Rapid soil measurement – a review of potential benefits and opportunities for the Australian grains industry

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Summary

A revolution in environmental sensing and measurement is underway. Sensors are becoming smaller, faster, more energy efficient, wireless and cleverly programmed. Soil measurement is now receiving much greater attention because of the demands of precision agriculture and the need for better technologies to support contamination and remediation investigations.

This review outlines why soil measurement is needed to improve the efficiency of crop production in Australia. Potential technologies for rapid soil measurement are described, along with an assessment of their ability to determine key properties affecting crop growth (soil water content, available water capacity, nitrogen, phosphorus, potassium, pH, salinity, sodicity, soil strength, drainage). There are several promising sensors and the priority effort should be directed towards integrating these into practical measurement systems for agriculture. A key issue is determining whether real-time or *near* real-time measurement is required — in most cases the latter will be adequate.

Some practical issues in mapping soil properties are discussed along with the challenges associated with monitoring soil change. The review concludes with a commentary on the need for a multi-pronged approach to the development of an improved soil information base for Australian agriculture.

We have identified the following areas to be worthy of investment.

Specimen acquisition and preparation

- Rapid geo-referenced sampling systems are necessary for collecting soil specimens from the field (disturbed soil and undisturbed cores) for near-surface and deeper soil characterisation.
- Automatic preparation equipment (drying, grinding and homogenising) is needed to supply these specimens in prepared batches for analysis using various rapid sensors (e.g. mid infrared, near infrared).
- Likewise, rapid coring systems are necessary for deeper soil characterisation.
- The implementation of ion-selective field effect transistors requires further development of automatic sampling and extraction systems.

Measurement platforms

- The potential for automatic core scanning using a range of sensors should be investigated — options for down-borehole scanning should also be considered.
- There is potential for improving mid-infrared data acquisition (e.g. automatic staging and batch analysis) and combining these with other spectral ranges in the near infrared and visible.
- There is merit in developing integrated ground-based measurement systems that include a full set of sensors.

Sensors and measurement systems

- Increasing the scanning area of mid-infrared instruments will improve predictions of soil properties. This requires the involvement of instrument manufacturers.
- Several improvements to electromagnetic (EM) survey instruments are feasible and these should be investigated as a means for obtaining soil water content profiles and information on electrolyte concentrations.
- Ion-selective field effect transistors have considerable potential both for real-time measurement and low-cost batch measurement. Confirmation of the robustness of these sensors would be beneficial.
- Cheap telemetry systems are opening up new and cost-effective possibilities for monitoring soil water content across the landscape. Opportunities for these systems in dryland farming should be investigated.
- Resin-based soil measurement systems will probably never achieve real-time reporting, but laboratory and *in situ* assessment of soil nutrient status using multi-element capability resins is worth further evaluation. In particular, their potential use during the cropping season needs to be assessed.
- A watching brief should be maintained on measurement technologies that at present are either very expensive (e.g. field-based X-ray fluorescence, laser luminescence) or at a very

preliminary stage of development (e.g. chemiresistors, ‘electronic noses’, ‘labs-on-a-chip’, nano-technology).

Integrated soil and crop measurement

- Temporal remote sensing with a frequent return interval during the growing season has the potential to identify differences in crop water use and soil hydraulic properties. Further investigation is needed to determine whether these methods can be of assistance to farmers.
- Analysis is needed of the potential for balanced soil and plant analysis systems to ensure targeted and effective measurement — direct soil measurement is not always the best option for identifying soil-related problems (e.g. nutrient deficiencies, waterlogging).

Key data sets

- Calibration data sets for mid-infrared measurements are needed across the major soils used for cropping in Australia.
- Soil hydraulic property measurements are needed on representative soils across the cropping lands of Australia to provide a better basis for estimation using rules of thumb and more formal pedotransfer functions (e.g. for plant-available water capacity, permeability).
- High-resolution digital elevation models are invaluable and steps should be taken to ensure that a better coverage is obtained for the cropping lands of Australia.
- A basic level of land resource survey is required across the cropping lands of Australia to ensure greater awareness of soil-based limitations to crop production and to provide basic data sets (e.g. for hydraulic property estimation). Such a survey framework can provide a first approximation of likely soil properties limiting production along with remedies.

