Step 2 – Identifying horizons and preparing sampling benches.

The first step when digging a soil pit is to dig a short trench (2 m long x 0.75 m wide x 1.5 m deep) to allow the horizon boundaries to be identified and sampling depths to be determined (see Section 4.4.3). Once horizon sampling depths are determined, the rest of the pit can be benched back at these levels to create a flat surface for sampling. A backhoe can be used initially if available, or else they can be dug by hand (Photo 6.9). If only a small number of core samples are to be taken from a horizon or layer, a small bench just large enough can be cut out of the profile face (Photo 6.10). The surface of the layer to be sampled should be levelled and smoothed off with a spade prior to sampling. Smearing of the surface will not matter here even if the cores are planned for infiltration measurements as the cores should be hit in at least 1cm below this surface when sampled. The smeared surface will then be trimmed off. For soil profiles with abrupt horizon boundaries, the cores can be sampled at the top of the horizon in question. However where the

boundaries between horizons are gradual with significant areas of transition, it is then preferable to sample these horizons in their middle.

#### *Sampling the row and interrow areas in cane fields*

It is best to dig pits lengthwise along the interrow area and to take two separate sets of core samples from both the row and interrow areas for any soil layers occurring within the top 50 cm. This is because soil compaction in the interrow area by traffic can be significant down to around this depth. For subsoil layers below 50 cm, samples can be taken from the interrow area along the pit.

### Step 3 – Driving in the cores

Once the surface is prepared, ring cylinders can be placed on the surface to be driven in. Using



Photo 6.9. A soil pit with sampling benches cut in by a backhoe at depths close to the soil horizon boundaries. Surface preparation is simply finished off with a spade before sampling.



Photo 6.10. Sampling a lower horizon on a small ledge cut into the profile face.

the Tanner sampler, pictured in the field kit (Photo 6.6), the three legs of the guide are first driven into the surface to anchor the guide before the sampling ring is placed in it. A blunt blank ring of the same dimensions is then placed on top of the sampling ring. The metal collar is then placed on top of the blank ring inside the guide. The metal collar is then driven into the guide to a predetermined depth with a hammer set to ensure that the top of the sampling ring is at least 2cm below the soil surface at the end (Photo 6.12). Using a sliding hammer setup to hit the sampling rings, instead of a conventional hammer, can help reduce the risk of disruption to the core sample during this process. Core samplers and sampling techniques are described in detail in McIntyre (1974a, b).

Note that once rings are driven into the surface it is important to excavate the soil cores and process them for storage as quickly as possible. If the soil is allowed to dry before the cores are processed for storage, it may all have to be redone.

If laboratory soil hydraulic measurements are also planned, an additional four cores for unsaturated hydraulic conductivity, and a further four cores for saturated hydraulic conductivity can be taken from the surface (row and interrow) as well as from the most impeding layer (in addition to measurements done on these layers in the field).

#### Step 4 – Extracting the intact soil cores

Once all of the ring cylinders have been driven into the soil, it is time to begin carefully



Photo 6.11. Sampling rings placed on the row and interrow areas ready for sampling.



Photo 6.12. Hitting rings into the soil with a Tanner sampler.

excavating them. To begin the excavation, the first step is to create a soil edge in front of the cores which is at least 5 cm deeper than the depth that the bottoms of the rings were hit into the soil. Once this is done, a process of digging around the edges of the rings with a trowel can begin. What we found to be a successful strategy was to push a pedology shovel or a trowel under the ring (at least a few cm below the ring) and lever it before then inserting the pedology shovel next to the core and levering it from that angle while holding a spatula or trowel under the ring (in the soil 3 cm below the ring – see Photo 6.13). This procedure usually manages to extract the ring and its intact soil core with an additional few centimetres of excess soil above the top of the ring and below the bottom of the ring.



Photo 6.13. Extracting the sample ring with intact soil core contents.

### Step 5 – Trimming back the soil cores, transport and storage.

Excess soil material is trimmed off the cores with a sharp paring knife. The excess soil is cut off by cutting plum against the edge of the ring, while leaving a slight mound (0.5 cm) in the soil at the centre of the ring at each end of the core (Photo 6.14). This mound is left to allow for more precise trimming back at the laboratory as well as allowing for the surface to be picked back in the case of laboratory hydraulic conductivity measurements. Any strong roots protruding from the soil core can be trimmed back with a sharp pair of scissors.

When taking cores for bulk density only, it is common practice to fill in craters with soil and smooth it over when things go wrong trimming the core. This may be all right for bulk density but is not appropriate for cores collected for water retention or hydraulic conductivity measurements because structural integrity is important. For these cores, if any piece of soil falls off creating a crater in the core during the excavation or trimming processes, that core

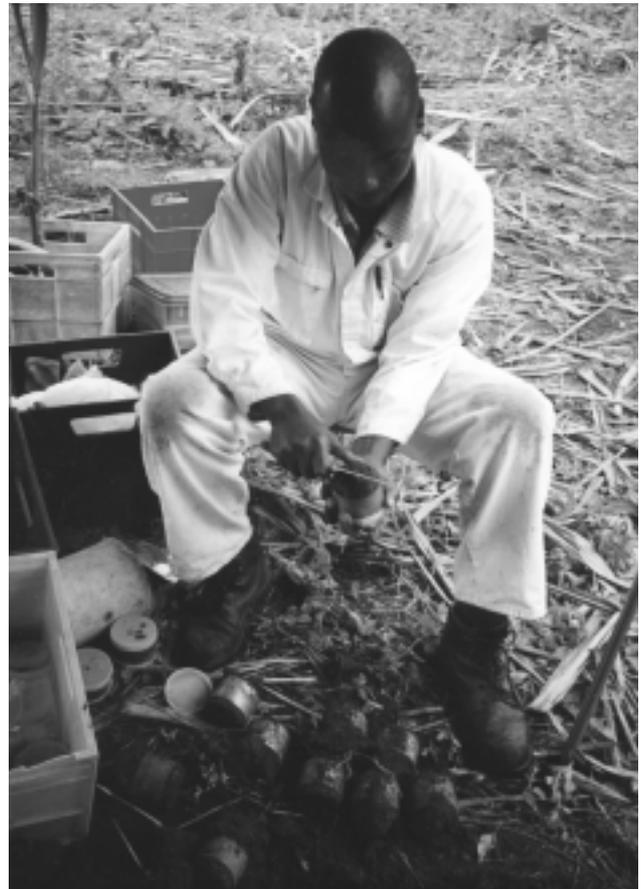


Photo 6.14 Trimming back the extracted soil cores. Note the trimmed soil cores already have their plastic lids on ready for sealing off with tape.

must then be discarded and another one collected.

Once trimmed back, a snug fitting plastic lid is then placed on each end of the ring containing the intact soil core. The lids are then taped on to each end of the rings with electric tape to secure them as well as to create a seal that prevents the soil cores drying out in transit (Photo 6.15). The packaged cores are labelled on the cylinder ring, noting site name, horizon and sampling depth, before being loaded in a milk crate and put in the shade. Once back at the laboratory, the core samples are stored in the fridge until they can be analysed.

For core samples taken for the measurement of bulk density alone, it is desirable to trim the cores back flat and flush at each end of the



Photo 6.15. Sealing soil core samples with a plastic lid and electrical tape helps prevent them from drying out before they get to the laboratory.

sampling ring cylinder. They can then be sealed and packaged for transport as above, or else have their soil contents emptied into a plastic bag for later drying and weighing. But emptying sampling rings of their soil core contents is a very time consuming process and is usually only done if supplies of sampling rings are limited.

## 6.7 APPLICATIONS OF BULK DENSITY MEASUREMENTS

The key applications of bulk density measurements are as an indication of soil structure and soil quality; a measure of aeration status; and for the conversion of gravimetric data to volumetric data (Chan 2002).

### Soil structure

Within a given soil material (of a particular texture grade) changes in bulk density will reflect changes in soil structure because of the relationship between bulk density and porosity. This relationship is complicated however for high shrink-swell soils whose bulk density also changes with moisture content. For these soils, any comparison of bulk density is only valid if the samples measured have the same water content (Chan 2002).

With increasing bulk density the strength of the soil tends to increase while porosity decreases, resulting in root growth eventually being limited at some critical bulk density value. For a given crop, this value varies with soil texture (Chan 2002).

### Aeration status

Bulk density allows the total pore space per unit volume (total porosity) of soil ( $\text{mm}^3 \text{mm}^{-3}$ ) to be calculated using equation 6.4. Knowing the soil's gravimetric water content and bulk density, volumetric water content can be calculated using equation 6.3. Air filled porosity ( $\epsilon_a$ ) can then be calculated using equation 6.5 (Chan 2002). Air filled porosity ( $\epsilon_a$ ) values between 0.05 and 0.15 ( $\text{mm}^3 \text{mm}^{-3}$ ) have been used as critical limits below which aeration is thought to be limiting to root growth (Stepniewski *et al.* 1994). Air filled porosity at field capacity ( $\text{AFP}_{\text{FC}}$ ) can be calculated using equation 6.6, and this provides an indication of the minimum volume of air available to plants during the wettest drained soil condition and as such may represent the minimum aeration capacity of the soil that the plant may experience for prolonged periods of time (Cass 1999). A critical value is thought to be around 10% or 0.10  $\text{mm}^3 \text{mm}^{-3}$  (Hall *et al.* 1977) below which the storage of oxygen is low and  $\text{CO}_2$  exchange is likely to be impaired

(Cass 1999). Hall *et al.* (1977) provide a system of evaluating the physical status of soils based on air filled porosity at field capacity in combination with plant available water data (PAW).

### Converting gravimetric data to volumetric data

Laboratory analyses of soil nutrients and water contents are usually expressed on gravimetric or weight to weight basis. To be of more use for decisions on land management this information often needs to be expressed on a mass per volume basis (Chan 2002). For example, to calculate the mass of soil nutrient in kg/ha to a depth of 20cm from a gravimetric laboratory result in mg kg<sup>-1</sup> (ppm), the formula would be:

$$A = \frac{L \times BD \times d}{10} \quad (6.12)$$

where

A = the mass of nutrient per area of land (kg / ha) to a soil depth of d cm

L = the laboratory result for the nutrient concentration in mg kg<sup>-1</sup> or ppm.

BD = the bulk density in g / cm<sup>3</sup> (same as Mg m<sup>-3</sup>)

d = depth of soil (cm)

#### Worked example

For a soil with bulk density (BD) of 1.5 g / cm<sup>3</sup> (BD = 1.5) and a laboratory result showing the soil has a concentration of 300 mg of nutrient per kg of soil (L = 300), the quantity of nutrient in kilograms per hectare to a depth of 20 cm (d = 20, the standard sampling depth for sugar industry soil testing) would be calculated as follows:

$$A = \frac{300 \times 1.5 \times 20}{10}$$

= 900 kg / ha

Therefore the laboratory result of 300 mg of nutrient per kg of soil is therefore equivalent to 900 kg/ha of nutrient for the 20 cm deep section of the soil in question.

One of the commonest uses of this calculation is for fertiliser recommendations, where the objective might be to raise the soil level of a nutrient by a certain number of mg per kg of soil. By substituting the required increase in

soil nutrient level value (mg kg<sup>-1</sup>) into the above formula along with values for BD and d, the amount of nutrient required to be applied on a kilograms per hectare basis can be calculated.

## 6.8 APPLICATIONS OF LABORATORY ESTIMATIONS OF DUL AND LL

The laboratory measurements listed below allow DUL, LL, SAT, and PAWC to be estimated for horizons from which small cores were taken (using the formulae already outlined). These properties are important for both irrigation scheduling and crop system modelling (e.g. APSIM).

Volumetric water content of a saturated soil core equilibrated to a matric potential of -10 kPa or 0.1 bar (estimate of field capacity moisture content)

Volumetric water content of a saturated soil equilibrated to a matric potential of -1500 kPa or 15 bar (estimate of permanent wilting point)

Soil bulk density

Using pressure chambers and tension plates in the laboratory to replicate DUL and LL conditions in small intact soil cores is one approach for obtaining values for DUL and crop LL. But we need to be aware that these values are only estimates or approximations and not actual measured values done in the field, as DUL and LL are after all field measured properties by their very definition (Section 6.2).

A method to measure these properties in the field is outlined in Section 6.9. This involves sampling a soil profile in the field at a time when field monitoring indicates field capacity (DUL) or wilting point (crop LL) conditions are present and then determining volumetric moisture contents.

### Irrigation scheduling

These data allow all of the parameters in Section 6.2 to be calculated. PAWC can be calculated for each soil horizon using the formulae presented earlier. Knowing the effective rooting depth (observed in pit), the actual plant available water (PAW) that the

plant has access to when the soil is at field capacity can be determined. Such information allows irrigators to determine how much water they will need to apply to return soil moisture levels back to field capacity when scheduling irrigation. Measurements of infiltration rate, either on soil cores or in the field (Section 7), can further assist irrigation scheduling by setting starting points for irrigation application rates for overhead sprinkler systems, to help minimise water losses due to runoff.

### **APSIM model inputs**

Results from the above measurements on small soil cores provide most of the required data for calculating soil water input parameters for the SOILWAT2 module of the APSIM model (DUL, LL, and SAT) [see APSIM data set Section 3.2.4. and also Section 8.3]. If the purpose of this information is to produce a soil input file for modelling with APSIM, then it is important that each soil horizon that is present in the soil profile down to the rooting depth is sampled. If the crop is only a recently planted crop or a 1st or 2nd ratoon crop, then the soil horizons down to what is estimated to be the potential rooting depth should be sampled.

As mentioned earlier, the laboratory estimate of lower limit (LL15) is thought to be an acceptable substitute for the soil moisture measurements associated with field induced permanent wilting point in sugarcane. This is because the -1500 kPa matric potential is believed to produce results close to that observed in the field (Inman-Bamber, pers.com. 2001). Consequently, this laboratory based approach is considered a justifiable alternative to the field monitoring approach outlined in Section 6.9.

The main advantage of the laboratory approach of estimating DUL and LL is that no soil moisture monitoring gear is required in the field, cores can be sampled at any time in the field, and bulk densities determined on these samples are usually highly accurate. It does not involve the same amount of time and effort as the field monitoring approach where field staff have to monitor soil moisture and infiltration until the DUL state is reached and also monitor crop condition until PWP or crop LL is reached. Monitoring can take many

weeks and involve specialist monitoring equipment (e.g. neutron moisture meter probe). This can be a real disadvantage if the site is a long distance from the home base of the staff and costs can sometimes mount up. The main disadvantages of the laboratory approach to estimating soil DUL and LL are the need to excavate a soil pit for sampling and the cost and slowness of laboratory testing, which can mean it is months before results are available.

### **Potential rooting depth**

The concept of 'potential rooting depth' or 'rooting depth' associated with determining potential available water capacity in a soil profile for a crop is very different to the concept of 'effective rooting depth' outlined in Section 4 Pedology. Potential rooting depth is taken as being the total depth the roots of a crop are likely to reach over their lifetime in a specific soil profile. To determine this, rooting depth can be observed in a soil pit excavation in a cane field with an advanced crop (last ratoon in cropping cycle). But if the investigation is at the beginning of the crop, an estimate will have to be made on the basis of the likely resistance the soil material poses to root growth (strength / consistency) and ideally also on local knowledge from root depth observations in previous soil pit excavations in the soil type in question. The author has made observations of sugar cane roots growing at depths of 2m+ in the bottom of soil pits. This is especially the case in the Burdekin catchment where a number of the soil types are underlain at depth by coarse textured soil materials which provide little resistance to root growth. There has been little work on the capability of sugarcane to extract water at depth (Inman-Bamber pers. com. 2002), so the contribution of such roots to water extraction is still largely unknown. Roots are believed to be effective in extracting water at all depths and may even be more effective at depth than at the surface in terms of uptake per unit length (Inman-Bamber pers. com. 2003). Water extraction by sugarcane crops at depths well below 2 m has been recorded in red kandosol soils in the Childers area (Geoff Inman-Bamber, pers. com. 2003). In the absence of any obvious maximum rooting depth in the soil pit profile due to impeding soil layers, the maximum sampling depth in the case of soil pit sampling

may have to be taken as 180cm. This is based purely on the practical limitations of sampling. A soil pit excavation is limited to a depth of 150cm on the basis of OH and S grounds. With the addition of a small 30cm deep excavation within the pit floor, the sampling depth could be extended to 180cm. Even using the current larger thin walled steel push tube design for bulk density and moisture sampling for the field monitoring method (Section 6.9), sampling is limited to a depth of 180cm.

For the field monitoring method, which does not use a soil pit excavation for sampling, the only opportunity to assess the rooting depth of the crop is by taking long push soil cores in the row area (perhaps during installation of the access tube for water monitoring) and hoping that crop roots are captured in the sample. If there is evidence of roots continuing down past the bottom of the excavated soil cores, there may be an argument for installation of access tubes deeper than 2m for monitoring soil moisture. But to get valid soil moisture and bulk density samples below this depth would prove very difficult using conventional sampling gear. Having said that, it is possible to imagine a need to monitor soil moisture in cane crops to depths of up to 3 metres in some cases, using neutron moisture meter (NMM) or other moisture measuring equipment, in order to fully account for the moisture uptake from the soil.

One method of obtaining DUL and LL data below 180 cm is to use a jackhammer sampler as outlined in Section 4 to collect a 1.5 m core at the bottom of the soil pit. This core could then be sliced up and have its bulk density estimated using the approach outlined in Section 6.9, while the DUL and LL could be estimated in the laboratory using loose soil samples. Although not ideal, this approach would at least provide a 'rough estimation' of DUL and LL from the depths of 180 cm to 300 cm, which would be much better than no information at all.

## 6.9 FIELD MONITORING METHOD OF MEASURING DUL AND LL

The field monitoring approach involves firstly inducing field capacity (DUL) and wilting

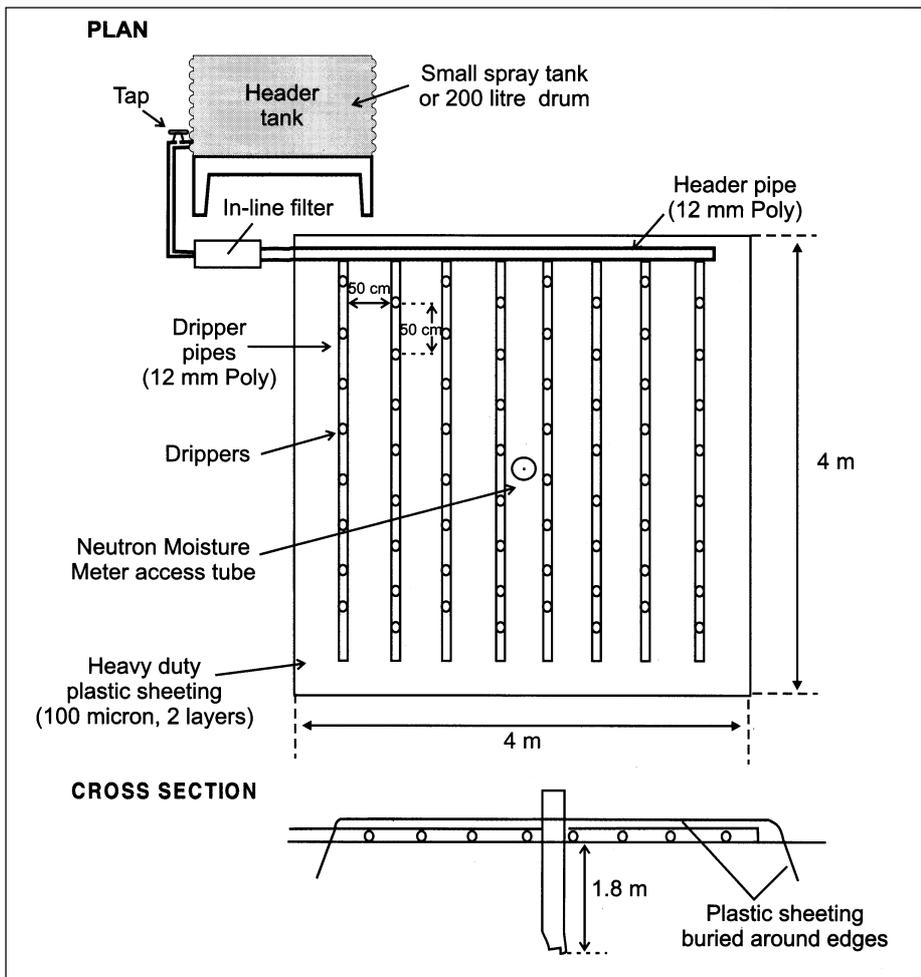
point (crop LL) conditions in a section of soil in the field and then taking soil core samples to the depth required, which is based on the potential depth of rooting of the crop (Dalglish and Foale 1998). For sugarcane the default maximum sampling depth is usually taken as 180cm, for the reasons already discussed in the previous section on the laboratory method. Soil cores are sampled at set depth increments and are assessed for gravimetric soil moisture content and bulk density. This is the method outlined by Dalglish and Foale (1998). It was developed for the uniform to gradational black cracking clay soils of the Darling Downs region of Queensland.