Training and protocols

- Effective application of new and existing technologies for soil measurement requires training programs for technical groups, consultants and farmers.
- Protocols are needed for site-specific rules of soil-test interpretation.

1. Introduction

Crop production is strongly influenced by soil properties, rooting depth, nutrition, agronomic management, and their interaction with climate. The advent of precision agriculture and demands for more efficient crop production have both highlighted the need for timely information on soil properties, preferably as maps for individual paddocks. This information is needed to:

- diagnose constraints to production
- reduce risks associated with decisions on the quantity and timing of inputs
- manage off-site impacts.

In Australia there is a lack of site-specific information on soil conditions for most farms (e.g. maps of critical soil properties relating to nutrition, subsoil constraints, plant-available water capacity). Unlike the United States, detailed soil survey programs to support crop production have not been undertaken across large parts of Australia's cropping lands[1].

However, it is widely considered that new technologies for soil measurement are now creating an efficient means for providing farmers with relevant information to support better systems for crop production. Some of these technologies are in their infancy. Others are well developed in terms of their instrumentation but have few agreed procedures for data analysis and interpretation of crop performance.

This review reports on the potential benefits and opportunities for real-time or near real-time soil testing, to help determine priorities for investment by the Grains Research and Development Corporation. While there is a focus on the information requirements of precision agriculture, the task of providing more appropriate soil information to the complete grains industry is also considered. The review provides assessments of:

- the potential benefit of soil information to farmers, assuming that it can in fact be provided at a reasonable cost
- technical aspects of new methods in relation to their capacity to efficiently measure soil properties relevant to crop production. This includes identifying the uncertainties associated with particular technologies and evaluating the range of soil conditions over which they work well.

Assessing the potential benefit of soil information for farmers is a difficult task because it requires a clear model of how information is used in decision making. It is essential, therefore, to consider the benefits and costs of soil information in the broader context of technical, financial and other sources of information used for decision making.

[1] See McKenzie (1991) for a review of the issues. Note that County surveys in the United States are usually at a scale between 1:10,000 and 1:20,000. For a map to be useful for most farmers, a cartographic scale of 1:5000 is usually required. Note also that dividing the scale by two requires roughly four times the survey effort.

2. Why is soil measurement needed?

The value of soil measurement depends entirely on whether it can change a farmer's management choices — the change in management, if it does occur, is the result of a reduction in uncertainty about the impacts of different management strategies. Pannell and Glenn (2000) outline a range of related insights that follow from this simple principle.

- The range of climates, land management options, soil types and perceptions of risk varies between farms and regions — the utility of soil measurement will likewise vary considerably across the cropping lands of Australia.

- The value of soil measurement may reduce with time as uncertainty is reduced. In some instances, a few measurements may suffice and further measurements will have limited value. For example, an initial soil survey may indicate that particular land management units are moderately acid, and spatially quite uniform — there may be sufficient knowledge to recommend an appropriate long-term liming strategy and further frequent monitoring (e.g. on an annual basis with near real-time equipment) may be deemed unnecessary.

- Soil measurement will be of zero benefit if there is no realistic probability of a resulting change in management.

- The value of soil measurement will be high if production or environmental outcomes are sensitive to management choices. This is often not the case. Conversely, if production or environmental outcomes are very sensitive to management choices, then the best management strategy may be so obvious that measurement is not needed.

- The greater the current level of uncertainty about a soil factor, the greater is the value of measurement, provided it leads to a reduction in uncertainty. For example, there are usually significant uncertainties about soil nitrate concentrations whereas knowledge relating to other variables is usually more certain (e.g. pH and organic matter content).

- Soil measurement will be beneficial when there is a close relationship between the measured soil property and the payoff from different management options. For example, knowledge of the pre-season available water store in conjunction with seasonal rainfall outlooks is invaluable for planning crop management; in particular, estimating nitrogen requirements.