### Determining field capacity or DUL in the field

For this method, field capacity or drained upper limit is induced in the soil profile by either creating a circular soil bund area (1.5 m radius) and filling it with water or by wetting up the soil with a small trickle irrigation setup (4 m x 4 m) supplied by a drum or tank (Photo 6.16 and Figure 6.2). Alternatively, one can wait until the site's soil profile wets up to saturation by natural rainfall and then simply monitor the soil profile until DUL conditions are present. The point at which the soil profile is at field capacity or drained upper limit is determined by monitoring changes in moisture levels in the soil profile with a neutron probe (Photo 6.17). Field capacity is taken as the point where negligible drainage occurs after the profile has been saturated. Negligible drainage is taken to mean < 1mm per day (Cassel and Nielson 1986, Dalglish



Photo 6.16. A trickle irrigation setup suitable for wetting up the soil at a sampling site. (Courtesy of Neal Dalglish, APSRU, Toowoomba)



**Figure 6.2.** Layout of the trickle irrigation setup with the tank supplying water to the trickle dripper pipes which are covered by plastic sheeting to stop evaporation (Dalglish and Foale 1998, © CSIRO 1998)



**Photo 6.17.** Monitoring the progress of wetting up a soil profile using a neutron moisture meter probe (NMM). (Courtesy of Neal Dalglish, APSRU, Toowoomba)

and Foale 1998). Cass (1999) emphasises the importance of excluding evapotranspiration from this process, which can be achieved by laying a plastic sheet over the soil surface at the monitoring area, as shown in Photo 6.17.

Dalglish and Foale (1998) emphasise the importance of correct calibration procedure if a neutron moisture meter (NMM) is used for this purpose. A neutron moisture meter (NMM) has to be calibrated to measure soil moisture content for the particular soil type under investigation. An accurate calibration equation can be derived for a particular soil type from data sets of NMM readings and corresponding actual soil volumetric water contents for when the soil is dry (often at access tube

installation), when the soil is wet, and at a number of intermediate water contents (Dalglish and Foale 1998). Additional information on the use of the neutron moisture meter probe (NMM) and other soil water monitoring equipment is also outlined in Charlesworth (2000). Operator manuals should be consulted before using such equipment. It should be noted that the neutron moisture meter does have some OH and S issues related to usage and monitoring of radiation exposure. Local worksafe authorities should be consulted for procedures and guidelines in this regard.

### **Determining the crop lower limit in the field**

The crop lower limit (LL) or wilting point can be induced in a crop with the use of a rain shelter (Photos 6.18 and 6.19). This methodology is outlined in detail in Dalglish and Foale (1998). It basically involves inducing wilting in a crop by placing a rain shelter over the crop and excluding runoff water from the



Photo 6.18. A rain exclusion tent being used in a cotton crop to ensure the eventual occurrence of wilting point conditions in the soil. Note the provision of air vents at the apex of both ends of the tent to allow the flow of moist air out of the tent. (Courtesy of Neal Dalgliesh, APSRU, Toowoomba).



Photo 6.19. Perspex inserts are fitted to the rain exclusion tent rooftop to improve light to the growing crop. (Courtesy of Neal Dalgliesh, APSRU, Toowoomba)

crops under the shelter with trenches and mounds around the tent. Air vents are also a feature at the base of both ends of the rain shelter tent to allow moist air to flow out of the tent. At permanent wilting point, three soil cores are taken to crop potential rooting depth or a maximum of 180cm. Bulk density and gravimetric water content are determined for each sample to allow volumetric water content to be determined for each depth interval down the core. Since evaporation can dry the soil in the top 30cm to below the crop LL, Dalgliesh and Foale (1998) recommend adjusting the water contents in the top 30cm to equal those in the soil layer immediately below 30cm.

### Sampling the soil with extra large diameter push tubes

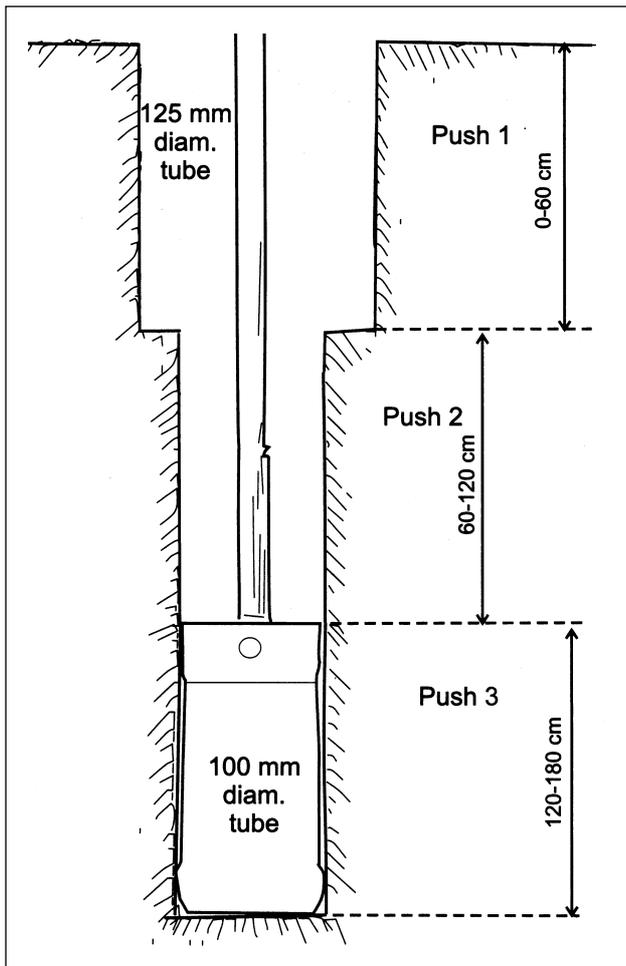
When DUL or CLL conditions are judged to be present in the soil by field monitoring, the soil is sampled using specially designed thin walled steel push tubes which are quite wide (75 mm, 100 mm and 125 mm ) and short (60 cm) in order to minimise core compaction (Photo 6.20). These tubes are usually well lubricated with oil before sampling to increase the chances of the soil core being removed later in an intact undisturbed condition. When sampling with the wide steel sampling tubes pictured in Photo 6.20, the 0-60 cm soil core sample is taken with the widest sampling tube (125 mm) followed by

the 100 mm tube and then finally the 75 mm sampling tube, which takes the 120-180 cm deep sample (Figure 6.3, overpage). The core is usually pushed out of the tube using a pole with a flat base attached to its end to avoid damaging the soil core.

It is best not to use sampling tubes less than 75 mm in diameter for this type of sampling because the narrower sampling tubes are much more prone to cause compaction of the sample.



Photo 6.20. The larger diameter soil sampling tubes used for bulk density and moisture sampling to determine DUL and CLL in the field. (Courtesy of Neal Dalgliesh, APSRU, Toowoomba).



**Figure 6.3.** Sampling for bulk density using wide coring tubes of different diameters. (Source: Dalgliesh and Foale 1998, © CSIRO 1998)

The first step once the soil core is removed from the sampling tube is to assess it for evidence of soil compression from the sampling. The 'recovery ratio' needs to be calculated for each core sample taken. The formula for this (McKenzie and Cresswell 2002) is:

$$\text{Recovery ratio} = \frac{\text{length of core specimen sampled}}{\text{depth of hole from which core was removed}} \quad (6.9)$$

The recovery ratio value needs to be greater than 0.98 to allow a valid mean value of bulk density to be calculated from these samples (Bridge 1981). In some soils with a high bulk density, expansion can occur in the sampled core. If this occurs, Dalgliesh and Foale (1998) recommend adjusting the lengths that these cores are cut for samples in proportion to allow for this expansion, especially if the recovery ratio value is greater than 1.2.

Typically, soil cores are sliced up and sampled

at set depth increments. Mazzucchelli *et al.* (1997) recommend sampling depths of 0-15, 15-30, 30-45, 45-60, 60-90, 90-120, 120-150 and 150-180 cm. Each soil sample is weighed on an electronic balance in the field, its volume is determined from measurements of the sampling tube diameter (internal diameter of the cutting edge) and sample length. When the use of an electronic balance in the field is not an option, the sample should be placed in an air tight sealable container for transport back to the laboratory for later weighing. Electrical tape can be wrapped around the lid of the container as extra insurance against moisture loss. The sample is later oven dried at 105°C for 48 hours and again weighed to allow the determination of gravimetric water content, bulk density and then, from these, volumetric water content (Dalgliesh and Foale 1998). Soils with strongly developed soil horizons and soil layers with only a weak coherence present some difficulties for this method and this is discussed in the following section.

The resultant values of DUL and crop LL for the soil profile can be combined with average soil nutrient level data to this depth to produce a soil input file for modelling with APSIM (see Section 8 modelling applications). It must however be stressed that mineral nitrogen levels must come from a separate more comprehensive sampling where samples are kept cool in a fridge or esky in the field. Mineral nitrogen certainly cannot be determined on the oven dried DUL and LL samples as much of the nitrogen in these soil samples would have been driven off in the oven drying process.

### **Problems in applying the field monitoring methodology to sugarcane soils**

The field monitoring approach to measuring DUL and LL documented by Dalgliesh and Foale (1998) is well suited to assessing soils that are both coherent (usually heavier than a loam) and have a soil texture profile that is uniform or only gradually increases in clay content with depth (gradational). This would include some of the deeper cracking clay soils in the Home Hill area of the Burdekin, some of the uniform and gradational textured kandosol, dermosol, and ferrosol soils, as well as the uniform clay soils common in the back swamp locations in

many of the alluvial floodplains up and down the coast.

It is, however, quite common for sugarcane soil profiles to consist of a series of distinctive layers of soil materials of contrasting texture overlying each other with each soil layer having an abrupt boundary between it and the next layer. Sometimes this is the impact of past alluvial processes on the formation of these soils, as much of Australia's sugarcane is grown on coastal floodplains and deltas. Loose incoherent sand bands are also common in alluvial soil profiles. Abrupt horizon boundaries between very different textured soil materials in a soil profile present difficulties for the soil sampling approach associated with this method and some of these difficulties are outlined below.

#### *Sampling difficulties*

The presence of distinctive soil horizons as well as loose sandy layers presents a number of problems for the Dalgliesh and Foale (1998) approach in which the soil is sampled with a series of push core samples, which are then cut into set depth increments for moisture content and bulk density assessment. The first of these problems is the fact that set depth increments will result in sampling which cuts across soil boundaries. This can produce spurious results where layers of contrasting textures are combined in a single sample.

The second problem associated with this approach relates to the difficulty of obtaining credible bulk density results from samples that are taken by slicing up such cores. There are difficulties associated with the possible compaction of the soil profile by this sampling technique. There are also practical problems associated with extracting the core from the tube in an intact state, especially where loose sandy materials are involved, making any sampling for bulk density and moisture content suspect and unreliable.

#### *Shallow water table complications to determining crop lower limit.*

The effect of groundwater uptake on wilting point determination is another complication with sugarcane fields which are often located low in the landscape and commonly have perched water tables present in sandy layers.

These supplementary supplies of water to the crop can make it very hard to induce wilting conditions in the field using rain shelters. Shallow water tables are believed to be quite common in sugarcane areas (Sweeney *et al.* 2001). In this situation, the only option may be to sample the soil profile with small cores and then estimate the lower limit in the laboratory (LL15). This will at least allow the PAWC of the soil to be calculated. But the difficulty for modelling the soil water balance and crop production remains, due to the contribution of this external source of water which is difficult to characterise. The application of the DUL / LL model in the SoilWat2 model is not valid in this instance.

Additional monitoring of water table heights throughout the year using installed piezometers may provide some enlightenment as to the duration and seasonality of this potential contribution if the crop's rooting depth is known as well. For research on crop water use it may be best to simply avoid these areas. This can be done by assessing a potential site during a wetter time of the year by extracting a few 1.5 m deep soil cores from the site and then observing any evidence of a watertable in the holes created.

#### *Difficulties in using rain exclusion tents in sugarcane crops*

The sheer height of advanced sugarcane crops makes the use of rain exclusion tents very difficult if not totally impractical. The main problem is that the height required for a tent to cover a cane crop tends to make the tent unstable and prone to toppling during windy periods, which are quite common in the tropics during the wet season (Geoff Inman-Bamber, pers. com. 2003).

#### **Recommended amendments to the sampling procedure**

For the reasons outlined above, two important modifications to the methodology of Dalgliesh and Foale (1998) are recommended in order to make the method more suitable for research in sugarcane soils. These modifications are the adoption of (i) "horizon based" sampling of cores, and (ii) additional soil pit cores for bulk density in soil profiles containing unconsolidated loose sediments. An

explanation of how these modifications can be incorporated into the methodology of Dalgliesh and Foale (1998) to help overcome some of these soil sampling difficulties is provided in the following section.

#### *Horizon based sampling depths*

The first of these modifications relates to the soil sampling procedure once field monitoring has confirmed that DUL or CLL conditions are present in the soil. It is suggested that the first step before sampling should involve taking a 5 cm diameter x 150 cm long soil core (or ideally a 180cm long soil core) immediately adjacent to where the soil samples are to be collected. This core is used to identify soil horizons and determine the depths of horizon boundaries (as per method outlined in Section 4.4.3). Once horizons and their depths have been identified, suitable sampling depths based on horizon boundaries can be chosen for the samples which will be taken in subsequent cores. The main objective is to make sure that the sample depth ranges will fall within the horizon boundaries. It is probably best to choose sampling depth intervals that are in the middle of horizons rather than near the boundaries. Additional samples may also be considered for very thick soil horizons or ones showing signs of gradational texture change. Samples can be as few as only one 10 cm long section within a soil horizon or alternatively samples can be taken at a number of depth intervals as long as they fall within the boundaries of each horizon and do not cross over boundary points. It is obviously preferable to sample as much of the soil material in the layer as possible. The main point is to make sure that the sampling depth intervals all fall within the horizon's boundaries.

Once the horizon based sampling depth intervals have been chosen, sampling using the wider diameter sampling tubes can commence in an area within 50 cm of where the first soil core was taken to determine the horizon depths.

#### *Supplementary pit based bulk density samples*

To overcome problems associated with determining bulk density on unconsolidated loose soil core samples, it may be possible to use the disrupted sample from the wide push tube core to determine only the gravimetric soil

moisture content at CLL, and then to take a separate small soil core sample by hand from a later pit excavation at the site for a more accurate bulk density determination. The bulk density from the small core sample from that horizon could then be combined with the soil moisture data from the original disrupted sample to calculate volumetric soil moisture content at CLL or DUL for that horizon. This approach offers the best of both worlds by overcoming the difficulties of determining bulk density from often loose push core samples while obtaining the benefits of quick results associated with simple laboratory determinations (bulk density and gravimetric moisture content versus soil water retention).

#### *Using the laboratory estimate of crop lower limit (LL15)*

Given the difficulties in using rain exclusion tents in sugarcane crops, it may be preferable to take additional cores when sampling for DUL and to sample each layer in these additional cores for bulk density before then taking a separate sample for the laboratory estimation of crop lower limit by equilibrating a saturated soil sample to 1500kpa (LL15).

## **6.10 MODEL INPUT FILES**

For more information on how to process and bring soil water retention and bulk density data together and combine it with other soil data (e.g. soil chemistry) to produce a soil input file for modelling, refer to Section 8, Modelling applications.

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# SECTION 7. Measuring infiltration in soils

Measurable properties associated with infiltration have important practical applications to irrigation scheduling as well as being important data requirements for commonly used hydrology models (e.g. SWIMv2, HYDRUS). The intention of this section is to provide a brief outline of basic infiltration theory and methods of measuring infiltration which are relevant to the sugar industry. For a more detailed treatment of the soil physics associated with infiltration refer to soil physics texts such as Marshall *et al.* (1996) or Hillel (1998). A key reference for methods of measuring these properties is 'Soil Physical Measurement and Interpretation for Land Evaluation' (McKenzie *et al.* 2002a). Geering (1991) is another useful reference.

## 7.1 Soil water infiltration – basic theory

### Hydraulic conductivity

Hydraulic conductivity (K) is a measure of the ability of a soil to transmit water. It is the flow rate per unit area (m/sec or mm/hr) of water transmitted through the soil at a hydraulic head gradient of -1.

Saturated hydraulic conductivity is measured when the soil is fully saturated with water, while measurements of unsaturated hydraulic conductivity are carried out when the water content of the soil is less than saturation.

### Darcy's Law

Darcy's Law is fundamental to most calculations of hydraulic conductivity as it describes the movement of water through saturated and unsaturated soils at a constant water content.

The formula for this is:

$$\frac{Q}{A} = -K \frac{d\psi}{dx} \quad (7.1)$$

where Q is the flow rate, A the cross sectional

area, K the hydraulic conductivity and  $d\psi/dx$  is the potential gradient. McKenzie and Cresswell (2002a) note that the main practical difficulty with applying this theory is the requirement for it to be applied at a scale which enables the average properties (k,  $d\psi/dx$ ) to be derived. The variability associated with macropores, soil structure, impeding layers and cracks often results in the notional representative elementary sample volume being impractically large (McKenzie and Cresswell 2002a). Darcy's Law assumes that the moisture content is uniform and constant throughout the soil medium, but the reality is that soil moisture content varies and unsaturated conditions are most common. To deal with predictions of soil water movement under these conditions the Richards equation was developed.

### Richards' equation

The Richards equation (Richards 1931) is a flow equation which was derived by combining Darcy's Law with the principle of conservation of mass. The one dimensional form of the flow equation is:

$$\frac{d\theta}{dt} = \frac{d \left[ K \frac{d\psi}{dx} \right]}{dx} \quad (7.2)$$

where  $\theta$  is soil volumetric moisture content, t is time, K is hydraulic conductivity and  $\psi$  is soil water potential. The Richards equation is used in the SWIM simulation model (Verburg *et al* 1997) and this is discussed further in section 8 on modelling.

### Soil water movement in unsaturated soil

In unsaturated soils the larger macropores are filled with air, leaving only the finer pores to accommodate water movement. The driving force for unsaturated water flow is the matric potential gradient (the difference in matric potential ( $\psi_m$ ) between the moist areas and the dry areas into which water is moving). Matric potential of the soil is the suction

exerted by the dry soil on the soil water due to forces of capillarity and adhesion. The unsaturated hydraulic conductivity (K) is continually changing as the soil matric potential changes with soil moisture ( $\theta$ ). Unsaturated hydraulic conductivity is most commonly measured with a disc permeameter under suction (negative head) where the soil has to draw the water out of the disc permeameter. The size of the soil pores contributing to the water flow is determined by the suction applied (Table 7.1).

**Table 7.1.** A comparison of the pore sizes contributing to water flow under the different methods (adapted from Hazelton and Murphy 1992)

| Method of measuring K | Diameter of the largest pore size contributing to water flow (mm) |
|-----------------------|---|
| Ponded (Ksat)         | All pores regardless of size                                      |
| Suction (-1cm) (K1)   | 3.0   |
| Suction (2cm) (K2)    | 1.5   |
| Suction (-4cm) (K4)   | 0.75  |

Contents of the above table are based on the generalised relationship (Craze and Hamilton 1991):

$$\text{Pore diameter (mm)} = \frac{3.0}{\text{soil water tension (cm)}}$$

### Soil water movement through saturated soil

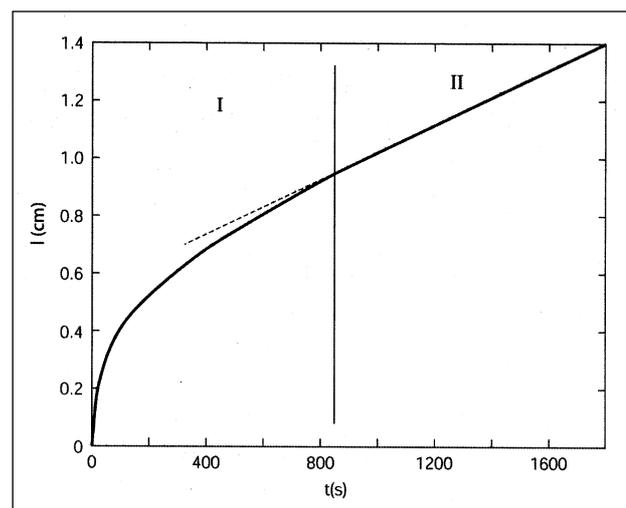
In saturated soils almost all pores (both large macropores and smaller pores) are filled with water and the dominant forces driving water through saturated soils are gravity and hydraulic pressure (depth of surface water etc).

The hydraulic conductivity of a saturated soil (Ksat) with a stable structure is constant or steady, since the whole of the pore space is always water – filled (Marshall *et al.* 1996). The Ksat of a soil is normally determined from infiltration measurements under ponded or positive head conditions to ensure all pore sizes are contributing to the water flow. This involves a ring infiltrometer setup.

### Infiltration in the field

The reality of water infiltration in the field is obviously a complex combination of steady

saturated flow and unsteady unsaturated flow (Marshall *et al.* 1996). In the early stages of infiltration, the rate of water movement into the soil is dominated by capillarity (sorptivity) until a steady infiltration rate is reached. At this point gravity and flow geometry are the dominant influences (Figure 7.1). But even the steady state flow associated with saturation has a component of it accounted for by capillarity (Cook 2002). This is due to the capillarity affects around the edge of the 3D wetting front.