- The greater the degree of uncertainty about the consequences of different management strategies, the lower will be the value of measuring the related soil property. For example, several nutrient-related soil properties (e.g. pH, available P, nitrate) may be important to crop yield but rainfall patterns and root pathogens may substantially increase the uncertainty about how these soil properties influence yield. These uncertainties diminish the value of the measurement program — while it is known that soil factors may limit yield, investing in measurement will not necessarily help to identify the optimal approach to crop management.

These principles have been used to derive the following criteria for identifying circumstances where soil measurement is worthwhile.

- The farm or farmer should have a suspected or known soil-based management problem or opportunity that controls production to a high degree.
- In at least some situations, it is worth changing management practices to deal with the issue (e.g. changes to fertiliser or soil amendment additions, tillage or rotations).
- The payoff has some sensitivity to the soil management option, so the farmer benefits from its adoption.
- The payoff is not so sensitive to the soil management option that it is obvious whether the option should be adopted.
- There is a high degree of uncertainty about the magnitude and dynamics of the soil property to be measured.

- There is low uncertainty about links between the measured soil property, management practices and system output (e.g. crop yield, water quality etc).
- The soil property can be measured reliably and accurately.
- The cost of measuring the soil property is relatively low.

2.1 Existing soil information for farmers

Australian agriculture has traditionally operated with very poor information on the soil resource base. There are many reasons for this surprising state of affairs including the historically low input nature of extensive farming, the high cost of soil testing compared to other countries, and the dominance of seasonal weather conditions on crop performance. The trend to higher input farming, better weather predictions and unrelenting demand for efficiency has highlighted the importance of soil factors in new ways. The results of precision agriculture have also given a new appreciation of the potential gains possible through better matching of management practices with soil conditions (e.g. Cook and Bramley 1998, 2000; Bramley and Janik 2003). Before considering the potential benefits of rapid soil measurement, context is needed on existing soil information for farmers. Existing sources of information can be considered in a simple hierarchy (Table 1).

Table 1: Summary of forms of published soil information available to farmers arranged according to resolution

Type of soil information	Range in resolution	Supporting soil measurement	Relevance to management and cost	Cost to farmer
Broad soil types & crop performance	>1000 km^2	Minimal	Limited	Public information
Conventional soil maps supported by extension activities	100 ha – 10 km^2	Soil description with restricted soil chemical and physical analysis	Provides broad context	Public information
Farm plans and soil test results	10–100 ha	Paddock level testing of nutrients (usually restricted to near surface)	Basis for some management decisions (e.g. fertiliser)	Modest (<\$1 ha^{-1})
Precision agriculture	0.01–1 ha	Intensive measurement within paddocks	Detailed tracking of system inputs, outputs and soil condition	Significant (>\$5 ha^{-1})

Broad soil types and performance
Most farmers rely on informal and often apparently vague definitions of soil types on their farm and in their district (e.g. red loam, black clay). Typical values for key soil properties are generally unavailable and it is therefore difficult to diagnose soil factors limiting crop production. This level of information does not provide a reliable framework for applying extension and research recommendations.

Furthermore, knowing that a field contains two or more soil types is not necessarily helpful and it may lull a farmer into believing there is only limited soil variation. The results of over three decades of work on the spatial variability of soil properties (Beckett and Webster 1971, Wilding and Drees 1983, Burrough 1993, McBratney and Pringle 1999) have shown that soil properties can be highly variable and do not necessarily cluster into distinct groups either spatially (as coherent map units) or in a multivariate sense (as conceptual soil types). The issue of the correlation structure of soil properties has many practical implications — it is considered in Section 6.

Conventional soil maps supported by extension activities
The cropping lands of most countries have soil maps with a reasonable level of detail. For example, cropping lands in the United States have maps at a scale of 1:15,000 or better and so soil patterns in individual fields are depicted to the point where at least major differences in soil type are shown.

There are very few areas in the cropping lands of Australia with a comparable coverage. A few regions have a legacy of good soil survey — for example, the soil type names and distinctions widely used on the Darling Downs are a result of pioneering soil surveys in the 1950s (e.g. Thompson and Beckmann 1959).

Some states now have a regional scale coverage that allows the major soil types in each district to be identified and mapped at a broad level (e.g. Western Australia and South Australia have cropping lands mapped at 1:100,000 or 1:250,000 in more marginal areas)[2]. Some of these surveys have associated extension programs that use soil-pit field days at representative sites across cropping districts.

These have generated substantial benefits to farmers including:

- identification of key soil physical and nutrient factors limiting production (e.g. subsoil constraints)
- a framework for understanding soil and landscape variation in a district
- a better basis for interpreting whether extension and research results apply to their farm given area
- local rules for identifying and estimating soil properties constraining crop production.

The spatial resolution of this information is usually too coarse to enable tailoring of crop and soil management at the paddock level.

Less than half the cropping lands of Victoria, New South Wales and Queensland have soil surveys at a medium level of detail or better (i.e. more detailed than 1:100,000). This situation is unlikely to change substantially during the next five years due to limited public funding.

Farm plans and soil test results

Farm planning and soil testing have improved the general awareness of soil-based constraints to crop production and, in some cases, broader issues of natural resource management. While differences in soil type may be delineated, most management practices are uniformly applied across paddocks. Routine soil testing is widely encouraged (e.g. Glendinning 1999, FIFA 2001) but it is still undertaken by a minority of farmers and the interpretation of some test results to guide decisions on fertiliser application is fraught with uncertainty (Cook and Bramley 2000). While soil chemical testing has been seen as a routine procedure for deciding on fertiliser and lime requirements for some time, the advent of farming system modelling is demanding measurement of soil physical properties, particularly plant-available water capacity (e.g. Dalgliesh and Foale 1998).

Precision agriculture

Crop yield variations within paddocks can be considerable (e.g. Pringle et al. 2003) and uniform management can result in significant inefficiencies (Cook and Bramley 1998) in the form of yield losses and environmental problems. Precision agriculture aims to match the application of inputs and treatments across a paddock with soil variation and crop requirements. This differential treatment can be applied in a continuous manner or to management zones within the paddock (see Section 6.2). McBratney and Pringle (1999) show that, for soil surveys to be done at scales that are consistent with precision agriculture, grids of no bigger than 20 metres would be required. However, there may be limited extra gains when the number of management zones is increased beyond three or four because of the flat response curve between financial return and input levels.

Either way, there is a demand for within-paddock information on soil properties that control crop performance. The cost and time required for traditional soil sampling and chemical analysis are much too large for economic use in precision agriculture (Viscarra Rossel and McBratney 1998a) and this has led to the widespread interest in the development of real-time or near real-time soil sensing systems, hence this review.

2. Western Australia: See Schoknecht and Tille (2002) - http://www.agric.wa.gov.au/progserv/natural/assess/index.htm

South Australia: http://sustainableresources.pir.sa.gov.au/pages/soils/information/products/landuse_cd.htm

3. Potential technologies for rapid field measurement

For the purpose of this review, it is useful to start with a survey of measurement technologies before considering their capacity to measure key soil properties influencing crop production. We have restricted our assessment to technologies that, in our view, have the potential to be used for practical field-based soil measurement in the coming decade.

A watching brief should be maintained on measurement technologies that at present are either very expensive (e.g. field-based X-ray fluorescence, laser luminescence, various systems used in Martian exploration[3]) or at a very preliminary stage of development (e.g. chemiresistors, 'electronic noses', 'labs-on-a-chip', nano-technology).

Several of the most promising technologies for rapid field measurement are based on spectral reflectance imagery or imaging spectroscopy of soil specimens. These sensing methods use measurements of reflected or emitted radiation for diagnostic wavelengths within the electromagnetic radiation spectrum (Figure 1). Passive systems, such as those commonly used in satellite-based remote sensing, rely on the sun's reflected radiation. Active systems are more useful for soil sensing and they rely on materials being illuminated at close range by sources with known spectral characteristics and brightness — analysis of the absorbed, transmitted or reflected radiation is used to identify constituents.