**Figure 7.1.** Graph of cumulative infiltration versus time. Area 1 is the infiltration prior to steady state flow and also includes the very initial infiltration period dominated by sorptivity. Area II is where steady state flow has been reached. The steady-state flow is calculated from the slope of the straight line in area II of the graph. (Sourced from Cook 2002, © CSIRO 2002)

### Rating soil infiltration measurements

Without experience in measuring infiltration rates on a broad range of soils it is difficult to know how a soil's infiltration rate compares with that found on other soils. Table 7.2 provides a list of relative ratings expressed in various measurement units to help with this.

**Table 7.2.** A table of relative ratings for hydraulic conductivity across the broad range of measurement units used (sourced from McKenzie and Cresswell 2002a)

| Rating         | Measurement units |        |                      |         |
|----------------|-------------------|--------|----------------------|---------|
|                | mm/hr             | mm/day | m/s                  | m/day   |
| Extremely slow | 0.01              | 0.24   | $2.8 \times 10^{-9}$ | 0.00024 |
| Very slow      | 0.1               | 2.4    | $2.8 \times 10^{-8}$ | 0.0024  |
| Slow           | 1                 | 24     | $2.8 \times 10^{-7}$ | 0.024   |
| Moderate       | 10                | 240    | $2.8 \times 10^{-6}$ | 0.24    |
| Fast           | 100               | 2 400  | $2.8 \times 10^{-5}$ | 2.4     |
| Very fast      | 1000              | 24 000 | $2.8 \times 10^{-4}$ | 24      |

## 7.2 IMPORTANT SOIL FACTORS TO CONSIDER

There are several soil factors that have an important influence on soil hydraulic conductivity measurements. Some more important ones are macropore spatial variability, vertic properties (high shrink-swell cracking soils), aggregate stability, water repellence, profile water content and the presence of impeding subsurface soil layers close to the surface (McKenzie and Cresswell 2002a).

### Macropores

The importance of larger pores for the hydraulic conductivity of soil can be appreciated when one considers that the total flow rate in soil pores is proportional to the fourth power of the radius. As a consequence the flow through a pore 1 mm in radius is equivalent to that which occurs in 10,000 pores with a radius of 0.1 mm, even though it only takes 100 pores of radius 0.1 mm to give the same cross-sectional area as a 1 mm pore (Brady 1990). Table 7.3 presents some measurements on surface soils at different suctions to illustrate this point. The contribution of macropores to saturated flow (ponded K<sub>sat</sub>) is very evident as the soil on the cane row, with abundant macropores, drains a lot faster than the highly compacted soil in the

**Table 7.3.** Measurements of K at -2 cm and -4 cm suction and ponded K<sub>sat</sub> on surface samples from the row and interrow area on a light clay, near Kalamia, Burdekin catchment

| Method of measuring K  | Cane row (surface) K (mm/hr) | Cane interrow (surface) K (mm/hr) |
|--|------------------------------|-----------------------------------|
| Disc permeameter Suction (-4 cm) (In lab on small cores r = 3.5cm) | 2.33                         | 0.30                              |
| Disc permeameter Suction (-2 cm) (In lab on small cores r = 3.5cm) | 2.61                         | 0.32                              |
| Ponded (K <sub>sat</sub> ) (In field, ponded ring r = 15cm)        | 314                          | 1.6                               |

interrow area. The pores have allowed a fast rate of infiltration (314 mm / hour) through a fine textured clay soil which would otherwise have a very slow drainage, as is evident in the interrow K<sub>sat</sub> result of 1.6 mm/hr. Obviously the relative influence of macropores on K<sub>sat</sub> may be less drastic on coarser textured soils such as sands and sandy loams where there can be numerous large spaces already present in the soil material due to the packing of these coarser particles.

### Vertic properties

Although cracks have a major influence on infiltration, they also cause big problems for current methods of measuring hydraulic conductivity. As such, the only reliable measurement of hydraulic conductivity on high shrink-swell soils is that which can be done when the soil is moist and the cracks absent. There are however some infiltration models (Collis-George 1980, Cook *et al.* 1989) which include a crack filling term. It would be worthwhile to refer to these models when investigating infiltration in cracking soils.

### Aggregate stability

Slaking and dispersion will reduce a soil's hydraulic conductivity. Problems with slaking can be minimised by carefully wetting up the soil, while dispersion may be overcome by using a 0.01M CaCl<sub>2</sub> solution for the infiltration measurements (McKenzie and Cresswell 2002a).

### Water repellence

Water repellence tends to be more of a problem for lighter textured soils such as sands and loams. If present, it is best to eliminate the effects of water repellence on soil hydraulic conductivity by carefully pre-wetting the soil surface before measurements (McKenzie and Cresswell 2002a).

### Profile antecedent moisture content

A uniform soil moisture profile is a theoretical requirement for measuring soil K. Flexibility in fieldwork schedules is required to allow measurements of K to be made when moisture conditions are appropriate (McKenzie and Cresswell 2002a).

### Impeding subsurface layers

The presence of impeding subsurface layers such as clay pans, hard pans and B horizons close to the surface (<20 cm deep) can also have an impact on hydraulic conductivity measurements done on the surface. This is especially the case for texture contrast or duplex soil profiles where, for example, a rapidly draining shallow light textured sandy loam topsoil may overlie a medium clay subsoil which is impermeable. In this situation, a bottle neck in the drainage is likely to develop at the top of the impermeable layer when the wetting front below the infiltrometer reaches this point. Such a change should be detectable in the data. In this situation it may be more effective to take core samples from the soil surface layer and determine hydraulic conductivity (K) in the laboratory later.

### Important crop / land management influences

Any plan to assess infiltration in a cropped field needs to take into account the likely influences of agricultural practices on the measurements. In sugar cane fields for example, it is important to be aware of what stage of the crop cycle the sugarcane is at in the field, the differences between row and interrow surface areas due to compaction effects, and the influence of tillage practices. These factors need to be taken into account to ensure that measurements are both representative and valid for the field in question. (Refer to Section 6.5 for a more detailed discussion of these factors).

## 7.3 MEASURING SOIL HYDRAULIC CONDUCTIVITY

All effective methods of determining saturated hydraulic conductivity of a soil ( $K_{sat}$ ) involve measuring conductivity under a positive head (ponded measurements of infiltration). This is to ensure that all of the different sized macropores are contributing to the infiltration being measured. Two methods which are useful for sugarcane investigations are the single ring (cylinder) infiltrometer and the twin ring infiltrometer methods (Scotter *et al.* 1982) and these are covered in more detail in a later section. A number of researchers have reservations about the once popular double

ring method and these are discussed in the section on sorptivity.

Unsaturated hydraulic conductivity ( $K_{us}$ ) is measured under a negative head (suction) using a disc permeameter. This effectively eliminates larger sized macropores from participating in infiltration (Table 7.1) and can be very useful for comparing the impacts of agricultural practices on the infiltration of two different sites. Table 7.3 illustrates the impact of excluding larger macropores on hydraulic conductivity. The Reynolds and Elrick (1991) method of determining  $K_{us}$  that was recommended by McKenzie and Cresswell (2002a) is presented in detail in a later section.

### 7.3.1 Spatial variability in infiltration

A high degree of spatial variability in infiltration rates across a field or paddock is quite common. It is due largely to variations in the abundance and size of macropores across the field, which is in turn due to variability in soil macrofaunal activity as well as root growth. Such variation does not only occur laterally across the paddock surface, it is also present in a vertical direction down through the soil profile. Variation in the vertical direction reflects the activities of burrowing soil fauna and root growth, as well as natural changes in soil morphology (e.g. soil texture, structure) associated with soil formation and development.

The reality that soil infiltration rates are usually highly variable spatially, means that a large number of infiltration measurements (often >20) are required to obtain a reasonably accurate estimate of the mean field soil hydraulic conductivity (see Section 7.3.3).

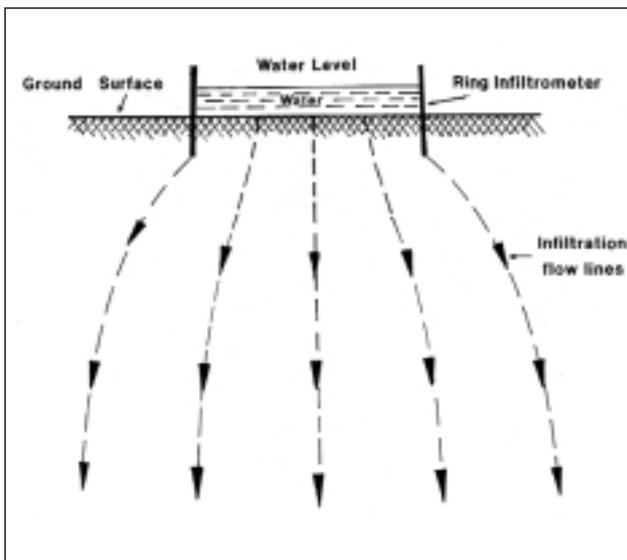
### 7.3.2 Soil capillarity (sorptivity)

The sorptivity (S) of a soil has a significant influence on its hydraulic conductivity. It results in a lateral divergence in the flow of water under the infiltrometer (Figure 7.2). Dry soil surrounding the saturated wetting front in effect exerts a suction force (matric potential) on the wetting front, drawing it out. This results in the infiltrometer measurements overestimating the true vertical infiltration rate. Thus the influence of sorptivity needs to be

measured or accounted for in order to determine hydraulic conductivity accurately. Two approaches are discussed in the following sections.

### Very large infiltrometer ring (Ksat)

One approach is to try to physically minimise the influence of sorptivity on infiltration measurements. This can be done by making the infiltrometer ring as large as possible. This approach is based on research results which show that soil sorptivity or capillarity is strongly related to the infiltrometer ring circumference ( $2\pi r$ ) while gravitational force is related to the area within the ring through which the water flows ( $\pi r^2$ ) (Cook 2002). Any increase in ring diameter will therefore decrease the effect of capillarity on steady state flow (Cook 2002). But without any measurement of sorptivity, results from the very large ring approach will always have a question over them in terms of the unknown impact of sorptivity. The width of cane rows also tends to rule out this approach as it limits the size of a ring which can be installed to a diameter of only 50cm.



**Figure 7.2.** Lateral divergence in the flow of water under the ring cylinder due to soil capillarity and adhesion (adapted from Bouwer 1986)

### Double ring (Ksat)

Another approach is to try to keep the soil in the area around the infiltrometer ring saturated during the infiltration measurements, in an attempt to negate the impact of sorptivity on steady-state flow in the ring area where

measurements are taken. This is the approach taken by the double ring method, which involves putting a smaller ring cylinder (the one to be used for infiltration measurements) concentrically inside a bigger ring cylinder also filled with water (Photo 7.1). This approach is not currently in favour as Bouwer (1986) noted a number of studies which question its success in minimising the effects of capillarity (e.g. Bouwer 1961, Swartzendruber and Olson 1961a, 1961b, Burgy and Luthin 1956).



**Photo 7.1.** The once popular double ring set up for measuring Ksat. (Photo: Lowan Turton, NSW Agriculture)

### Measuring sorptivity

The conventional way of dealing with sorptivity by measuring it is based on the method proposed by White *et al.* (1992) and involves obtaining  $S$  from the very first measurements at the earliest stages of infiltration.  $S$  is determined from the slope of the straight line portion of the graph of cumulative infiltration versus the square root of time.

This is the approach used for  $K_{sat}$  calculations for the single ring method and is discussed in more detail in the later section on this method. It is worth noting that both Cook (2002) and McKenzie *et al.* (2002b) note some important deficiencies with this method. One of these is the fact that the time for which capillarity dominates the flow process can be very short and as such it can be difficult to capture the sorptivity in the early measurements. Another is the fact that the capillarity at the wetting front when steady-state occurs may be different from that experienced at the surface when the sorptivity was measured, if there are water content or soil structure changes with depth.

### Methods not requiring a direct measurement of Sorptivity (S) to determine K

Two methods which do not require a direct measurement of S are the twin ring method for determining K<sub>sat</sub> and the Reynolds and Elrick (1991) method of determining unsaturated hydraulic conductivity (K<sub>us</sub>). Both of these methods use the steady-state infiltration rate only. The twin ring method calculates sorptivity from measurements of steady-state infiltration for a number of different diameter rings, utilising the relationship between ring circumference and the influence of capillarity on steady-state infiltration. The Reynolds and Elrick (1991) method uses only steady-state measurements under progressively smaller suctions (or wetter potentials) on the one site to determine unsaturated hydraulic conductivity (K<sub>us</sub>). These are the two methods recommended by McKenzie and Cresswell (2002a).

### 7.3.3 How many measurements are required?

#### For a very accurate estimate of mean K

There is no simple answer to this question. Obviously the greater the number of replicates, the lower the standard error will be for the estimate of the mean value of K (Cook 2002). Bower (1986) cites one study which found 20 measurements were necessary to get the standard deviation down to 10% of the mean at one site with a loam soil. He also cites another study on a silty clay loam soil which found that 11 measurements were required to give a mean vertical hydraulic conductivity that was within 20% of its true value (Bower 1986). Geering (1991) also notes that a minimum of 20 determinations is often required to obtain a representative result for a given area with one soil type

The procedure outlined in Section 6.6.1, using formula (6.11), should be used to determine the number of measurements required to achieve a given accuracy in the estimate of mean soil K when a high level of accuracy is required. Such a level of precision in the measurement of soil K is usually only justified (on the basis of cost) for research projects which are specifically searching for statistically significant differences in soil K between sites subjected to different treatments. Sample number is usually

compromised and reduced to a more manageable number for other more practical investigations.

All of the above suggestions on sample numbers relate to surface measurements only. For measurements on subsoil layers, one is restricted to the 2 or 3 measurements that can fit on a surface in a soil pit.

#### For an approximation of K

Because measurements of K are often expensive and time consuming, the number of measurements done is usually pragmatically reduced to a manageable number for most practical investigations.

In most cases, four measurements on each soil material being assessed would be sufficient to provide a reasonable approximation of K<sub>sat</sub>. This approach is recommended as a minimum standard for the determination of K<sub>sat</sub> for field scale hydrology modelling applications and practical irrigation applications. The option of going for greater precision is of course always there, but with it is the burden of greater expense. Weighing up these two competing issues within the confines of a project budget is always the big dilemma.

For CRC Sugar modelling work using SWIM® and HYDRUS®, as few as 3 measurements of the K<sub>sat</sub> were done on the surface row area, the surface interrow area, and the impeding subsoil layer in some cases (i.e. where measurements varied by less than 50%). This was done with the realisation that the results were "ball park" estimates of K<sub>sat</sub> and not precise. They were combined with K<sub>us</sub> measurements done on small cores (4 from each layer) and soil water retention curve data and bulk density data for each soil horizon as well as *in situ* soil moisture measurements using time domain reflectometry sensors (TDR) (see Photo 7.2). This provided more than enough data to cross-check, develop, calibrate and refine a groundwater model of the field using either HYDRUS® or SWIM®.

Characterisations of infiltration for a representative soil profile are usually carried out at a site selected to have a soil profile representative and typical of the field in question, based on the soil variability survey (see Section 2). Infiltration is often measured at



Photo 7.2. TDR sensors installed in a soil profile for soil moisture monitoring.

the same time that samples are taken for soil bulk density and water storage characterisations. This is often the case when modelling applications are an intended use for the collected data.

The minimum effort to characterise a soil's infiltration usually takes the form of a few replicate measurements of Ks using a ring infiltrometer for the surface of the row area, the surface of the interrow area, and on an excavated flat horizontal surface within the most impeding subsoil layer.

## 7.4 FIELDWORK PLANNING

The following section outlines some practical tips to help with planning and carrying out field work for infiltration measurements.

### 7.4.1 The field kit

The following is a list of useful items for infiltration field work. Much of this equipment is in Photo 7.3.

#### Surface preparation (common to all methods)

- Sharp scissors or secateurs
- Sharp knife
- Epoxy resin
- Garden spade (subsurface layers only)
- Petrol-powered garden blower to clear debris from the soil surface.
- Spirit level (larger ones are better i.e.

- 50cm+ long)
- Hand pump-action spray bottle

#### Soil sampling (for single ring and twin ring Ksat methods)

- Sealable containers (soil moisture samples)
- Electrical tape
- Tanner sampler, hammer, bulk density rings.
- Plastic lids for BD rings.
- Permanent marker pen
- Spatula or putty knife
- Sharp knife
- Pedologist or trenching shovel (for digging out BD rings with core sample)

#### Water supply (common to all methods)

- Water tanker trailer (300+ L) – most cane growers have these.
- 2 x 50 L plastic garbage bins with lids.
- 2 L graduated plastic measuring cylinder.
- Water delivery: Disc permeameter or Mariotte vessel or buckets (10 x 5L)
- Piece of sponge (10 cm diameter) – for bucket supply of water to single ring.

#### Ring infiltrometer gear (Ksat)

- |   |                        |
|---|------------------------|
| 1 Ring cylinder infiltrometer           | 6 Bucket (5L)          |
| 2 Fitted heavy steel lid (installation) | 7 Large plastic mallet |
| 3 Inclined scale rule                   | 8 Sponge               |
| 4 Gas burner and pot                    | 9 Fieldwork book       |
| 5 Candle wax                            | 10 Spirit level        |
|   | 11 Electronic timers   |
|   | 12 Sharp knives        |

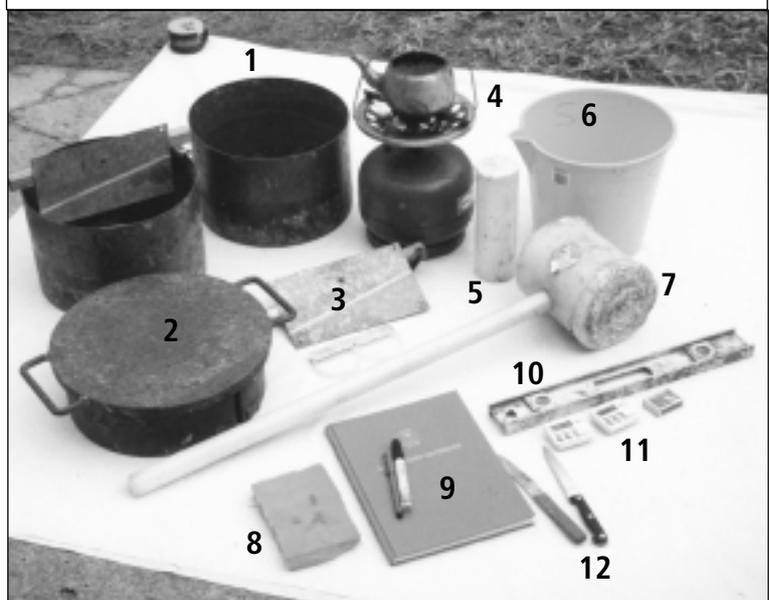


Photo 7.3. A Field kit for measuring soil Infiltration (Photo: J. Kemei, CSIRO).

## Infiltrometer installation

*Gear common to all ring infiltrometer methods*

Spirit level (larger ones are better i.e. 50cm+)

Small piece of wooden dowel (for compacting soil around outside of ring for seal)

Paraffin or candle wax

Bentonite

Small billy or saucepan (1.5 L)

Tea pot or pot with spout

Portable gas cooker, matches

Sharp knife

Hessian material (cut to fit on soil surface inside ring)

Hand pump-action spray bottle

Mallet

Timber board

Small piece of dowel and bentonite or local clay to seal outside of ring for ponded measurements.

*Additional gear for large single ring method*

4 Infiltrometer ring cylinders (30 cm diameter x 20 cm high – welded galvanised sheet metal)

Large mallet hammer (plastic ones ideal, also wood or steel ok)

Customised heavy steel lid or thick wooden plank (10 cm+ thick x 15 cm+ wide x 50 cm+ long)

*Additional gear for twin ring method*

A set of rings of different radii. Cook (2002) recommends a range from 50mm to 250mm

*Additional gear for disc permeameter ponded measurements*

The standard ring custom made for this disc permeameter setup.

*Gear for disc permeameter Kus method:*

Unsaturated disc permeameter apparatus for infiltration measurements under a –ve head or suction. Ones with a water supply system which is detached from the disc and not above it are best.

Bucket and reverse bicycle pump for filling the disc perm with water.

A plastic syringe with a length of thin tubing (for adjusting water level in bubbling tower.

Wetex™ or towelling to check for air leakage.

3mm high ring and steel rule to make the sand pad for the disc perm to sit on.

Fine (<250 μm diameter) sand (moistened enough to allow the sand pad to hold its shape).

Metal rule and small spirit level for preparing the sand pad.

Fine weave netting or bridal tulle to lie between the soil surface and the sand pad when large macropores or cracks are present.

## Measurements

Electronic timer (measures to the second and up to 10 hours)

Record sheets, pen, folder, and calculator.

Metal rule

*Additional gear for large single ring method*

Sheet of plastic film or sheeting (hold water up in ring before initial measurements)

Plastic or steel ruler (30 cm)

Inclined scale ruler (customized to fit in ring)

Floating water level measurers (ours made of plastic BD core lids & aluminium tags)

*Additional gear for disc permeameter  $K_{us}$  method*

Audio tape system of timing for disc permeameters as outlined in Cook (2002) is another option.