While spectroscopic methods have a very long history in science and technology, it has been only in recent decades that miniature systems with associated data analytic capabilities have become available at relatively low cost.

The potential of these systems for soil sensing depends primarily on:

- frequency range of the instrument
- richness of the electromagnetic radiation spectrum in the specific range for identifying soil constituents
- specimen preparation requirements.

3.1 Mid infrared

Principle and applications

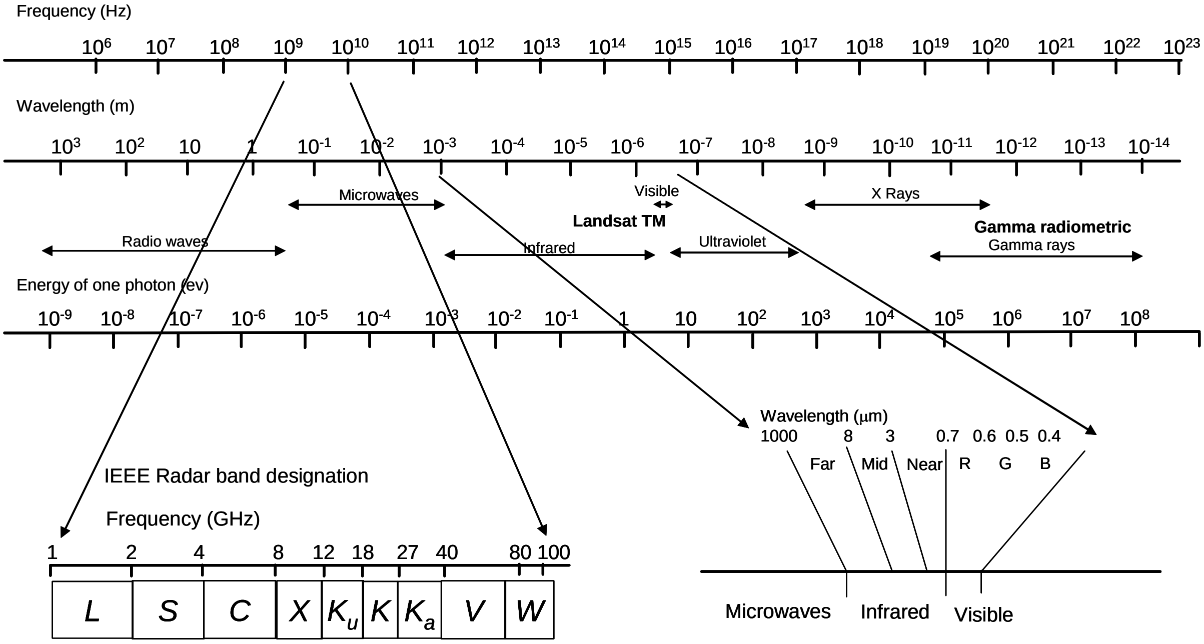
Many soil properties are dependent on soil constituents that can be recognised by the number, position and sharpness of characteristic peaks in their infrared patterns. Infrared methods have advantages over X-ray methods in that spectra are sensitive to amorphous organic and inorganic compounds, adsorbed water, as well as crystalline minerals (e.g. clay minerals) (Janik et al. 1995). The fundamental molecular frequencies for most soil constituents lie in 2500–25 000 nm mid-infrared range and they have overtone and combination modes both in the 700–2500 nm near-infrared range, as well as the mid-infrared range. These overtones and modes have reflectance peaks that are less clear than those at the fundamental frequencies.

Another very significant advantage of mid infrared is its sensitivity to quartz — this mineral makes up most of the silt and sand fraction in Australian soils. The ability to discriminate quartz therefore allows good prediction of clay content (i.e. the complement of percentage sand + silt content). In combination with determinations of organic constituents and clay mineralogy, this allows good characterisation of many physical and chemical properties.