## Accessories

Fold up camping stools

Comfortable mats or knee pads (i.e. for kneeling down to read measurements)

Tarpaulin, tent poles, pegs and ropes (for shade and also to shelter site from rain)

## 7.4.2 Locating measurement sites in the field

For soil characterisation work for modelling and general applications it is acceptable practice to locate the site of investigation in an area with a soil profile that has representative (modal) morphology based on the soil variability survey (as outlined in Section 2). All characterisation of surface soil (the row and interrow areas) can be done in a 20 m radius of this site, while a soil pit can be dug for subsoil infiltration measurements. This work is usually combined with other soil

characterisation activities following the soil profile morphological description (i.e. loose bag sampling of soils for chemical analysis, and sampling of small cores for bulk density and soil water characteristic assessments in the laboratory).

For the surface soil layer, there is always the option of a more precise assessment of hydraulic conductivity with 20 or more measurements. If this approach is to be taken, a stratified regular grid approach to determining site assessment locations would be desirable. But row and interrow areas would again need to be assessed separately as different soil entities.

### 7.4.3 Soil assessments

When carrying out surface measurements it is advisable to dig a small hole (at least 40cm deep) for soil assessment, ideally around 1 metre away from the site intended for measurements. Any soil horizon boundary changes or evidence of compaction should be noted. Such an assessment can help prevent inaccurate measurements associated with situations where the soil horizon overlying impeding layers is very thin. In this situation, a laboratory assessment of K of this soil horizon done on small core samples may be more appropriate (McKenzie and Cresswell 2002a). Once the infiltration measurements are complete it is also worthwhile digging down below the site of measurement to examine the depth of the wetting front. This can yield valuable insights into the movement of water through the soil.

### 7.4.4 Soil surface preparation

Preparation of the soil surface for infiltration measurements is basically the same for all the different infiltrometers in use.

#### Surface layer

In sugarcane fields, the soil surface is usually covered with a dense layer of trash from the previous year's harvest. To prepare the surface for infiltration measurements, this trash should be gently lifted and removed to expose the underlying soil surface. Any weeds or grass vegetation on the surface should be clipped as low as possible to the ground. This can be

done with shears or heavy duty kitchen scissors. Any cane in the way can be cut away with a cane knife. A petrol-powered garden blower or a vacuum cleaner can be used to remove any loose soil from the surface (Cook 2002). For measurements on the row, try to locate the rings in vacant areas between the cane stools where possible. Placing a ring over a cane stool may result in a higher rate of infiltration due to loose soil areas around the base of the stool. Avoid trying to flatten out the surface of the intended ring site with a shovel as this may smear over and block soil pores at the surface. It is usually only necessary to cut out surface irregularities with a sharp cane knife if they are significant (> 5 cm), and likely to interfere with measurements.

#### Subsoil layers

Preparation of the surface of a subsoil layer involves preparing a flat surface area that is large enough to accommodate the ring. This is usually done with a spade which often smears the surface. This smearing then has to be removed. One way of removing the smearing is systematically picking back the surface with a knife in such a way as to ensure that the smearing caused by the knife is removed as you proceed across the surface (Cook 1994). Applying 5 minute epoxy on the surface and leaving it to set for a few minutes before removing it to expose an unsmear surface is another method (Koppi and Gearing 1986).

### 7.4.5 Setting up the water supply

It is important to have an adequate and easily accessible supply of water when doing infiltration measurements. A minimum of 150 litres of water should be close by for measurements on the row surface which can drain rapidly. The water supply needs to be easily accessible for quick refills. Numerous 4 litre buckets along with two large plastic garbage bins or a large 100 litre plastic drum with its top cut off are ideal (Photo 7.4). The buckets and open garbage bins or drums allow quick access to water for refills during measurements. The open drums and bins can also be easily loaded into the back of 4WD vehicles for transporting water from the supply source. If the cane grower can fill up a 500 litre trailer tanker with water and leave it at the site,

it is ideal (see tanker in background of Photo 4.25).

Not only is it important to have an adequate supply of water for the measurements, but it is also essential to have a means of protecting the measurement area in the advent of rainfall and two methods for this are shown in Photos 7.4 and 7.5.



Photo 7.4. Two large plastic garbage bins and several buckets full of water provide an easily accessible supply of water for infiltration measurements. The tarp cover is worthwhile when rain is a possibility.



Photo 7.5. The beach umbrella is another handy addition to a field kit. In this instance, it prevented showers from ruining Ksat measurements in a soil pit.

## 7.5 FIELD MEASUREMENTS OF SATURATED HYDRAULIC CONDUCTIVITY

The commonly used abbreviation for saturated hydraulic conductivity ( $K_s$ ) is the term Ksat. The two methods of measuring saturated hydraulic conductivity advocated in this text are the 'single ring' method and the 'twin ring' method. The single ring method is

recommended for characterisation work where an approximation or 'ball park' estimate of average Ksat is considered satisfactory. This would be the case for most practical investigations and most hydrology modelling work. The twin ring method is recommended for research work where a higher degree of precision is required, such as for studies looking for statistically significant differences between different treatments. The following sections will outline the methodology for both of these methods, but less attention will be given to the twin ring method as a detailed explanation of this method can be found in Cook (2002).

### 7.5.1 Single ring method

The single ring cylinder method (Talsma 1969) is a practical method for determining Ksat in the field. As mentioned earlier, there are advantages in using as large a ring as possible for these measurements. In the case of sugarcane crops in Queensland, the maximum size of the ring is restricted to a diameter of less than 40 cm due to the rows (planted mounds) typically being only 50 cm wide. Soil characterisation work for CRC Sugar found a 30 cm diameter infiltrometer ring with a height of 15 to 20cm to be satisfactory for these measurements (Photo 7.6). In the method presented here, special efforts are also taken to measure infiltration rates at the very beginning of infiltration, so as to allow the sorptivity to be determined and its influence accounted for in the calculation of Ks (see calculation section). The method for measuring and calculating soil

hydraulic properties of sorptivity and hydraulic conductivity presented here is the more traditional approach outlined by White (1988) and White *et al.* (1992) and is based on Wooding's (1968) analysis of the three dimensional flow from a shallow circular pond or surface disc.

#### Installing the rings

The following instructions are for the installation of any sized ring cylinder



Photo 7.6. Single ring method of determining soil infiltration parameters.

infiltrometer and as such are relevant to the twin ring method as well as the single ring method.

#### *Cutting through roots*

Once the surface has been prepared (Section 7.4.4) the ring is then placed on the surface. In the case of surfaces covered in vegetation or for the row area for sugarcane, a sharp knife is used to cut a few centimetres into the soil around the outside edge of the ring. This is done to sever any roots or stems that could disrupt the soil when the ring is driven in (Cook 2002).

#### *Driving the rings in*

A customised steel plate lid or a piece of hardwood timber is then placed over the top of the rings and struck with a large hammer to force the rings no more than 1 to 2 cm into the ground (Photo 7.7). To go any deeper than this is likely to confine the flow of water through the soil, and therefore undermine the validity of the  $K_s$  calculations.

#### *Levelling the top of the ring*

As the ring is driven into the soil a spirit level can be placed on top of the ring to check that it is installed level at the top.

#### *Sealing the soil / ring edge*

Soil around the outside of the ring should then be pushed down and compacted. Any blunt object such as the wooden handle of a hammer or a piece of dowel would be suitable for this. It may also be necessary to pack extra soil



Photo 7.7. Driving a ring cylinder into the soil with a customized steel lid and a plastic hammer

around the outside of the ring (Cook 2002). Wetting the soil slightly can make it easier to compact and achieve a better seal (Photo 7.8). For very coarse gravely soils where it is not possible to insert the ring into the soil, the outside of the ring can be sealed onto the soil surface using bentonite or other sealants (Cook 2002). If there is poor contact between the soil and the inside the ring, a sealant such as hot candle wax or bentonite can be applied around the edge of the ring. Melted candle wax or paraffin wax is generally poured around the inner edge of the ring, allowed to cool and solidify, then cut and picked back to 1 cm from the edge of the ring (Photo 7.9). Bouwer (1986)



Photo 7.8. Sealing the soil around the outside of the ring by packing it down.



Photo 7.9. Using hot wax to seal the soil around the inside of the ring infiltrometer.

actually recommends pushing or packing the soil back against the ring edge. A typical infiltration measuring workstation is shown in Photo 7.10.

#### *Crusted soils*

Spraying water as a fine mist onto a crusted soil to moisten the top 2 mm before installing the rings can help prevent fracturing of the crusted surface during ring installation.

Note that for ring installation it is critical that the bottom cutting edge of the infiltration rings is kept as sharp as possible. This will help ensure that the edges of the rings keep good contact when they are pushed into the soil.

#### **Deciding on a water delivery system**

There are three main options for supplying water to the ring during infiltration measurements. These are the disc permeameter (ponded measurement version), the Mariotte bottle, and the bucket/or measuring cylinder. Bucketing by hand supplies water as a variable falling head, while both the disc permeameter and the Mariotte bottle supply water at a constant head within the ring.

#### *Disc permeameter*

The disc permeameter setup is only designed to deliver water to its customised ring and as such is not an option for other sized rings. The "ponded measurement" version of the disc permeameter delivers water to the ring at a

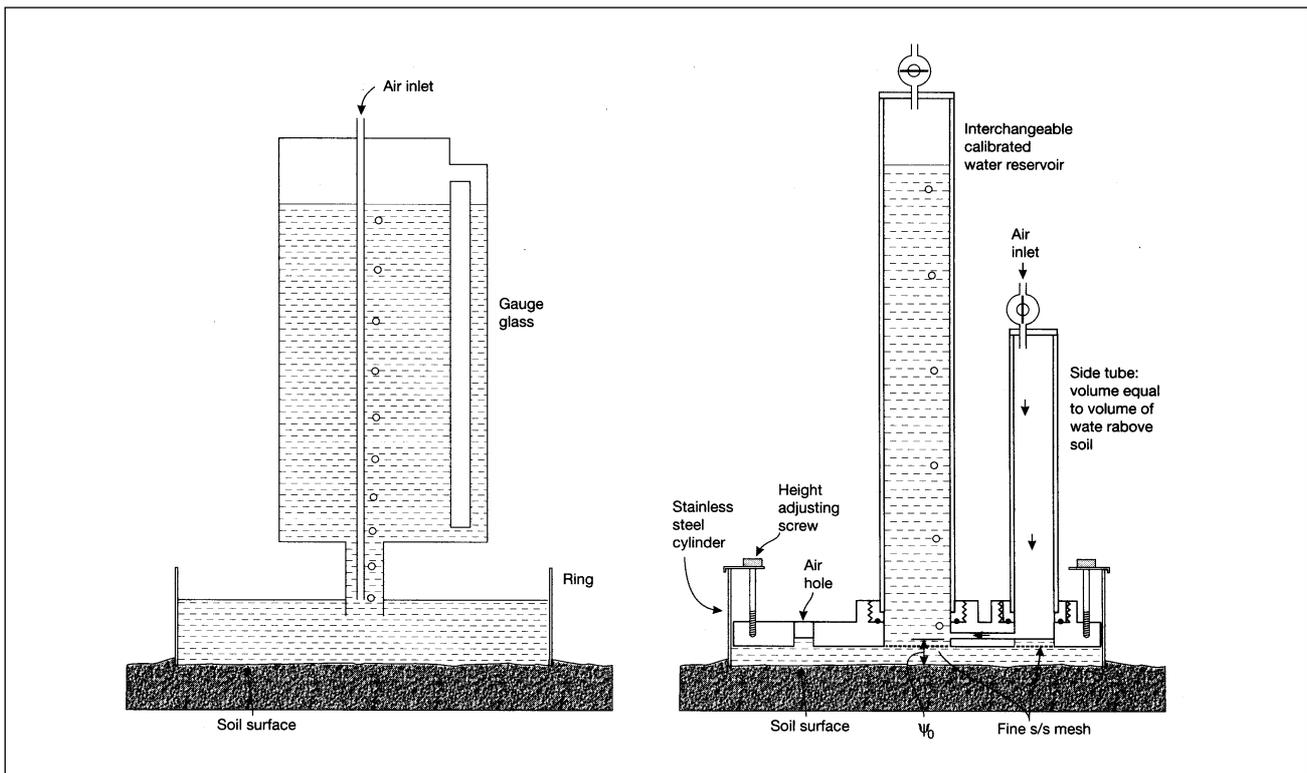


Photo 7.10. A ring infiltrometer workstation in a cane field at Tully

constant head based on the same principle as the Mariotte bottle.

The disc permeameter used for ponded measurements of  $K$  ( $K_{sat}$ ) is a slightly different design to that used for measuring unsaturated hydraulic conductivity. This disc permeameter design is shown in Figure 7.3. It is in effect a Mariotte style delivery system which allows a constant positive (+ve) head to be maintained throughout measurements. Its additional feature however is the side tube, which can be filled with the exact volume of water necessary to fill the area between the reservoir and the soil surface. This allows instantaneous infiltration measurements to be taken at the very beginning of infiltration, thus ensuring that sorptivity is likely to be measured.

The use of the 'ponded measurement' version of the disc permeameter definitely has potential for  $K_{sat}$  measurements in subsurface layers and the compacted surface layer in the interrow area of cane land. But it may be less useful on row areas of sugarcane land as infiltration in this area can be so rapid that there may not be enough time for the steady state infiltration rate to develop before the water supply is emptied. In this situation, measurements would be disrupted while the empty disc permeameter was replaced with a pre-filled, second disc permeameter. Also, in newly ploughed soil the weight of the full permeameter can push the permeameter into the soil. This can seal off the bottom of the permeameter and prevent flow.



**Figure 7.3.** Two water delivery systems: (a) simple Mariotte vessel design, and (b) the original CSIRO disc permeameter setup for saturated hydraulic conductivity (White *et al.* 1992) (Sourced from Cook 2002).

### *Mariotte bottle*

A Mariotte bottle is another supply vessel which allows water to be supplied to infiltrometer rings at a constant head (Figure 7.3 and Photo 7.11). The components of this setup are demonstrated in Figure 7.4. The +ve head level is set by adjusting the position of the bottom of the air tube (A), which is connected to the atmosphere via its top end and protrudes outside the vessel. Water flows out of the mariotte bottle via tube (B), which is water filled and supplies water to a height level in the infiltrometer ring which is level with the bottom of the air tube (A). Thus a constant head can be maintained in the ring while measurements of the water level in the Mariotte bottle are taken and the time recorded (i.e. water level versus time). This system only fails in situations where soils are so rapidly draining that the Mariotte bottle setup lacks the capacity to deliver water to the ring at a fast enough rate to keep up with the infiltration rate, resulting in the head dropping. This can only be overcome by using a setup with a larger diameter outflow tube. Where infiltration rates are very high, bucketing by hand may be the only practical water delivery option for ring infiltrometer measurements. This can often be the case on the row areas of

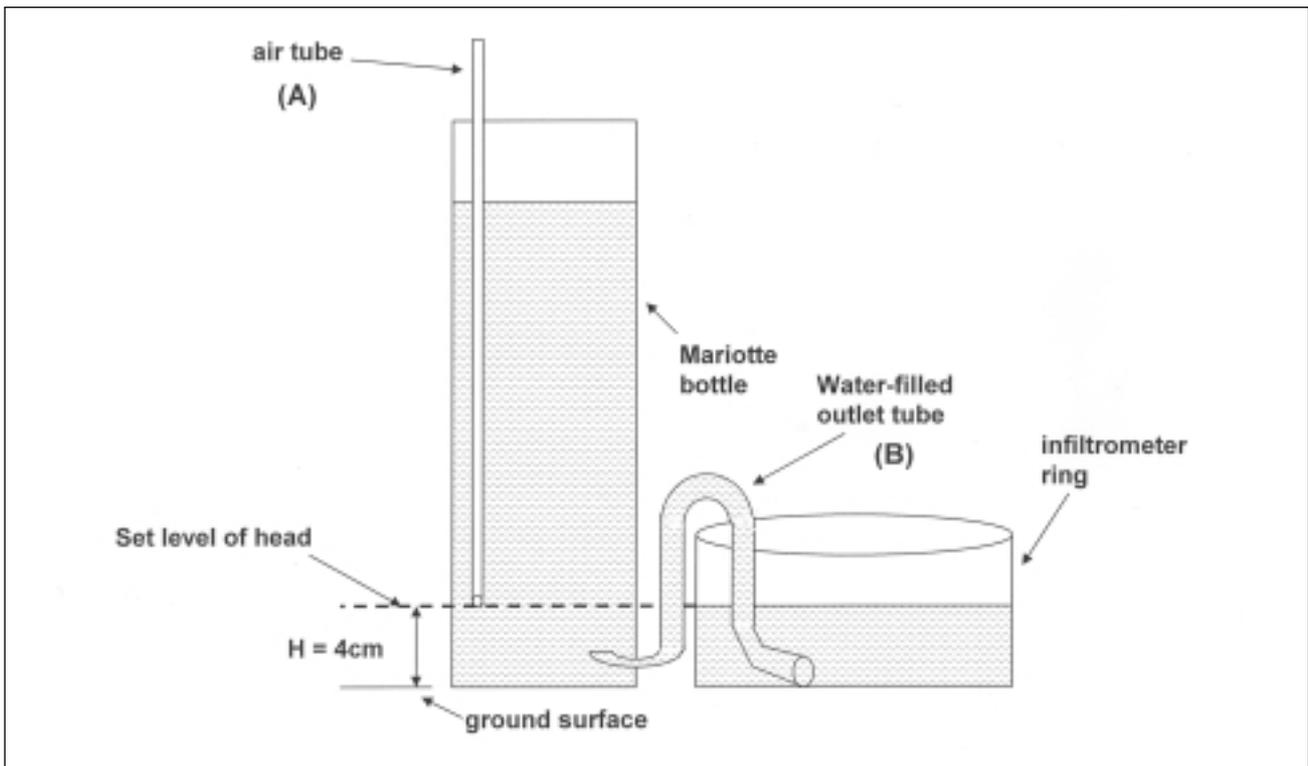
sugarcane fields where the soil is often highly porous.

### *Manually bucketing water*

The supply head provided by bucketing water into the ring by hand is variable and falling. Varying the head by only a few centimetres however is thought to have very little overall affect on the steady state infiltration measurements and  $K_{sat}$  determinations (Cook 2001, pers.com.). The main advantage of the bucketing by hand / falling head approach is that it allows the water level to be kept up in larger diameter rings on rapidly draining soils and it does this without the refill disruptions to



**Photo 7.11.** A customised Mariotte bottle setup supplying water to the ring at constant head.



**Figure 7.4.** Principles behind the Mariotte bottle setup for delivering water to the ring cylinder infiltrmeter at a constant head.

measurements that occur with Mariotte bottles. This is particularly relevant to measurements on the row areas of sugarcane fields.

When filling the ring with water from the bucket, place a large sponge (10 cm diameter) onto the soil surface and pour water onto the sponge. This helps dissipate the energy of the water and prevent any destruction of surface soil structure and pores (Photo 7.12). For soils with a fragile surface soil structure, it is also advisable to place a piece of hessian (cut to fit the ring area) on the soil surface (Cook pers.com. 2001).

Although a ruler can be used to measure the drop in water level relative to the top of the

ring over time, a 1: 5 inclined scale rule can provide greater accuracy. It is important to ensure that the tin sheet, which the scale rule is on, has a perfect horizontal orientation. This can be checked with a spirit level. Floating measuring markers can make reading the drop in water level against the inclined scale a lot easier (Photo 7.13). The inclined scale rule is probably more suited to soils with lower infiltration rates, while the steel ruler is better suited to measuring infiltration in the faster draining soils as it is less cumbersome.

Note that it is important to record the volume of water poured through the ring cylinder over time as well as the rate of drop in water level, as this will help with the later graphing of



**Photo 7.12.** Bucketing the water onto a sponge to supply water to the ring.



**Photo 7.13.** Use of an inclined scale and floating markers can make readings easier.

cumulative infiltration (mm) vs time. Volumes can be recorded by either pouring the water into a large measuring cylinder before decanting into the ring, or else by having volume graduations marked on the buckets.

### Sampling and measurements

Data required to allow soil Ksat to be calculated include:

Sorptivity of the soil(S)

Steady state flow rate(q)

Initial volumetric water content of the soil at the supply source ( $\theta_i$ )

Final volumetric water content of the soil ( $\theta_f$ ),

Radius of the infiltrometer ring (r)

Distance from top of ring to ground surface when installed.

#### *Initial soil water content and bulk density*

Cook (2002) recommends taking core samples for determining bulk density and initial water content in an area between one and two times the radius away from the edge of the ring, so as to ensure representativeness yet at the same time avoid having an impact on the infiltration measurements.

Cores should be taken using the method outlined in the core sampling section (Section 6.6). It is advisable to take at least three core samples. Lubricating the inside of the core sampling ring with vegetable oil will allow easier transfer of the core sample from the ring to an air tight container (McKenzie and Cresswell 2002b). It is also worth taping around the lid of the air tight container with electrical tape to ensure that it is sealed. Bulk density and volumetric water content are determined in the laboratory by the methods outlined in Section 6.2.

#### *Infiltration measurements*

#### Terminology and units

Before dealing with the details for measuring infiltration using a single ring infiltrometer, it is worthwhile to first outline the standard symbols and units used in infiltration measurements and calculations. These are outlined below:

**Q** Cumulative volume of water which has

flowed through the soil from the start of infiltration at time zero. Units are expressed as volume ( e.g. mm<sup>3</sup> or m<sup>3</sup> ).

**q** Volumetric flow rate. Units are expressed as volume/time (e.g. mm<sup>3</sup>/hr or m<sup>3</sup>/hr).

**K** Hydraulic conductivity. Units are expressed as length/time (e.g. mm/hr or m/s)

**S** Sorptivity. Units are expressed as length/time<sup>1/2</sup> (e.g. mm/hr<sup>1/2</sup>)

I or (**Q** /  $\pi r^2$ ) is cumulative infiltration. It is the cumulative volume that has flowed through the soil (Q) divided by the cross-sectional area of the ring through which it flowed ( $\pi r^2$ ). It is expressed in units of length (e.g. mm or m).

#### Calibration factor – Mariotte bottle and disc permeameter

Provided there is an awareness of what has been measured and where it fits into the calculation formulae, any confusion can be avoided. Usually what is measured in the field is an increment drop in water level against time and this has to be converted back to a cumulative volume (Q) to allow the values for the key parameters of steady state flow rate (q) and (S) to be derived graphically.

The important thing is to ensure that the necessary information is recorded in the field to allow increment drop recordings (e.g. length vs time) to be later converted to a cumulative volume (Q) value. For disc permeameter and Mariotte bottle water supply systems, a calibration factor has to be determined for this conversion. The procedure outlined here is sourced from McKenzie *et al.* (2002b) and involves placing the setup on a balance. In the case of the disc permeameter the base is removed and the supply vessel is inverted upside down in a stand on the balance before successive volumes of water are added, with the scale reading on the cylinder and the mass being recorded for each addition. An average volume value per scale length can then be calculated for the entire scale by assuming a water density of 1.00 Mg/m<sup>3</sup>. This is the calibration factor (C). A calibration factor (C) value of 200 mm<sup>3</sup> / mm would mean a 2 mm drop in the water level on the scale for a flow of 400 mm<sup>3</sup> from the reservoir.

Once C is known, the scale reading data can be converted to volume data as follows

Flow rate ( $q_i$ ) for a given time interval

$$q_i = \frac{C\Delta R}{\Delta t} \quad (7.3)$$

where  $\Delta R$  is the difference in the scale reading for the time interval  $\Delta t$ .

Cumulative Infiltration ( $Q / \pi r^2$ )

$$\frac{Q}{\pi r^2} = \frac{C(R - R_i)}{\pi r^2} \quad (7.4)$$

where  $C$  is the reservoir calibration,  $R$  is the scale reading of interest and  $R_i$  is the initial scale reading.

#### Calibration for the 'falling head manual bucketing' approach

For the falling head bucketing by hand approach for supplying water to the ring, it is important to keep records of the actual volumes of water added to the ring throughout the time of the measurements. This can be achieved by pouring water into the ring from a full 2 to 5 litre measuring cylinder, noting how much water was added to fill the ring and at what time the ring was full. If this cannot be achieved for the whole period of measurement, as may be the case for rapidly draining soils, it should be done at least for the first 5 to 10 minutes of measurement (to determine sorptivity) and for another 10 minute period later on when a steady state flow rate is finally achieved. Obviously, keeping on top of the volume of water added to the ring will not be a problem for slow draining soils.

A calibration factor ( $c$ ) can also be calculated for the single ring infiltrometer by measuring the radius of the ring in mm and calculating the area of the circle ( $\pi r^2$ ). This area will equal how many  $\text{mm}^3$  of water flow through the soil for every measured mm drop in water level inside the ring. The flow rate between each successive measurement can then be calculated using formula 7.3. The tricky aspect of this approach occurs with the adjustments associated with refilling the ring. To make this adjustment all that needs to be known is the volume of water added to the ring (in  $\text{mm}^3$ ) since the last reading and the area of the ring in  $\text{mm}^2$ . By dividing the volume of water added ( $\text{mm}^3$ ) by the area of the ring, the height of water added to the ring can be determined based on the formula for the volume of a

cylinder ( $\pi r^2 h$ ). This length is then added to  $\Delta R$  (change in reading value) to determine the adjusted water level drop between the reading before refill and the reading immediately after refill.

**Table 7.4.** Example of field measurements and calibration calculations for ring infiltrometer data

| Site Details   |   |                                       |                              |                    |
|--|---|---------------------------------------|------------------------------|--------------------|
| Site Name: Smith's - Burdekin  |   |                                       |                              |                    |
| Date: 20/05/2000   |   |                                       |                              |                    |
| Location: Mill Rd, Kalamia.  |   |                                       |                              |                    |
| Measurement details: Ksat (single ring) on layer 2 (B2 horizon), depth = 15cm (see soil profile no. 42).                                   |   |                                       |                              |                    |
| Recorded by: Joe Bloe  |   |                                       |                              |                    |
| <b>Radius of ring</b> = 150 mm   |   |                                       |                              |                    |
| <b>Area of Ring</b> = $\pi r^2 = 70,650 \text{mm}^2$   |   |                                       |                              |                    |
| <b>Calibration:</b> volume of water in each 1mm drop in water level in ring = $\pi r^2 h = 70,650 \text{mm}^3 = 70.65 \text{ ml}$ of water |   |                                       |                              |                    |
| Volume of water (ml) $\div$ 70.65 = Ring Water level adjustment in mm  |   |                                       |                              |                    |
| Time (min sec)   | Water height (distance from top of ring mm) | Comments                              | Q ( $\text{mm}^3$ ) x $10^6$ | Q / $\pi r^2$ (mm) |
| 0min 00sec   | 10 mm                                       |                                       |                              |                    |
| 1min 00sec   | 70 mm                                       | After reading - refilled with 4240 ml | 4.24                         | 60                 |
| 3min 0 sec   | 20 mm                                       |                                       | 4.9                          | 70                 |

In the above example, the reading before refill was 70mm from the top of the ring at time 2 minutes, and the reading after refill was 20mm (at time 2min 30 sec), while the amount of water added to the ring in the refill was calculated to represent an addition of 60mm to the water height.

In this case the adjusted water level drop for the first reading after the refill is as follows:

20mm (1<sup>st</sup> reading after refill) – 70mm (last reading before refill) +60mm (refill addition) +10mm flow for this 0.5minute period.

Thus using this approach, the real water level drops due to infiltration for each period between successive measurements can be calculated for the whole time of infiltration. These can then be added up and divided by the

area of the ring to provide cumulative infiltration ( $Q / \pi r^2$ ) values for the whole period of measurement.

#### Initial Infiltration rate (early / medium time data)

For the single ring method which uses one diameter of ring for all measurements, it is important to start measuring infiltration as soon as possible after the water is supplied to the ring. This early time data at the very beginning of infiltration is important for determining sorptivity, which is needed to calculate hydraulic conductivity.

The best chance of capturing the initial infiltration rate for ponded ring measurements is to lay plastic sheeting or film over the soil surface within the ring to form a barrier between the water and the soil for the first filling (Cook pers. com. 2001). The plastic film sheet must be of sufficient size to cover both the soil surface within the ring and the sides of the inside of the ring (Photo 7.14). Once this is laid over the soil and the sides of the ring, the ring can be filled to the desired level. Thin, poor quality (i.e. weak strength) garbage bag liners are ideal for this purpose as they are flexible enough to mould to the shape of the ground surface and ring when water is added to the ring. In contrast, stronger, less flexible plastic sheeting tends to be too rigid for this purpose. In the case of manual bucketing, it is best if the ring is filled to within 1cm of the top (this added volume of water should be recorded, as should every subsequent refill



Photo 7.14. Use of plastic sheeting in a ring infiltrometer to increase the likelihood of catching the sorptivity phase of infiltration (Photo: Lowan Turton, NSW Agriculture).

during the measurement period). It is also best if the inclined scale is not used for these initial measurements as it will get in the way when the plastic sheet is removed. When ready, the clock is started at time zero just as the plastic sheeting is pulled from the ring, bringing the water in contact with the soil. Measurements are then taken in rapid succession for the first 2 minutes. For the manual falling head approach to water supply, a ruler can be used to measure the drop in water level relative to the top of the ring for the initial measurements. After this period the inclined scale may be added and used.

For the Mariotte bottle setup the same approach of using plastic sheeting applies, the only difference being the setting of the water level to a fixed height for the head. Placing of a sheet of hessian over the soil surface under the plastic sheeting is also recommended to help protect the soil surface from the initial flows of water from the Mariotte bottle. A flat piece of sponge placed under the Mariotte bottle outlet tube may also help protect the soil surface from turbulence.

#### Steady state flow rate

The steady state can be considered to be reached when the flow rate for five successive measurements is approximately the same and is not changing systematically (Cook 2002). This would mean approximately the same time for five successive increment drops in the standpipe in the case of a Mariotte bottle or disc permeameter setup, or alternatively five similar water level drops in succession over set time intervals for the falling head with manual bucket supply setup. Once this point is reached, the measurements can end.

#### Final soil water content

Sampling for final soil water content at the end of infiltration measurements is a difficult exercise which is subject to many potential sources of error. All free water should be allowed to drain before sampling as otherwise the final soil water content may be found to exceed the porosity of the soil (Cook 2002). The soil should be sampled when water has drained from the surface to the point where the soil surface loses its glistened appearance. The ring should be removed and a trowel or spade used to dig down along the side of the ring

area to determine the depth of the wetting front. It is better to sample to a depth which accounts for the majority of this wetting front depth rather than just the top 1 cm of the soil surface (Cook, pers.com. 2001). Again it is worthwhile taking at least three samples. The samples are collected with a spatula and transferred to an air tight container and the volumetric moisture content is then determined as per the standard method, using the bulk density values obtained from the cores sampled for the initial soil moisture content determinations. If an error is found to have occurred in sampling the final water content (i.e. final water content exceeds porosity), a backup option is to calculate the saturation water content for that soil, using the formula in the soil water property section.

#### Dimensions of installed ring infiltrometer

In addition to the radius of the ring, which is needed for adjustments associated with water refills when manually bucketing water into the ring, it may also be worthwhile measuring the distance from the top of the ring to the soil surface when the ring is installed. This may sometimes be helpful in later water volume calculations. Additional measurements will be required if there is a change over to the use of an inclined scale for water level readings during the run. The measurements required for this are the distance from the soil surface to a point on the inclined scale as well as the distance from the top of the ring to this same point on the inclined scale.

#### **Calculations**

The following procedure for calculating the soils saturated hydraulic conductivity ( $K_s$ ) is an earlier method used for the disc permeameter (White 1988, White *et al.* 1992).

#### *Step 1 - Data transformations*

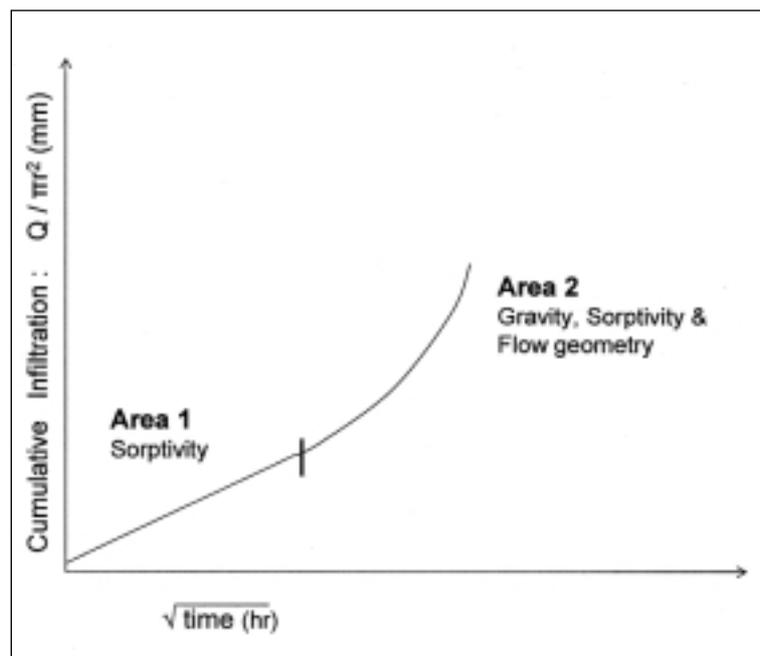
Raw data from infiltration measurements are usually a series of water height levels at corresponding times from time zero (beginning) until the achievement of steady state flow. These first have to be converted to a sequence of flow volumes ( $\text{mm}^3$  or  $\text{m}^3$ ) for each time interval between

measurements. This will involve the adjustments for refills noted in the calibration section for the manual bucketing water supply method. These flow volumes for each time interval between measurements are then progressively added to each other to give a cumulative flow volume ( $Q$  in  $\text{mm}^3$  or  $\text{m}^3$ ) for the whole period of measurement. These cumulative flow values can then be divided by the area inside the ring (i.e.  $\pi r^2$ ) to give the cumulative infiltration ( $I$ ) values, expressed in units of length (e.g. mm or m), for the whole period of measurement. These transformations are shown in Table 7.4 and discussed in the calibration section.

#### *Step 2 – Calculate the soil sorptivity*

#### Identify the sorptivity part of infiltration data

The 'sorptivity area' of infiltration is the period when soil sorption dominates infiltration. It occurs at the very beginning of infiltration. The sorptivity component of infiltration can be identified in the data by plotting cumulative infiltration ( $Q / \pi r^2$ ) vs square root of time (Anon 1988). The sorptivity component of infiltration, if detected, will be recognisable as a straight line section in the early time area of the graphed infiltration data (Figure 7.5). The end point for the sorptivity zone is marked by a significant steepening of the plotted line, which



**Figure 7.5.** Graph of cumulative infiltration vs square root of time, showing two zones of infiltration flow – (1) Initial early time infiltration associated with sorptivity, (2) Infiltration flows influenced by gravity, flow geometry and sorptivity.

signals the beginning of the period of infiltration where gravity and flow geometry start to have a dominant influence on the infiltration rate (area 2 on graph). This end point can be estimated by eye from the graph, or alternatively the end point can be determined by carrying out a linear regression on the sorptivity area data and by continuing to add data points until the slope value changes significantly.

### Calculate the soil sorptivity

There are two ways to determine sorptivity (S) from the data. One method is to carry out a linear regression on the straight line portion of the graph of cumulative infiltration (I) versus square root of time. The slope of the straight line is taken as the sorptivity in mm/hr<sup>1/2</sup> or m/s<sup>1/2</sup>. (Anon 1988). A preferable approach is the method favoured by Cook and Broeren (1994), which is based on the theory of Warwick (1992) and involves carrying out a calculation for each pair of I and t data determined to be in the sorptivity dominated area of infiltration by the previously mentioned graph.

The formula for this sorptivity (S) calculation is as follows

$$S = \frac{r\Delta\theta^2}{1.31\sqrt{t}} \left[ \sqrt{1 + \frac{2.63I}{r\Delta\theta^2}} - 1 \right] \quad (7.5)$$

Where:

$\Delta\theta$  is the difference between the initial volumetric soil moisture content ( $\theta_i$ ) and the final volumetric moisture content ( $\theta_0$ ) i.e. subtracting moisture contents when expressed in ratio terms e.g. 20% as 0.20.

r is the radius of the infiltrometer ring (mm)

t is the time interval between the successive infiltration readings (hr)

I is amount of infiltration which occurred during the time interval between readings  
(Q /  $\pi r^2$ ) (expressed as a distance in mm).

Use of the units suggested above will give a final value for sorptivity in mm/hr<sup>1/2</sup>.

Alternatively recordings in metres (m) and seconds (s) will give a sorptivity value in m/s<sup>1/2</sup>.

This is calculated for each set of measurements

from the first to the last one within the sorption zone of the data set. A mean average value of S is then determined for use in the formula to calculate hydraulic conductivity (K).

### *Step 3 – Determine the steady-state infiltration rate*

"Steady state" flow is the period where infiltration is dominated by saturated flow under the influence of gravity.

As mentioned earlier, the rate of flow (q) (mm<sup>3</sup>/hr) is usually determined to be consistent for several consecutive measurements, before the measurements are stopped in the first place. As such, the time at which the infiltration rate becomes steady state is known. If the steady state flow rates for consecutive measurements are virtually identical or vary by only + or - 5%, then these values can be averaged to give an estimate of the steady state flow rate (q) for formula 7.6.

However, if there is a little more noise than this in the data, it is advisable to graph cumulative infiltration (mm) against time and then do a linear regression on these steady state infiltration data points to give a line of best fit. The slope of this line is equal to the best estimate of the steady state infiltration rate (q/ $\pi r^2$ )(mm/hr) from this data. Plotting cumulative infiltration (Q/ $\pi r^2$ ) vs time (hr) allows visualisation of where the steady state infiltration begins. This is where infiltration rate is steady, giving a straight line relationship, as in region II of Figure 7.1.

### *Step 4 – Calculate the hydraulic conductivity (K<sub>s</sub>)*

Saturated hydraulic conductivity (K<sub>sat</sub>) can be calculated using the following formula:

$$K_s = \frac{q}{\pi r^2} - \frac{2.2S^2}{\Delta\theta\pi r} \quad (7.6)$$

where

q is the steady state flow rate (mm<sup>3</sup>/hr or m<sup>3</sup>/s). It can be determined as the slope value taken from a graph of Q (Cumulative volume of water infiltrated) versus time. Alternatively the whole q/ $\pi r^2$  value can be determined as follows

q /  $\pi r^2$  is the slope value taken from the graph of cumulative infiltration (Q/ $\pi r^2$ ) versus time (mm/hr or m/s).

S is the average of the sorptivity values

**Table 7.5.** Table of raw data and calculated hydraulic parameters (Q, I, and S) for the infiltration measurements for a site including (A) the early time measurements for sorptivity, and (B) the later measurements at 'steady state' (Source F Cook, CSIRO)

| <b>Disc permeameter details</b>  |                     |                    |                                      |          |                              |
|--|---------------------|--------------------|--------------------------------------|----------|------------------------------|
| Standpipe calibration: $18.03 \times 10^{-6} \text{ m}^3$ of water per cm drop |                     |                    |                                      |          |                              |
| Radius of disc ( $r$ ) = 0.1 m   |                     |                    |                                      |          |                              |
| Area of disc = $\pi r^2 = 0.0314 \text{ m}^2$                                  |                     |                    |                                      |          |                              |
| <b>Soil moisture data</b>  |                     |                    |                                      |          |                              |
| $\Delta\theta = 0.33 \text{ m}^3 \text{ m}^{-3}$                               |                     |                    |                                      |          |                              |
| <b>A. First infiltration measurements for sorptivity</b>                       |                     |                    |                                      |          |                              |
| Time   | Time <sup>1/2</sup> | Standpipe readings | Q                                    | I        | Warwick (1992) Sorptivity(S) |
| (s)  | (s <sup>1/2</sup> ) | (cm)               | (m <sup>3</sup> x 10 <sup>-6</sup> ) | (m)      | (m s <sup>-1/2</sup> )       |
| 0  | 0                   | 10.0               |                                      | 0        |                              |
| 1.98   | 1.407125            | 15.0               | 90.2                                 | 0.00287  | 0.001777                     |
| 4.62   | 2.149419            | 20.0               | 180.3                                | 0.005739 | 0.002102                     |
| 7.92   | 2.814249            | 25.0               | 270.5                                | 0.008609 | 0.002224                     |
| 12.24  | 3.498571            | 30.0               | 360.6                                | 0.011478 | 0.002232                     |
| 16.44  | 4.054627            | 35.0               | 450.8                                | 0.014348 | 0.002275                     |
| 21.72  | 4.660472            | 40.0               | 540.9                                | 0.017217 | 0.00226                      |
| 27.12  | 5.207687            | 45.0               | 631.1                                | 0.020087 | 0.002257                     |
| 34.26  | 5.853204            | 50.0               | 721.2                                | 0.022957 | 0.002205                     |
| 41.52  | 6.443601            | 55.0               | 811.4                                | 0.025826 |                              |
| 50.16  | 7.082372            | 60.0               | 901.5                                | 0.028696 |                              |
| 58.74  | 7.664203            | 65.0               | 991.7                                | 0.031565 |                              |
| 68.04  | 8.248636            | 70.0               | 1081.8                               | 0.034435 |                              |
| 80.04  | 8.946508            | 75.0               | 1172                                 | 0.037304 |                              |
| 89.88  | 9.480506            | 80.0               | 1262.1                               | 0.040174 |                              |
| 101.64   | 10.08167            | 85.0               | 1352.3                               | 0.043043 |                              |
| <b>B. Later measurements at 'steady state'</b>                                 |                     |                    |                                      |          |                              |
| 0  | 0                   | 2.0                |                                      | 0        |                              |
| 109.92   | 10.48427            | 40                 | 685.1                                | 0.021809 |                              |
| 125.82   | 11.21695            | 45                 | 775.3                                | 0.024678 |                              |
| 141.78   | 11.90714            | 50                 | 865.4                                | 0.027548 |                              |
| 157.86   | 12.56423            | 55                 | 955.6                                | 0.030417 |                              |
| 1741   | 3.19091             | 60                 | 1045.7                               | 0.033287 |                              |
| 190.62   | 13.80652            | 65                 | 1135.9                               | 0.036157 |                              |
| 207.18   | 14.39375            | 70                 | 1226                                 | 0.039026 |                              |
| 224.22   | 14.97398            | 75                 | 1316.2                               | 0.041896 |                              |
| 241.8  | 15.54992            | 80                 | 1406.3                               | 0.044765 |                              |
| 258.96   | 16.09223            | 85                 | 1496.5                               | 0.047635 |                              |

(mm/hr<sup>1/2</sup>) calculated for the early to medium time infiltration measurements.