[3] See instruments on the Beagle 2 Lander http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31033&fbodylongid=663

and NASA's Mars Exploration Rover Mission http://mars.jpl.nasa.gov/mer/mission/spacecraft_surface_instru.html

Figure 1: The electromagnetic spectrum, highlighting the useful parts for obtaining information on soil and environmental variables through remote and proximal sensing (McBratney et al. 2003)



Infrared spectra contain an enormous amount of information on soil constituents and, until recently, the complexity was overwhelming. The advent of robust multivariate statistical methods, such as partial least squares, now ensures more effective exploitation. These statistical methods require analysis of soil materials with known chemical and physical properties (i.e. determined using conventional chemical and physical methods). The resulting spectra form a calibration data set. The calibration set is then used to estimate soil properties for spectra determined on soils that have not been characterised using chemical or physical methods. Implementations of partial least squares in various software packages provide estimates of uncertainty with the predictions as well as an indication on whether the acquired spectra of a new specimen lie within the bounds of the calibration data set.

Specimens analysed by diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy can be in the form of finely ground soil powders that are air-dried. There is minimal preparation time and scanning usually takes less than two minutes. Commercial instruments suited to field use are available but experience to date in Australia indicates that they are still not sufficiently robust for soil-related work.

Bramley and Janik (2003) demonstrate the potential power of mid infrared in precision agriculture applications relating to viticulture. It has similar potential for broadacre cropping.

Potential development

There are various options for devising measurement platforms and changing the detection units to allow near real-time or real-time measurement with the equipment being mounted on a field vehicle. However, the alternative of developing a rapid system for specimen collection and preparation that delivers large batches to a field laboratory is very attractive.
It is cheap to characterise and analyse soils using mid infrared with partial least squares. Prices are summarised in Table 2.

Table 2: Approximate price and time for mid-infrared analysis compared to standard procedures

Analyses	Approximate price	Time
Standard set:		
C, N, CO_3, Cations, pH, EC, ESP, particle size, bulk density	$150	days
Extra variables:		
Phosphorus Buffer Index	$25	1 day
Mineralogy	$130	days
Water retention	$100	weeks
Mid-infrared for all of the above on fine ground soil	$25	2 min
Mid-infrared on <2mm soil	$17	

The accuracy and precision for a wide range of soil properties is summarised in Table 3. The values are for finely ground specimens but further calibrations are being carried out for <2 mm material. The latter tend to be about 80–85% as precise (i.e. 15–20% lower R^2 for calibration cross-validation). The use of <2 mm reduces the price of mid-infrared analysis.

The results in Table 3 are based on cross-validation within the calibration data sets — they have not been rigorously tested using independent data sets. Note also that implicit in the errors in Table 3 are the contributions from laboratory error and these can be significant.

Table 3: Summary of soil properties usefully predicted by mid-infrared (SECV: standard error of cross-validation, PLS: Partial Least Squares factors) (Janik unpub.) Note that some properties have been assessed on small or restricted data sets (EC, lime requirement (Adelaide Hills), ESP, XRD and XRF mineralogy).

Soil property	No. of calibration samples	R^2	SECV	PLS factors	Soil property	No. of calibration samples	R^2	SECV	PLS factors
Organic carbon	1225	0.93	0.28	14	Bulk density	1124	0.62	0.09	21
Total N	512	0.80	0.08	16	Clay	575	0.98	2.50	15
CO_3	290	0.93	0.53	19	Sand	580	0.98	3.20	22
CEC	463	0.88	2.08	17	Saturation water content	92	0.68	4.20	7
Exch-Ca	670	0.84	1.92	21	Water content (–10 KPa)	91	0.70	5.10	4
Exch-Mg	670	0.79	1.82	22	Water content (–50 KPa)	92	0.74	5.10	4
Exch-K	44	0.88	0.27	12	Water content (–0.5 MPa)	96	0.73	4.50	4
Exch-Na	670	0.72	1.20	37	Water content (–1.5 MPa)	96	0.73	4.70	4
NZ Phosphorus Retention Index*	90	0.91	5.30	17	Quartz	15	0.91	6.90	1
Phosphorus Buffer Capacity**	90	0.74	9.50	15	Kaolin	15	0.92	2.80	6
Phosphorus Buffer Capacity***	90	0.74	7.30	13	Smectite	15	0.88	4.20	4
pH_{water}	936	0.72	0.54	25	Si-XRF	100	0.98	2.80	6
pH_{ca}	1206	0.82	0.50	23	Al-XRF	100	0.94	1.50	14
Lime requirement	219	0.72	0.43	5	Fe-XRF	100	0.95	1.40	7
Electrical conductivity	145	0.80	0.33	27	Ca-XRF	100	0.76	0.47	11
Exchangeable Sodium Percentage	142	0.86	5.00	22	Mg-XRF	100	0.81	0.40	13