$\Delta\theta$  is the soil water content change (determined the same as outlined for the sorptivity

calculation).

$r$  is the radius of the infiltrometer ring (mm)

### Use of Units

The two commonly used units for expressing K are mm/hr and m/s. It is important that there is consistency in the use of the chosen units throughout all calculations no matter which one is used. For example, if m/s is the intended unit for expressing the final K value, then all distance measurements will need to be in metres and all time measurements will need to be in seconds for all inputs in the above calculations. If mm/hr is the chosen unit then all distance measurements will need to be in mm and all time measurements in hours for the calculation inputs.

### Worked example

The previously outlined method for calculating  $K_s$  for single ring measurements is demonstrated below using infiltration data from a disc permeameter presented in Table 7.5.

### Preliminary calculations

#### Step 1 – Data transformations

Cumulative infiltration (I) has to be calculated for the data set using formula 7.4.

To illustrate this procedure, a calculation of cumulative infiltration at time 4.62 seconds for the run A data in Table 7.5 would be as follows:

$$I \text{ (at time = 4.62 sec)} = \frac{(18.03 \times 10^{-6}) (20.0 - 10.0)}{0.0314} = 0.00574 \text{ metres}$$

#### Step 2– Calculate sorptivity

White (1988) graphical method:

A graph of cumulative infiltration versus the square root of time for measurements at the beginning of infiltration is shown in Figure 7.6. A linear regression for the straight line portion of this graph reveals the slope of the line and therefore the sorptivity (S) is  $4.58 \times 10^{-3} \text{ m s}^{-1/2}$ .

#### Method of Warwick (1992)

Table 7.5 shows a list of calculated sorptivity values using equation 7.5 for those data points judged to be in the straight line component of the graph in Figure 7.6 (over page). The final estimate of sorptivity from this procedure is the

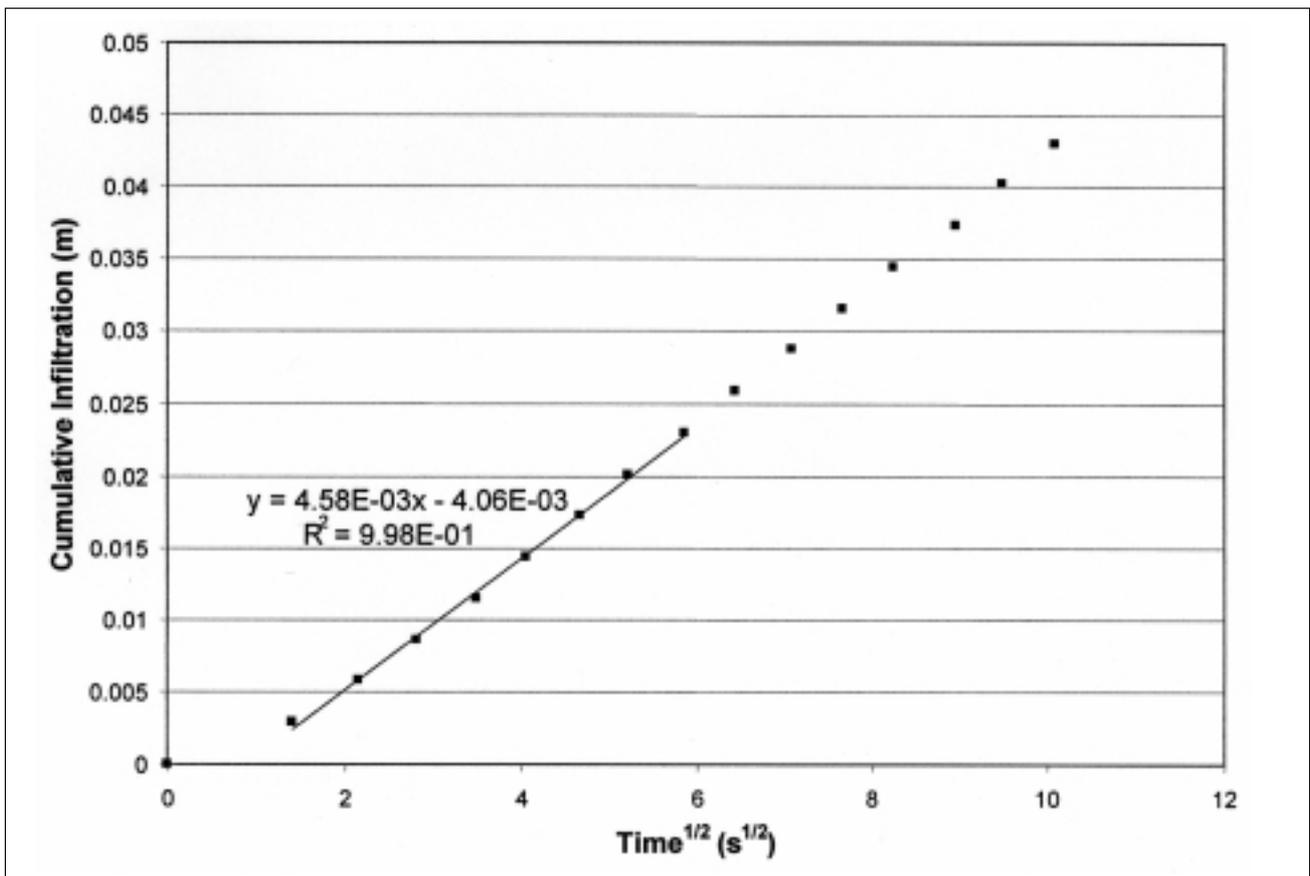


Figure 7.6. Graph of cumulative infiltration  $I (Q/\pi r^2)$  versus the square root of time for the early time infiltration data from Table 7.5.

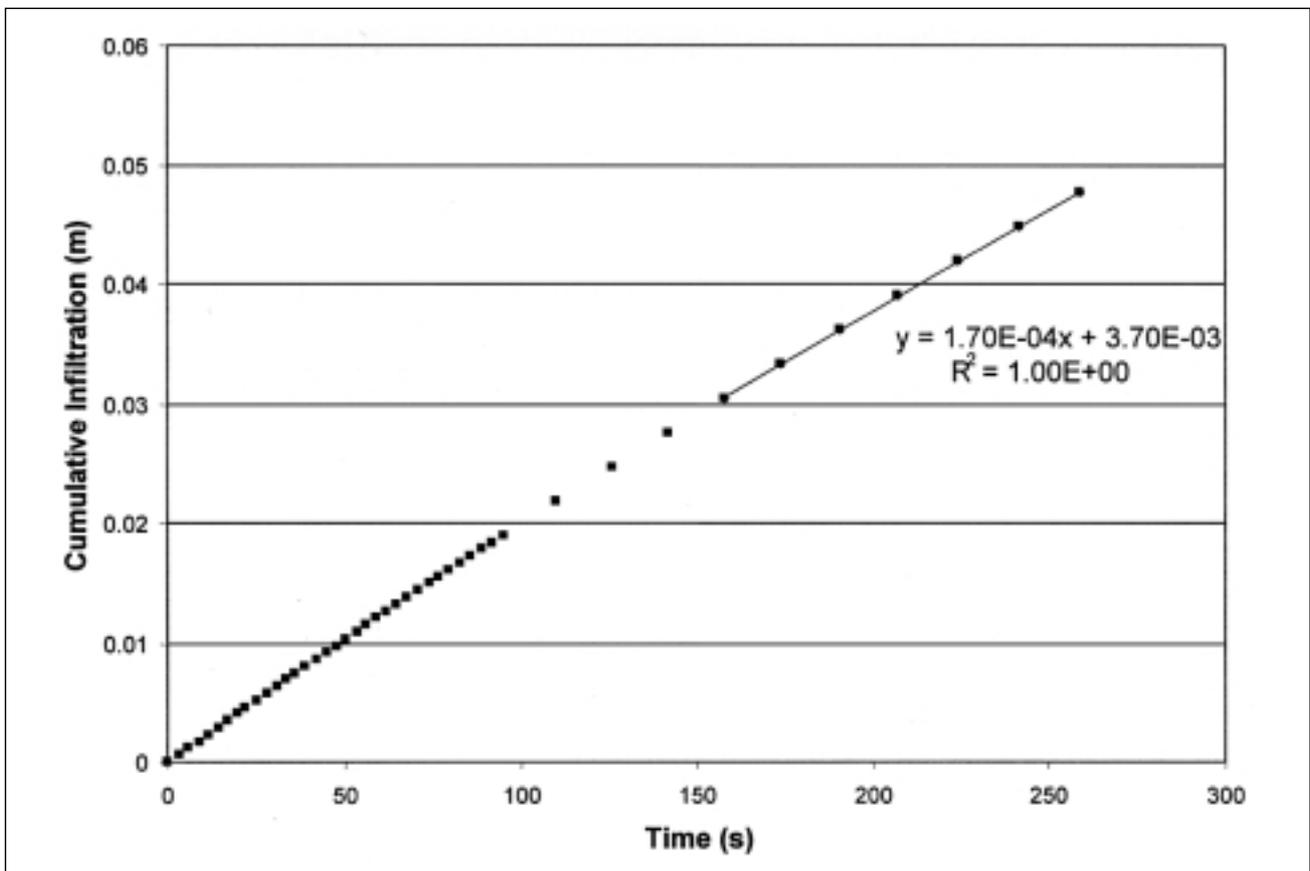


Figure 7.7. Graph of cumulative infiltration versus time for the later infiltration data from Table 7.5. A linear regression is carried out on the 'steady-state' flow data points.

average of these calculations, and in this case,  $S = 2.17 \times 10^{-3} \text{ m s}^{-1/2}$ .

### Step 3 – Determining the steady state infiltration rate ( $q/\pi r^2$ )

The steady state flow cumulative infiltration rate data ( $Q / \pi r^2$ ) from the later refill run in Table 7.5 is first graphed against time in Figure 7.7. A linear regression of the straight line component of this graph reveals that the slope of this line and therefore ( $q/\pi r^2$ ) is equal to  $1.7 \times 10^{-4} \text{ m s}^{-1}$ .

### Step 4 – Calculating K

Using graphically determined S value

$$K_s = \frac{q}{\pi r^2} - \frac{2.2S^2}{\Delta\theta\pi r}$$

$$K_s = 0.00017 - \frac{2.2 \times (0.00458)^2}{0.33 (0.314)}$$

$$= 0.00017 - 0.000445 = - 0.000275 \text{ m s}^{-1}$$

Using calculated S value (method of Warwick 1992)

$$K_s = 0.00017 - \frac{2.2 \times (0.00217)^2}{0.33 (0.314)}$$

$$= 0.00017 - 0.00009998 = 0.00007 \text{ m s}^{-1}$$

In this instance, the graphically determined S value produced a negative K value which is nonsense, while the Warwick method of calculating S produced a more sensible Ks value of  $+ 0.00017 \text{ m s}^{-1}$ . This highlights the advantage of the Warwick (1992) method in this instance.

#### *Common problems*

Failure to capture the sorptivity component of infiltration. It is often difficult to achieve the necessary early time infiltration measurements for calculating soil sorptivity. This is especially the case for rapidly draining soils, such as those on the row areas of sugarcane fields. When the sorptivity zone of infiltration has been missed, there are two options. One option is to just accept it, and record only the

"steady – state" infiltration rate. Another is to redo the measurements again, which is not only expensive but may still carry with it the same likelihood of missing the sorptivity.

Failure to capture the "steady-state" component of infiltration. This is a problem mainly associated with highly impermeable clay soil layers, especially the compacted interrow areas of the more clayey sugarcane soils. In these soils, the infiltration rate is so slow that even after a day, sorptivity is still the dominant influence on infiltration and the "steady-state" phase of infiltration is still yet to commence. Often the infiltration rate on these soils can be  $<10 \text{ mm/day}$ , with most of this meagre intake being associated more with evaporation and tropical heat than infiltration. In this situation, an average of the later measurements can be used to calculate this infiltration rate and it can be noted that steady state was yet to be reached. In all practicality, this infiltration rate could be used as a substituted for Ksat. If anything it would be an overestimation of Ksat, which is obviously very low.

### **7.5.2 Twin ring method (Ks)**

The twin ring cylinder method involves measurements using two or more different diameters of ring cylinders (method of Scotter *et al.* 1982). The twin ring method uses the steady state infiltration rates from two rings of different diameter to overcome the influence of sorptivity (Photo 7.15). This is the method for determining Ks that is recommended by McKenzie and Cresswell (2002a) and it is also outlined in detail in Cook (2002). The following



Photo 7.15 Twin ring method of determining Ksat (Photo - courtesy of Landcare Research, Hamilton, New Zealand)

is only a brief outline of the basic principles of this method. For more details readers are referred to Cook (2002) as this method is in some ways quite a complicated procedure. It involves calculating a number of additional parameters in the field in order to determine if more measurements are required (i.e. sensitivity parameter –  $ck$ ). It also involves calculating the ‘matric flux potential at saturation’ ( $\phi_s$ ) which needs to be known just to be able to determine the size of the ring which should be used for the additional measurements.

### Data required

Steady state infiltration (mm/hr or m/s)

Ring radius (mm or m)

Rings usually range in radius from 0.25 m to 0.05 m. The main advantage is that steady-state infiltration rate is the only measurement required. The main disadvantage is that it can further compound errors associated with under-sampling as it is dependent on an accurate estimate of steady state infiltration for each cylinder in order to account for sorptivity. There are also other complexities involved with this method such as sensitivity parameter calculations, and sampling considerations such as ensuring that the total area measured with each diameter ring is the same. Nevertheless this method would be appropriate where very accurate characterisations of the  $K_{sat}$  are required. The instructions and calculations for this method are outlined in Scotter *et al.* (1982) as well as in Cook (2002). All of the previous sections on surface preparation, ring installation, and water supply are just as relevant to this method as to the single ring method.

The twin ring apparatus can also be used to measure sorptivity when a few additional measurements and samples are taken. Additional data required for this include: initial infiltration rate, initial soil water content and bulk density, and final soil water content.

### The most basic calculations

The  $K_s$  calculation for this method is

$$K_s = \frac{q_1 r_1 - q_2 r_2}{r_1 - r_2} \quad (7.7)$$

where  $q_1$  is the mean steady state infiltration rate ( $m\ S^{-1}$ ) for the larger ring,  $r_1$  is the radius (m) of the larger ring,  $q_2$  is the mean steady-state infiltration rate ( $m\ S^{-1}$ ) for the smaller ring, and  $r_2$  is the radius (m) of the smaller ring.

The standard deviation is calculated using the following formula:

$$s(K) = \frac{\sqrt{\frac{(r_1 s_1)^2}{n_1} + \frac{(r_2 s_2)^2}{n_2}}}{r_1 - r_2} \quad (7.8)$$

where  $r_1$  is the radius,  $q_1$  the mean steady state infiltration rate (mm/hr) of the large ring, and  $r_2$  is the radius,  $q_2$  the mean steady state infiltration rate (mm/hr) of the small ring,  $s_1$  and  $s_2$  the standard deviation of  $q_1$  and  $q_2$  respectively, and  $n_1$  and  $n_2$  are the number of replicates for rings with radii  $r_1$  and  $r_2$  respectively (Cook 2002).

A thorough reading of both Cook (2002) and Scotter *et al.* (1982) is recommended before applying this approach to measuring  $K_s$ .

## 7.6 MEASURING UNSATURATED HYDRAULIC CONDUCTIVITY

### 7.6.1 Measuring soil $K_{us}$ with disc permeameters in the field

The disc permeameter (Photo 7.16) was developed by CSIRO to allow more thorough measurement of preferential flows through macropores. The disc permeameter allows



Photo 7.16 Using the basic model disc permeameter to measure ‘K’ at the BSES research station, Brandon.

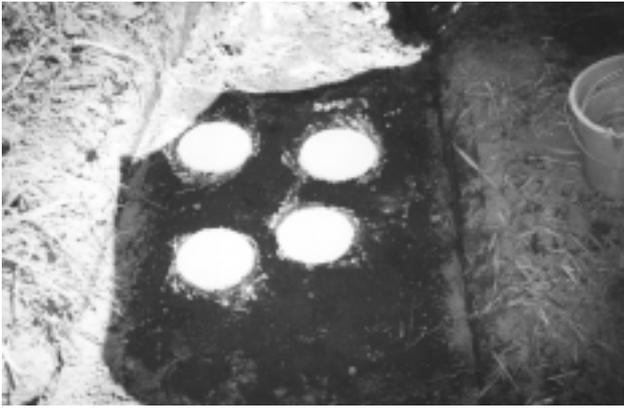


Photo 7.17 Sand pads in place ready for the disc permeameter to be placed on them.

water to be applied to the soil under a suction ( $-ve$  head or  $-ve$  soil water potential) where the soil has to draw water out of the disc permeameter. The maximum size of the soil pores contributing to water flow is controlled by the amount of suction applied. Common suctions used are  $-1\text{cm}$ ,  $-2\text{cm}$  and  $-4\text{cm}$ . These are set for the disc permeameter by adjusting the level of the air inlet tube in the bubble tower. Such measurements of soil hydraulic conductivity at different soil water potentials allow a more detailed assessment of the impact of management practices on soil porosity

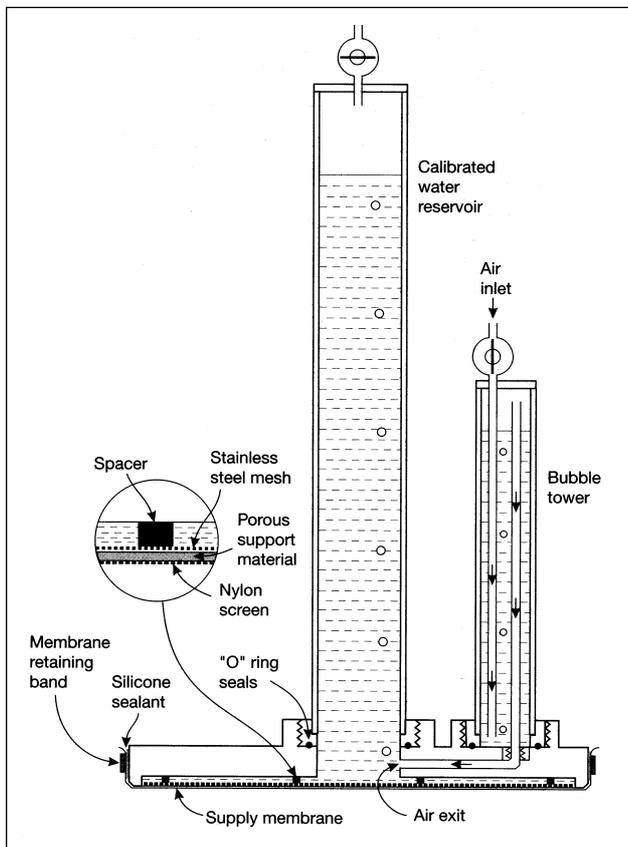


Figure 7.8. The CSIRO disc permeameter design (sourced from McKenzie et al. 2002b, © CSIRO 2002)

(Perroux and White 1988). The design of the disc permeameter is shown in Figure 7.8. The disc permeameter is usually placed on a flat sand pad on top of the prepared soil surface (Photo 7.17). Disc permeameter models with a detached water supply (Photo 7.18) have advantages over the conventional model for measurement of  $K_{us}$  on soft cultivated soil as this design prevents the weight of the reservoir from having any effect on the contact between the soil and the supply base. Photo 7.19 shows the use of a disc permeameter setup which uses pressure transducers to continuously log water height in the reservoir column versus time to a lap top computer, thus bypassing a need for manual recording. Cook (2002) however, notes that constant monitoring of system performance is essential for such automatic systems, as their apparent ease of use can be misleading. It should also be noted that although this section is focusing on the measurement of  $K_{us}$ , disc permeameters are also capable of deriving a number of other useful soil hydraulic properties such as sorptivity ( $S$ ), mean capillary pore size ( $\lambda_m$ ), macroporosity area ( $A_m$ ) and time to ponding ( $t_p$ ) (White *et al.* 1992).



Photo 7.18 A disc permeameter with a detached water supply system (photo: J. Kemei)



Photo 7.19 A disc permeameter setup capable of continuously logging infiltration data to a laptop computer via pressure transducer sensors.



Photo 7.20 Using disc permeameters to measure  $K_{us}$  in the laboratory on small soil cores collected from the field (CSIRO Davies Laboratory, Townsville).

The method for using the disc permeameter is outlined in both Perroux and White (1988) and the CSIRO disc permeameter manual (Anon 1988). McKenzie *et al.* (2002b) also provide a good coverage of the theory behind the disc

permeameter as well as practical tips for its use in the field. The method of Reynolds and Elrick (1991) which is outlined in McKenzie *et al.* (2002b) is recommended for calculating the soil's unsaturated hydraulic conductivity. This later method overcomes some of the limitations of the Perroux and White (1988) method noted by McKenzie *et al.* (2002b).

### Measurements and calculations

The methodology previously outlined in the single ring method has a number of shortfalls for calculating the saturated hydraulic conductivity of a soil. Some of these relate to the practical difficulties in measuring both sorptivity and soil moisture at the end of infiltration (McKenzie *et al.* 2002b). Another shortfall relates to the validity of the assumption that sorptivity measured at the early stages of infiltration ( $S_i$ ) is the same as that experienced at the wetting front at steady state. If soil is not homogenous with a uniform initial water content, this assumption is not valid and can result in negative values for  $K$  (McKenzie *et al.* 2002b).

The above problems can be overcome for disc permeameter (tension infiltrometers) measurements of  $K_{us}$  by adopting the Reynolds and Elrick (1991) procedure (McKenzie *et al.* 2002b). For this procedure, no measurement of sorptivity or final volumetric water content is required. Instead, hydraulic conductivity ( $K$ ) is determined from a sequence of measurements of steady-state flow ( $q_s$ , s<sup>-1</sup>) at a sequence of progressively higher potentials ( $\psi_1$ ,  $\psi_2$ ,  $\psi_3$ ) (i.e. lower suctions) on the one location. McKenzie *et al.* (2002b) recommend measurements at potentials ( $\psi$ ) of -13cm, -7cm, and -3cm. This will allow calculations of unsaturated hydraulic conductivity at potentials of -10cm and -5cm.

The data required to calculate  $K_{us}$  using this approach include: steady-state flow rate ( $q$ ) and the potential at which it was measured ( $y$ ) for at least two potentials (e.g. -7cm & -3cm), and the radius of the contact material (sand pad) area. The steady state flow rate ( $q$ ) can be calculated as the average flow rate when the steady state is achieved or else obtained from the slope of the linear portion of a plot of cumulative flow ( $Q$ ) versus time ( $t$ ). It is

important not to confuse cumulative infiltration ( $Q/\pi r^2$ ) and cumulative flow ( $Q$ ) here (McKenzie *et al.* 2002b).

Step 1 – Calculate  $\alpha$  (the soil structure parameter) for each successive ( $\psi, q$ ) data pair using the following formula where  $x$  measurement at potential ( $\psi$ ) 1,2,3 and  $y$  measurement at potential ( $\psi$ )  $x + 1$ :

$$\bar{\alpha}_{x,y} = \frac{\ln(q_x / q_y)}{(\psi_x - \psi_y)} \quad (7.9)$$

Step 2 – Calculate an average  $K$  for the same data pairs using the following formula, Where  $P = \psi_x / (\psi_x - \psi_y)$ ,  $x = 1,2,3$  and  $y = x+1$ , while  $G_d$  (the shape parameter) is given the recommended value of 0.25 (McKenzie *et al.* 2002b)

$$\bar{K}_{x,y} = \frac{G_d \bar{\alpha}_{x,y} q_x}{r(1 + G_d \bar{\alpha}_{x,y} \pi r) (q_x / q_y)^p} \quad (7.10)$$

Step 3 – Calculate the unsaturated hydraulic conductivity at the potential  $(\psi_x + \psi_y) / 2$  using the formula

$$K(\bar{\psi}) = \bar{K}_{x,y} \exp(\bar{\alpha}_{x,y} \bar{\psi}) \quad (7.11)$$

**Worked example** (adapted from McKenzie *et al.* 2002b)

*Input data;*

Steady state flow rates ( $q$ ) in  $\text{mm}^3 / \text{hour}$  for each measurement

$q_1$  ( $\psi = -40\text{mm}$ )  $5.775 \times 10^5 \text{ mm}^3 / \text{hr}$

$q_2$  ( $\psi = -30\text{mm}$ )  $1.068 \times 10^6 \text{ mm}^3 / \text{hr}$

Radius of contact material  $98.5\text{mm}$

Shape parameter ( $G_d$ ) – recommended value 0.25

*Calculations;*

Step 1 – calculating  $\alpha$

$$\bar{\alpha}_{x,y} = \frac{\ln \left[ \frac{5.775 \times 10^5}{1.068 \times 10^6} \right]}{(-40 - (-30))} = 0.061183$$

Step 2 – calculating average  $K$ :

(i) Parameter  $P$ ,

where  $P = \psi_x / (\psi_x - \psi_y) = -40 / -40 - (-30) = 4$

(ii) Insert values for  $P$  (4),  $\alpha$  (0.06183),  $G_d$  (0.25),  $r$  (98.5mm) and  $q_1$  and  $q_2$  into the formula

$$\bar{K}_{-40,-30} = \frac{0.25 \times 0.06183 \times 5.775 \times 10^5}{98.5 \times (1 + 0.25 \times 0.06183 \times 3.14159 \times 98.5) \left[ \frac{5.775 \times 10^5}{1.068 \times 10^6} \right]^4} = 44.788 \text{ mm/hr}$$

Step 3 – calculating the unsaturated hydraulic conductivity at the average of the two potentials.

In this example it is for the potential  $(-40 + -30) / 2 = -35\text{mm}$ .

$K(-35\text{mm}) = 44.788 \times \exp(0.06183 \times -35) = 5.1 \text{ mm/hr}$ .

## 7.7 LABORATORY MEASUREMENT OF HYDRAULIC CONDUCTIVITY

It is also possible to determine hydraulic conductivity (both saturated and unsaturated) on intact soil cores collected in the field (e.g. 70 mm diameter x 50 mm height). These small cores can be collected by following the method outlined in Section 6.

The main advantage of this approach is that it overcomes problems of measuring infiltration in the field (3D flow, sorptivity, water repellence). The disadvantages are that the soil cores are small and a larger number of samples may be required to deal with soil variability soil moisture conditions are important for core sampling and this approach requires either investment in equipment or else sending the samples to an outside laboratory that is able to make these measurements. Suitable laboratory methods for determining both saturated and unsaturated soil hydraulic conductivities are outlined in McKenzie *et al.* (2002c). Carrying out these measurements on a minimum of five replicate cores for each soil material being tested is recommended by McKenzie *et al.* (2002c). The CSIRO laboratory in Townsville is equipped to carry out these methods. A method of collecting larger cores (25cm diameter) for laboratory assessment of hydraulic properties to overcome the variability problems associated with smaller cores has been documented by McKenzie and Cresswell (2002b). A method for measuring saturated

hydraulic conductivity on large cores is also presented in McKenzie *et al.* (2002c).

## 7.8 USING RESULTS

The most important thing to note about infiltration measurements is the need to fully appreciate what has been measured, the limitations of those measurements, and to apply the information accordingly in resolving practical land management problems. High spatial variability is often a reality for infiltration measurements, and any lack of precision in capturing this variability needs to be taken into consideration in the application of that information.

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# SECTION 8. Modelling applications

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## 8.1 INTRODUCTION

The use of simulation models as research tools has become popular in recent times. Models have the potential to add value to research effort by allowing the results from field trials to be extrapolated over much longer periods of time and under different climatic conditions. Appropriate soil characterisation can help provide the necessary soil data to run such models. The following Section provides a brief outline of the potential of simulation modelling and then focuses on the soil data requirements of the APSIM modelling framework which is the main system used to model sugarcane crop growth in Australia.

## 8.2 WHY MODEL?

Models attempt to fulfil the following functions:

- To test and challenge our current understanding of how natural systems work
- To highlight knowledge gaps in our understanding of systems
- To provide a predictive capability which can help us address complex problems and systems
- To allow scenario analysis of the impacts over time of changes to a system
- To allow research results from a trial to be extrapolated over a longer period of time

Models provide a potential capacity for dealing with complex systems, multiple interactions, spatial and temporal variability, scenario analysis, and the extrapolation of experimental results and data in both space and time (Bristow *et al.* 2002, Dent 2000).

There are also standard pitfalls that need to be avoided in the application of simulation models. These include the need for adequate model validation, limitations in regard to the quality of parameterisation of model components, dangers of inappropriate extrapolation of model results and the

representativeness and quality of the input data. Such points are outlined in Philip (1991).

## 8.3 APSIM

The Agricultural Production Systems Simulator Model (APSIM) is a modelling framework which is capable of simulating cropping systems over different time periods using available meteorological data. "The framework provides a 'plug in plug out' facility, allowing users to select modules for modelling crops and their environments under a range of constraint conditions" (Lisson *et al.* 1999, p.10). It consists of a number of different biological, environmental and economic sub-models which can be selected in a number of combinations to model various aspects of agricultural production. A good reference for using APSIM in the sugar industry is Lisson *et al.* (1999).

## 8.4 REQUIREMENTS OF AN APSIM® INPUT DATA FILE

This section is concerned with putting together the required soils information for a soil input data file for the APSIM modelling framework. There are two models that can be used in APSIM for modelling soil water balance and solute balance. These are SoilWat and SWIMv2 (Verburg 1996) and these are the models that we are trying to supply with the necessary soil input data.

### 8.4.1 SoilWat

SoilWat (Probert *et al.* 1998) is a 'tipping bucket' type model that incorporates many of the features of PERFECT (Littleboy *et al.* 1989) and CERES (Jones and Kiniry 1986). It works on a tipping bucket model of infiltration where infiltration is allowed to occur to the layer below only after the layer in question is saturated, i.e. the bucket has to be full before soil water cascades into the next soil layer (Verburg 1996, Probert and Verburg 1996). SoilWat is the most commonly used water

balance module in APSIM.

The soil data required for SoilWat is listed in data set 4 in Section 3. It is listed again here for reference. It is desirable to obtain this information for at least each soil horizon to a depth of at least 150cm and 180cm if possible.

Data set 4 – APSIM –SoilWat model soil data

|   |
|---|
| Drained upper limit (DUL) in $\text{mm}^3/\text{mm}^3$  |
| Crop lower limit (LL) or 15 bar (-1500kPa) lower limit (LL15) in $\text{mm}^3/\text{mm}^3$  |
| Volumetric water content at saturation ( $\theta_s$ ) in $\text{mm}^3/\text{mm}^3$ (often abbreviated to SAT)   |
| Volumetric water content for air dry soil ( $\text{mm}^3/\text{mm}^3$ )   |
| Nutrient profile, especially soil N file inputs mineral N: $\text{NO}_3$ and $\text{NH}_4$ ppm, organic C%, total N%, and pH with profile depth (to 150+ cm) for field composite samples from > 15 deep soil cores *. |
| Maximum potential rooting depth in mm   |
| Layer depth interval in mm  |

\* In addition to the soil nitrogen (N) parameters listed in data set 4, there are also a number of other non soil properties which also need to be collected for the APSIM soil N parameter file. These include residue parameters such as the amount of pre and post harvest residue, the C:N ratio of the crop residue and crop N. Also climate data such as the temperature amplitude (highest minus the lowest average monthly air temperature °C) and the mean annual air temperature °C. Mazzucchelli *et al* (1997) provide guidance on the collection of this information.

Maximum potential rooting depth for sugar cane is still a difficult issue as water extraction has been measured at well below 2m under some cane crops (Geoff Inman Bamber, pers. com. 2002). But it is difficult to adequately sample soils to such depths with conventional sampling equipment. The minimum data set default of 180cm (Mazzucchelli *et al.* 1997) is one option.

### Collecting soil data using this manual

It is the quality of the soil input data in terms of its representativeness and accuracy that can

make the real difference between a successful model simulation and a mediocre result.

The soil variability survey procedures outlined in Section 2 in conjunction with the soil profile description process outlined in Section 4 can help ensure that a representative area of the field is selected for characterisation. The soil sampling and field measurement procedures outlined in Section 6 (6.5, 6.6, 6.9) provide guidelines on gathering the necessary soil data on soil water and porosity.

Two methods of determining DUL and LL for a soil are presented in Section 6. One involves monitoring the soil and crop in the field and sampling the soil when DUL and LL conditions are met (Section 6.9). The modifications to this field method outlined in Section 6.9 can help with the sampling of soils with strongly differentiated soil horizons and loose sandy layers. The other approach involves digging a pit in a representative part of the field and taking intact small soil cores from each horizon for later estimation or approximation of DUL and LL in the laboratory using pressure plate chamber and tension plate apparatus (Sections 6.5, 6.6).

Guidelines on deep core composite sampling for soil mineral N across a field is provided in Section 5.10.

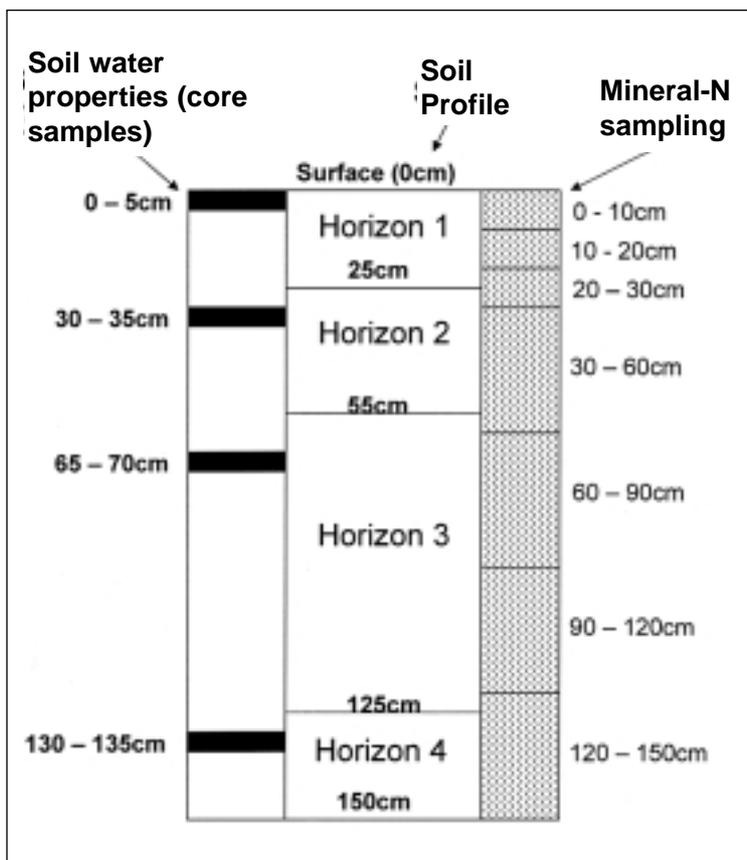
### Calculations

The formulae for calculating DUL, LL, SAT( $\theta_s$ ) and PAWC are outlined in Section 6.2.

### Combining soil nitrate data with soil horizon data

The APSIM model requires that the user select a set of depth intervals and that all soil data is entered into the system by those depth intervals. This means that soil water and mineral N data cannot be entered into the system at separate depth intervals. The mineral N data has to be combined with the soil water data to produce a set of common depth intervals for data entry (see Figure 8.1 and Table 8.1).

Combining the data is a straight forward procedure when the soil water data and the mineral N data were collected at the same sampling depth intervals as in the method



**Figure 8.1.** An example of two different soil sampling regimes (one for soil water properties and the other for soil mineral nitrogen) which will be combined with the soil horizon depths into a data set for entry into APSIM (Refer to Table 8.1).

outlined by Dalglish and Foale (1998) for uniform and gradational clay soils.

The procedure is a little more involved when the soil water data and the mineral N data have each been sampled in the field at different depth intervals. This will be the case when horizon based sampling is used to collect soil water and bulk density samples, as is recommended in this manual for soils with soil horizons that have abrupt boundaries.

The process involves subdividing the profile into common intervals. The first step involves allocating the soil water property data to the soil horizon depth intervals. If a sample was taken for each soil horizon it is a simple allocation process. If two or more samples were taken for a horizon, the horizons can be subdivided along the midpoint between the two soil water sample depths. The values of the soil water data are then transferred to these subsections of the soil horizon. At this stage the subdivided horizon depths are the most detailed soil depth interval divisions. This new

depth interval can now be referred to as "horizon based soil water depth intervals" (HBSW depth intervals).

The next phase is to transfer the mineral N data to these created sample depth intervals. When the nitrate profile data has been determined from a continuous sequence of sample depth increments down the length of the soil cores the process of combining the data is fairly simple. It involves transferring these values to those parts of the HBSW depth intervals that fall within the mineral N sampling intervals. This process further subdivides the profile where the mineral N sample depth interval boundaries fall within HBSW depth intervals.

Figure 8.1 illustrates a set of soil water property samples with another set of mineral N samples collected at different sampling depth intervals together with the soil horizon depths. The data in this example are presented in Table 8.1 and combined together to produce an input file for entry into APSIM SoilWat in the bottom half of Table 8.1.

A complication to the above situation arises where nitrate data are determined from soil samples taken at a number of smaller soil depth increments within each core, with the sampling not being continuous throughout the profile but rather having gaps between samples (as is the case with the soil water property sampling illustrated in Figure 8.1).

In this situation mineral N values can be transferred directly across to the depths where they were sampled. But it is the mineral N values in the areas between these samples that need to be extrapolated. One way of determining mineral N values for unsampled areas of the profile is to graph mineral N data versus soil depth at the midpoint of each sample. A nitrate value for areas of the soil profile not sampled for mineral N can then be determined from the graph.

#### 8.4.2 The SWIM model

SWIM (v2.1) is the second water balance model that can be used within the APSIM modelling

**Table 8.1.** An example of combining soil water and mineral N data from two separate sampling strategies (represented in Figure 8.1) with the soil horizon boundaries to generate depth intervals for data input into the APSIM model

| Sample depth<br>(cm)         | Soil properties                            |   |  |                          |                          |
|------------------------------|--|---|--|--------------------------|--------------------------|
|                              | DUL<br>(mm <sup>3</sup> mm <sup>-3</sup> ) | LL<br>(mm <sup>3</sup> mm <sup>-3</sup> ) | SAT<br>(mm <sup>3</sup> mm <sup>-3</sup> ) | NO <sub>3</sub><br>(ppm) | NH <sub>4</sub><br>(ppm) |
| <b>Soil water properties</b> |  |   |  |                          |                          |
| 0 – 5                        | 0.205                                      | 0.065                                     | 0.49                                       |                          |                          |
| 30 – 35                      | 0.225                                      | 0.120                                     | 0.36                                       |                          |                          |
| 65 – 70                      | 0.300                                      | 0.185                                     | 0.25                                       |                          |                          |
| 130 – 135                    | 0.285                                      | 0.180                                     | 0.29                                       |                          |                          |
| <b>Mineral N sampling</b>    |  |   |  |                          |                          |
| 0 – 10                       |  |   |  | 23                       | 0.95                     |
| 10 – 20                      |  |   |  | 19                       | 0.46                     |
| 20 – 30                      |  |   |  | 15                       | 0.58                     |
| 30 – 60                      |  |   |  | 10                       | 0.32                     |
| 60 – 90                      |  |   |  | 4                        | 0.55                     |
| 90 – 120                     |  |   |  | 12                       | 0.15                     |
| 120 – 150                    |  |   |  | 2                        | 0.12                     |
| <b>APSIM input data</b>      |  |   |  |                          |                          |
| <i>Horizon 1</i>             |  |   |  |                          |                          |
| 0 – 10                       | 0.205                                      | 0.065                                     | 0.49                                       | 23                       | 0.95                     |
| 10 – 20                      | 0.205                                      | 0.065                                     | 0.49                                       | 19                       | 0.46                     |
| 20 – 25                      | 0.205                                      | 0.065                                     | 0.49                                       | 15                       | 0.58                     |
| <i>Horizon 2</i>             |  |   |  |                          |                          |
| 25 – 30                      | 0.225                                      | 0.120                                     | 0.36                                       | 15                       | 0.58                     |
| 30 – 55                      | 0.225                                      | 0.120                                     | 0.36                                       | 10                       | 0.32                     |
| <i>Horizon 3</i>             |  |   |  |                          |                          |
| 55 – 60                      | 0.300                                      | 0.185                                     | 0.25                                       | 10                       | 0.32                     |
| 60 – 90                      | 0.300                                      | 0.185                                     | 0.25                                       | 4                        | 0.55                     |
| 90 – 120                     | 0.300                                      | 0.185                                     | 0.25                                       | 12                       | 0.15                     |
| 120 – 125                    | 0.300                                      | 0.185                                     | 0.25                                       | 2                        | 0.12                     |
| <i>Horizon 4</i>             |  |   |  |                          |                          |
| 125 – 150                    | 0.285                                      | 0.180                                     | 0.29                                       | 2                        | 0.12                     |

framework. The SWIM (v2.1) model which stands for **Soil Water Infiltration and Movement** was developed by CSIRO (Verburg 1996) to simulate soil water balance and solute balance. It is based on numerical solutions to the Richards equation for water flow and the advection-dispersion equation for solute transport (Verburg 1996).

### Requirements of a data input file for SWIM

The data required for SWIM (v2.1) are listed in soil data set 5 in Section 3 and are presented again below. The key soil hydraulic properties required by SWIM v2.1 are those required to solve the Richards equation and these are the storage (soil water retention curve) and transmission (soil hydraulic conductivity function) properties. The SWIM model deals

with a one dimensional soil profile which is not homogeneous in a vertical direction but is uniform in a horizontal direction. There is only one hydraulic conductivity function applied for each soil layer and it applies to the whole of that layer with no gradient from one layer to the next (Bristow and Verburg 1996).