* Blakemore et al. (1987)
** Ozanne and Shaw (1967)
*** Rayment and Higginson (1992)

The results in Table 3 have been generated using a universal calibration data set of Australian soils. There is good reason to expect better predictions for calibrations that have been derived for particular groups of soils — this should reduce confounding factors affecting the statistical analysis. Calibration data sets also need to be generated using consistent methods of specimen preparation and laboratory analysis.

Predictions using mid infrared can also be improved through the development of instruments with a larger scanning area. Large scanning areas are used routinely in near-infrared instruments because they are widely used for heterogenous materials (e.g. grain).

In summary, the most promising steps to improve mid-infrared measurement for rapid soil characterisation are:

- Develop comprehensive calibration sets for the range of soil materials encountered in the cropping lands of Australia to ensure accurate and precise prediction.
- Investigate options for mechanical specimen collection and preparation (particularly at depths greater than 0.20 m).
- Increase the scanning area of mid-infrared instruments.
- Investigate the option of coupled mid-infrared, near-infrared and UV-visible spectrometry (see below).
- Evaluate the reliability of core scanning (see below).

3.2 Near infrared

Principle and applications
The principles of measurement in the near-infrared range are similar to those for the mid-infrared range. Commercial units are available and they are used routinely in a wide range of laboratory, industrial and field settings. These factors, along with simpler electronics, result in near-infrared spectrometers being relatively cheap. Most applications of near-infrared spectroscopy directed towards rapid field measurement have demonstrated the technology’s capacity to estimate clay, organic matter and soil water contents (Viscarra Rossel and McBratney 1998b; Sudduth and Hummel 1993a, b). Hummel et al. (2001) report on the use of near infrared for the measurement of soil organic matter and soil water content. Dunn and Beecher (2002) demonstrate the utility of near infrared for predicting pH, CEC, exchangeable Ca, Mg and Na for a limited range of soils from rice-growing areas in southern New South Wales.

Perhaps the most notable application of near infrared is by Shibusawa and his colleagues (e.g. Sibusawa et al. 2001, 2003). Their real-time spectrophotometer includes a near-infrared unit mounted on a large tine — this allows real-time sensing to a depth of 0.15 m. In conjunction with sensors for electrical conductivity, soil strength and visible reflectance, predictions are possible for organic matter, NO_3-N, electrical conductivity, clay content and pH. See Section 5.2 for further discussion on the real-time spectrophotometer.

Hand-held near-infrared spectrometers have been developed for field geology with inbuilt data analysis capabilities and standard spectra. These units (e.g. PIMA II) allow measurement of the spectra of rocks and minerals in the field to assist with mineral identification, determine the degree of crystallinity, detect variations associated with weathering, and assess the extent of isomorphous substitution of elements in some crystal structures.

Potential development
As noted earlier, the mid-infrared range of the electromagnetic spectrum is better than the near-infrared range for predicting most soil properties, so most effort should be directed towards the former. However, near infrared and mid infrared can be used in a complementary way in conjunction with visible and ultraviolet measurements. These three sensors can be coupled using software that ensures the best part of the spectrum is being used to predict individual soil properties.