It is the requirement for soil hydraulic conductivity measurements and full soil water retention curve data that is the main difference in using SWIM instead of SoilWat in APSIM. Soil water retention curve data and hydraulic conductivity are used to generate hydraulic property functions for input into SWIMv2 (Verburg *et al.* 1996a).

## Data set 5 – the SWIMv2 soil data set

### Soil physics (ideally for each soil horizon)

Soil water retention curve  $\psi(\theta)$  for several soil water potential ( $\psi$ ) points between saturation ( $\psi = 0$  kPa) and wilting point ( $\psi = -1500$  kPa).

Saturated hydraulic conductivity ( $K_{sat}$ ) (cm/h)

Unsaturated hydraulic conductivity at a couple of tensions (e.g. 2 cm, 4 cm) (cm/h)

Layer (horizon) depth intervals

Solute concentration depth profile in soil (starting point) required for some applications

Nutrient profile, especially soil N file inputs mineral N:  $\text{NO}_3$  and  $\text{NH}_4$  ppm, organic C%, total N%, and pH with profile depth (to 150 cm+) for field composite samples from > 15 deep soil cores \* for APSIM applications.

\* Hydraulic conductivity measurements should at the very least be done for the surface of the topsoil (row and interrow if present) and the most impeding subsoil layer.

\* Soil profile morphology should be described at all sites where these data are collected.

### Data collection

Soil water retention curve data are determined in the laboratory on small, intact replicate cores sampled from each horizon in a soil pit using the method outlined in Section 6. Saturated hydraulic conductivity is preferably measured in the field (Section 7) but can also be determined on another set of small intact cores sampled using the approach outlined in Section 6. Unsaturated hydraulic conductivity measurements can be made on another set of intact soil cores collected using the same approach as for collecting the cores for water retention (Section 6). They can also be measured in the field using a disc permeameter (Section 7).

### Calculations

A method for determining the soil water

retention curve is outlined in Section 6.4, while calculations for  $K_{sat}$  are presented in Section 7.5 and the unsaturated hydraulic conductivity measurements and calculations are presented in Section 7.6. Solute concentration in the field soil at the modelling starting point can be determined by the methods outlined in Section 5.10.

The RETC program is often used to process the soil water retention curve and  $K_{us}$  data to generate the Brooks-Corey parameters ( $\alpha$ ,  $\lambda$ ,  $\theta_r$ , and  $\theta_s$ ) which are important inputs required for modelling with SWIM. Where alpha ( $\alpha$ ) is  $-1/\text{air entry-value}$ , lambda ( $\lambda$ ) is pore size distribution parameter, theta r ( $\theta_r$ ) and theta s ( $\theta_s$ ) are the residual and saturated water contents respectively. Brooks-Corey (1966) parameters, optimised by RETC, for the Kalamia soil profile described in Appendix 1 are presented in Table 8.2.

**Table 8.2.** A table of Brooks-Corey parameters generated from the Kalamia soil profile data featured in Appendix 1

| Soil layer | $K_s$ (cm/h) | $\alpha$ (1/cm) | $\lambda$ | $\theta_r$ | $\theta_s$ |
|------------|--------------|-----------------|-----------|------------|------------|
| L1-ZC      | 0.055        | 0.021           | 0.19      | 0.21       | 0.42       |
| L3-MC      | 0.508        | 0.027           | 0.8+      | 0.27       | 0.43       |
| L4-ZLC     | 1.15#        | 0.027           | 1.11#     | 0.21       | 0.37       |
| L7-FS      | 6*           | 0.031           | 1.59      | 0.07       | 0.39       |
| L8- KS     | 21*          | 0.043           | 2.1       | 0.04       | 0.41       |

RETC optimised, except \* Book value # Interpolated + Calibrated

## 8.5. APPLICATIONS

Following the 1999 CRC Sugar APSIM workshop at Townsville, the use of this model has become much more widespread in sugarcane research. Recent applications include work by Inman-Bamber *et al.* (2001) who used APSIM to simulate sugarcane crop response to the timing of water stress and were then able to determine optimum timing of limited irrigation in the Bundaberg and Isis regions. A study by Verburg *et al.* (1996b) successfully used SWIM as APSIM-SWIM to study the leaching of bromide and nitrate under sugarcane. In recent times, researchers in the CSIRO Davies Laboratory team in the Burdekin catchment have used APSIM-SWIM

to model nitrate leaching under sugarcane crops and crop water use efficiency (e.g. Stewart *et al.* 2003, Inman-Bamber and McGlinchey 2003).

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# APPENDIX 1. Examples of detailed soil characterisations

## EXAMPLE 1 – KALAMIA, BURDEKIN

### Site details:

Exposure: Soil pit

Date of description: 18/10/2000

Landform pattern: River delta

Landform element: Backplain

Slope: 1%

Location: Kalamia Mill, Burdekin. Grid

Reference 0541 390E 7838 642N

Watertable: (wet sand) at 2.45m.

Profile photo – see Photo 4.19.

### Soil classification:

ASC: Haplic massive Brown Vertosol, non-gravelly, fine / medium fine, moderate.

VE/AE/DF/CD – E,Q / R,Y / Anthroisol

### Soil profile description:

| Horizon                    | Description  |
|----------------------------|--|
| <b>Ap1</b><br>0 – 15 cm    | Very dark grey (10YR 3/1) silty light clay; weak pedality – 10-20mm polyhedral peds; dry, hardset and strongly cracked (fine crumb structure- <2mm when moist); many fine roots(1-2mm); weak to firm consistence(when dry); field pH 6.5;<br>Abrupt boundary to;                                       |
| <b>Ap2</b><br>15 – 35 cm   | Dark reddish grey (2.5Y 3/1) silty light clay; weak pedality – 10 – 20mm subangular blocky peds; moderately moist; very plastic; many fine (1-2mm) roots; very strong consistence (when dry);some compaction evident; field pH 6.5; (includes a mill ash layer at 24-27cm);<br>Clear wavy boundary to; |
| <b>A/B</b><br>35 - 65 cm   | Very dark grey (10YR 3/1), common (10-20%) medium (10-20mm) faint dark greyish brown (10YR 4/2) mottles (mixing from ploughing); silty medium clay; massive; moist; very plastic; fine roots(1-2mm) common; field pH 7.5;<br>Sparp irregular boundry to;   |
| <b>B2</b><br>65 – 80 cm    | Yellowish brown (10YR 5/4), few (2-10%) fine (<5mm) distinct yellowish brown (10YR 5/8) mottles; silty light clay; massive, moist, very plastic, 2-10% manganiferous segregations (2-6mm); fine (1-2mm) roots - common; field pH 7.5;<br>Clear boundary to;  |
| <b>2Db</b><br>80 – 93 cm   | Yellowish brown (10YR 5/4), clayey fine sand; loose apedal – single grained; moist; < 2% manganiferous segregations (<2mm); few fine roots; field pH 7;<br>Abrupt boundary to;   |
| <b>3Db</b><br>93 – 98 cm   | Pale brown (10YR 6/3), 20-50% distinct medium (10-20mm) brown mottles (7.5YR 4/6); fine sandy loam, <2% manganese segregations (<2mm); few fine roots; moist; slightly plastic; field pH 7;<br>Abrupt boundary to;   |
| <b>4Db</b><br>98 – 106 cm  | Brownish yellow (7.5YR 6/6) , 20-50% fine dull brown mottle (10YR 5/4); clayey fine sand; massive; moist; non-plastic; < 2% manganiferous segregations (<2mm); few fine roots; field pH 7;<br>Clear boundary to;   |
| <b>5Db</b><br>106 – 307 cm | Light brown (7.5YR 6/4); coarse sand; apedal – single grained; moist; roots down to at least 1.70m; field pH 7;<br>Layer continues;  |

## Soil chemical properties:

| Soil horizon                                 | Ap1                 | A/B                      | B2                       | 5Db                |
|--|---------------------|--------------------------|--------------------------|--------------------|
| Layer number                                 | 1                   | 3                        | 4                        | 8                  |
| Soil horizon depth (cm)                      | 0-10                | 35-65                    | 65-80                    | 106-130            |
| pH <sub>w</sub>                              | 7.23                | 8.35                     | 8.40                     | 7.29               |
| EC (dS/m)                                    | 0.02                | 0.14                     | 0.19                     | 0.06               |
| Organic C (%) (Heanes)                       | 1.74                | -                        | -                        | -                  |
| Available P (mg/kg)                          |                     |                          |                          |                    |
| P sorption (mg/kg)                           |                     |                          |                          |                    |
| Available Si (mg/kg)                         | 102                 | -                        | -                        | -                  |
| Exchange properties (cmol (+) / kg)          |                     |                          |                          |                    |
| CEC  | 21                  | 21                       | 17                       | 3.5                |
| ECEC   | 25                  | 21                       | 16                       | 2.9                |
| Ca   | 13                  | 12                       | 8.8                      | 1.4                |
| Mg   | 9.6                 | 7.5                      | 5.9                      | 1.2                |
| K  | 0.54                | 0.19                     | 0.17                     | 0.05               |
| Na   | 0.99                | 1.5                      | 0.94                     | 0.24               |
| H + Al                                       | -                   | -                        | -                        | -                  |
| Cl (%)                                       | 0.023               |                          |                          |                    |
| Base saturation (%)                          | 100                 | 100                      | 100                      | 100                |
| Base status (cmol(+) kg <sup>-1</sup> clay)  | 71.8<br>(Eutrophic) | 65.2<br>(Eutrophic)      | 63.8<br>(Eutrophic)      | 126<br>(Eutrophic) |
| ESP (%)                                      | 4.1                 | 7.1                      | 5.9                      | 8.3                |
| CEC to clay ratio (CCR)<br>(clay mineralogy) | -                   | 0.65<br>(high smectite ) | 0.64<br>(high smectite ) | -                  |

## Soil physical and hydraulic properties:

|  |            |              |       |       |         |         |
|--|------------|--------------|-------|-------|---------|---------|
| Soil horizon depth (cm)  | 0-15cm     | -            | 35-65 | 65-80 | 98-106  | 106-307 |
| Soil core sampling depth interval (cm)   | 2-7        | 2-7          | 43-48 | 65-70 | 100-105 | 130-135 |
| Horizon  | AP1<br>Row | AP1<br>Inter | A/B   | B2    | 4D      | 5D      |
| Texture  | ZLC        | ZLC          | ZMC   | ZLC   | CFS     | KS      |
| Bulk density (g/cc)  | 1.32       | 1.52         | 1.54  | 1.68  | 1.47    | 1.46    |
| Particle size (< 2mm fraction) (%)   |            |              |       |       |         |         |
| Coarse sand  | 10.4       | -            | 11.5  | 15.2  | -       | 87.0    |
| Fine sand  | 27.4       | -            | 24.5  | 42.7  | -       | 9.3     |
| Silt   | 28.6       | -            | 31.4  | 17.3  | -       | 1.4     |
| Clay   | 33.6       | -            | 32.5  | 24.8  | -       | 2.3     |
| Gravel content (% of total)  | -          | -            | -     | -     | -       | -       |
| Soil water retention   |            |              |       |       |         |         |
| Volumetric water content (mm <sup>3</sup> mm <sup>-3</sup> ) at matric potential ( $\psi_m$ ) =X |            |              |       |       |         |         |
| $\psi_m = 0.01m$   | 0.445      | 0.422        | 0.429 | 0.388 | 0.406   | 0.412   |
| $\psi_m = 0.10m$   | 0.421      | 0.419        | 0.427 | 0.388 | 0.400   | 0.410   |
| $\psi_m = 0.30m$   | 0.380      | 0.415        | 0.425 | 0.373 | 0.376   | 0.255   |
| $\psi_m = 0.50m$   | 0.364      | 0.412        | 0.416 | 0.355 | 0.233   | 0.107   |
| $\psi_m = 1.00m$   | 0.342      | 0.400        | 0.396 | 0.335 | 0.125   | 0.072   |
| $\psi_m = 3.06m$   | 0.298      | 0.352        | 0.361 | 0.280 | 0.081   | 0.042   |
| $\psi_m = 30.6m$   | 0.245      | 0.304        | 0.332 | 0.265 | 0.073   | 0.040   |
| $\psi_m = 51.0m$   | 0.230      | 0.291        | 0.316 | 0.254 | 0.070   | 0.042   |
| $\psi_m = 153.0m$  | 0.220      | 0.281        | 0.307 | 0.249 | 0.068   | 0.040   |
| Drained upper limit or field capacity (mm <sup>3</sup> mm <sup>-3</sup> )                        | 0.342      | 0.400        | 0.396 | 0.335 | 0.125   | 0.072   |
| Lower limit (LL15) or permanent wilting point (mm <sup>3</sup> mm <sup>-3</sup> )                | 0.220      | 0.281        | 0.307 | 0.249 | 0.068   | 0.040   |
| Plant available water capacity (PAWC) (mm mm <sup>-1</sup> )                                     | 0.122      | 0.119        | 0.089 | 0.086 | 0.057   | 0.032   |
| Total porosity (mm <sup>3</sup> mm <sup>-3</sup> )   | 0.50       | 0.43         | 0.42  | 0.37  | 0.45    | 0.45    |
| Saturation (mm <sup>3</sup> mm <sup>-3</sup> )   | 0.46       | 0.39         | 0.39  | 0.33  | 0.38    | 0.38    |
| PAWC (vol %)   | 12.2       | 11.9         | 8.9   | 8.6   | 5.7     | 3.2     |
| Porosity (vol %)   | 50         | 43           | 42    | 37    | 45      | 45      |
| Saturation (vol %)- calculated   | 46         | 39           | 39    | 33    | 38      | 38      |
| <i>Hydraulic Conductivity</i>  |            |              |       |       |         |         |
| Unsaturated Kh –4cm (on small cores r=3.5cm) (mm / hour)   | 2.33       | 0.13         | 0.30  |       |         | 4.52    |
| Unsaturated Kh –2cm (on small cores r=3.5cm) (mm / hour)   | 2.61       | 0.15         | 0.32  |       |         | 103.4   |
| Field saturated (Ksat) (mm / hour)   | 314        | 0.17         | 1.6   |       |         |         |

## EXAMPLE 2– LANGBECKERS RD, BUNDABERG

Location: Langbeckers Rd, Bundaberg. Grid  
Ref: 0440 214E 7244 923N  
Profile photo: See Photo 4.1.

### Site details:

Exposure: Soil pit  
Date of description: 11/09/2001  
Landform pattern: Alluvial plain  
Landform element: Terrace  
Slope: 1%

### Soil classification:

ASC: Ferric-Sodic Mesotrophic Red Kandosol –  
thick, non-gravelly, clay loamy A1/ clayey B,  
very deep. KA / AA / AG / HC – C, E, M /  
O,

### Soil profile description:

| Horizon                     | Description  |
|-----------------------------|--|
| <b>Ap1</b><br>0 – 32 cm     | Dark greyish brown (10YR 4/2); sandy clay loam; massive, hardest and compacted on the interrow / soft surface condition on the row, with a firm consistence when dry; moderately moist; fine roots(1-2 mm) common; field pH 6.5;<br>Sharp boundary to;         |
| <b>A2 / B1</b><br>32 – 70cm | Brownish yellow (10YR 6/6) (10YR 6/3 – dry) with 10-20% faint fine yellowish brown (10YR 5/4) mottles (<5 mm); clay loam-fine sandy; massive; moderately moist; strong consistence when dry; fine (1-2 mm) roots common; field pH 5.0;<br>Gradual boundary to; |
| <b>B21</b><br>70 – 122 cm   | Red (2.5YR 4/8) with 20-50% coarse prominent brownish yellow (10YR 10/6) mottle (15-30 mm); silty clay loam; massive but crumbly when moist; 2-10 % fine ironstone nodules (2-6 mm); few fine roots (1-2 mm); field pH 6;<br>Clear boundary to;                |
| <b>B22</b><br>122-150 cm    | Red (2.5YR 4/8); silty clay loam; massive; moderately moist; very strong consistence when dry; 20-50% coarse ironstone nodules (6-20 mm); few fine roots (1-2 mm); field pH 6;<br>Layer continues;   |

## Soil chemical properties:

| Soil horizon                                 | Ap1                 | A2/B1               | B21                  | B22                  |
|--|---------------------|---------------------|----------------------|----------------------|
| Layer number                                 | 1                   | 2                   | 3                    | 4                    |
| Soil horizon depth (cm)                      | 0-32                | 32-70               | 70-122               | 122-150              |
| Sample depth intervals (cm)                  | 0-10                | 32-57               | 90-122               | 122-150              |
| pHw  | 6.35                | 4.44                | 5.48                 | 5.92                 |
| EC (dS/m)                                    | 0.06                | 0.07                | 0.05                 | 0.06                 |
| Organic C (%) (Heanes)                       | 1.44                | -                   | -                    | -                    |
| Available P (mg/kg)                          |                     |                     |                      |                      |
| P sorption (mg/kg)                           |                     |                     |                      |                      |
| Available Si (mg/kg)                         |                     |                     |                      |                      |
| Exchange properties (cmol (+) / kg)          |                     |                     |                      |                      |
| CEC  | 8.0                 | 2.2                 | 2.4                  | 4.1                  |
| ECEC   | 6.6                 | 1.3                 | 3.4                  | 3.5                  |
| AEC  | -                   | -                   | -                    | 0.74                 |
| Ca   | 5.4                 | 0.89                | 2.2                  | 1.9                  |
| Mg   | 0.90                | 0.19                | 0.94                 | 1.40                 |
| K  | 0.14                | 0.02                | 0.02                 | 0.03                 |
| Na   | 0.16                | 0.17                | 0.19                 | 0.27                 |
| H + Al                                       | -                   | 1.16                | 0.143                | 0.116                |
| Cl (%)                                       | 0.036               | -                   | -                    | -                    |
| Free Fe (%)                                  | -                   | -                   | 0.08                 | -                    |
| Base saturation (%)                          | 100                 | 52.3                | 95.7                 | 96.8                 |
| Base status (cmol(+) kg <sup>-1</sup> clay)  | 45.5<br>(Eutrophic) | 4.3<br>(Dystrophic) | 8.7<br>(Mesotrophic) | 9.7<br>(Mesotrophic) |
| ESP (%)                                      | 2.4                 | 7.0                 | 5.4                  | 7.3                  |
| CEC to clay ratio (CCR)<br>(clay mineralogy) | -                   | 0.08<br>(kaolinite) | 0.09<br>(kaolinite)  | 0.1<br>(kaolinite)   |

## Soil physical and hydraulic properties:

|  |         |       |       |        |         |
|--|---------|-------|-------|--------|---------|
| Soil horizon depth range (cm)  | 0-32 cm | -     | 32-70 | 70-122 | 122-150 |
| Soil core sampling depth interval (cm)   | 2-7     | 2-7   | 35-40 | 90-95  | 135-140 |
| Horizon  | AP1     | AP1   | A2/B1 | B21    | B22     |
|  | Row     | Inter |       |        |         |
| Texture  | SCL     | -     | CL-fs | ZCL    | ZCL     |
| Bulk density (g/cc)  | 1.50    | 1.80  | 1.72  | 1.65   | 1.72    |
| Particle size (< 2mm fraction) (%)   |         |       |       |        |         |
| Coarse sand  | 49.1    | 49.7  | 39.1  | 33.2   | 34.7    |
| Fine sand  | 28.3    | 26.7  | 21.9  | 19.9   | 19.8    |
| Silt   | 8.1     | 8.5   | 9.5   | 8.5    | 8.2     |
| Clay   | 14.5    | 15.1  | 29.5  | 38.4   | 37.2    |
| Gravel content (% of total)  | 0.56    | 0.44  | 0.11  | 1.15   | 23.5    |
| Soil water retention   |         |       |       |        |         |
| Volumetric water content ( $\text{mm}^3 \text{mm}^{-3}$ ) at matric potential ( $\psi_m$ ) = X |         |       |       |        |         |
| $\psi_m = 0.01\text{m}$  | 0.412   | 0.304 | 0.343 | 0.400  | 0.364   |
| $\psi_m = 1.00\text{m}$  | 0.215   | 0.252 | 0.278 | 0.324  | 0.269   |
| $\psi_m = 3.06\text{m}$  | 0.130   | 0.174 | 0.208 | 0.255  | 0.217   |
| $\psi_m = 153.0\text{m}$   | 0.089   | 0.121 | 0.184 | 0.221  | 0.202   |
| Drained upper limit or field capacity<br>( $\text{mm}^3 \text{mm}^{-3}$ )                      | 0.215   | 0.252 | 0.278 | 0.324  | 0.269   |
| Lower Limit (LL15) or permanent<br>wilting point ( $\text{mm}^3 \text{mm}^{-3}$ )              | 0.089   | 0.121 | 0.184 | 0.221  | 0.202   |
| Plant available water capacity<br>(PAWC) ( $\text{mm} \text{mm}^{-1}$ )                        | 0.126   | 0.131 | 0.094 | 0.103  | 0.067   |
| Porosity ( $\text{mm}^3 \text{mm}^{-3}$ )  | 0.434   | 0.321 | 0.351 | 0.377  | 0.351   |
| Saturation ( $\text{mm}^3 \text{mm}^{-3}$ )  | 0.379   | 0.266 | 0.301 | 0.327  | 0.301   |
| <i>Hydraulic Conductivity</i>  |         |       |       |        |         |
| Field saturated (Ksat) (mm / hour)   | 687     | 37    |       | 231    |         |