The implementation of near infrared is restrained by the paucity of systems for automatic specimen collection and core scanning.

3.3 Visible and near-visible reflectance

Principle and applications
Airborne and satellite-mounted sensors provide frequent and routine measurements in the visible and near-visible portion of the electromagnetic spectrum across the cropping lands of Australia. Multispectral sensors have been in routine use for several decades and they typically detect 4–7 broad spectral bands. Newer hyperspectral sensors have over 100 bands and tend to cover the same spectral range. This is very useful for vegetation, environmental monitoring and mineral exploration. However, soil measurement using remote platforms is often difficult because of complications caused by plant cover, surface geometry, illumination and surface condition. While the reflectance properties of soils are well documented (e.g. Baumgardner et al. 1985), measurement and mapping of soil properties using remote-sensing in the visible and near-visible range require careful field calibration. There has been some success in selected environments for particular soil properties (e.g. Hill and Schütt 2000). A number of ground-based sensing systems have been developed but most are directed towards the sensing of plant attributes, particularly for nitrogen status (e.g. Reusch et al. 2002, Solie et al. 2002).

Various sensors in the visible and near-visible range have been used for close-range direct soil measurement but most have been restricted to a few frequencies. Sensors have been mounted on tines to allow real-time soil measurement in the upper portion of the A horizon (e.g. Shonk et al. 1991, Shibusawa et al. 2001, 2003). These methods invariably require recalibration according to the soil type and landscape.

Several soil probes have been developed for measuring soil colour including imaging penetrometers (e.g. Rooney et al. 2001). Local calibrations of soil colour have been used for predicting soil properties including organic carbon (Viscarra Rossel et al. 2003).

Potential development
Hyperspectral sensing in the visible and near-visible range can be applied to soil specimens (e.g. sieved and dried fine-earth fraction or intact cores) or to the land surface. Again the conclusions on mechanised specimen collection and preparation and on core scanning are relevant.

Hyperspectral sensing in the visible and near-visible range is likely to be of greatest benefit for crop monitoring. Vehicle-mounted units can be used to assess the health and vigour of crops and these results used to guide decisions on topdressing and so forth (e.g. Reusch et al. 2002, Solie et al. 2002). An assessment of these technologies is beyond the scope of this review.

3.4 Ion-exchange resins

Ion-exchange resins have many advantages over conventional chemical soil extraction procedures, in that they more closely simulate the action of plant roots in terms of ion uptake by providing a sink for nutrients or contaminant elements. Ion-exchange resins have been used for almost four decades with most of the early papers using resins to extract nutrient anions from soils, particularly P (Sibbesen 1978, Saunders 1964). Early work with resins used resin beads and, to aid in separation of resin beads from soil, resins were usually enclosed in mesh bags when shaken with soil in a water matrix. Free resin beads have also been used, and in Brazil a major routine laboratory soil testing service has commercialised this technique (van Raij et al. 1986, van Raij 1998).

With the development of resin membranes (essentially strips of resin exchange material), the separation of resin from soil was simplified dramatically. Combined cation/anion resin membranes have proved to be convenient multi-element soil testing procedures in the laboratory (McLaughlin et al. 1993, 1994; Qian et al. 1992). A combination of cation- and anion-exchange resins, coupled with the multi-element analytical capacity of inductively coupled plasma atomic emission spectroscopy (ICP-AES), can accurately determine a range of nutrient elements in soil simultaneously.

Most resin techniques reported in the literature have been laboratory-based. There are two exceptions, and these have now been commercialised. The ‘Phytoavailability Soil Test’, or PST, has been commercialised by Skogley and co-workers from Montana State University (Dobermann et al. 1994, Skogley 1992, Skogley and Dobermann 1996, Skogley et al. 1990, Yang and Skogley 1992). This procedure combines anion- and cation-exchange resin beads in a tight mesh 'capsule' for burial in soil *in situ*, and subsequently the PST capsule is removed, sent to the laboratory, ions desorbed and an assessment of resin-extractable nutrients made.

The second *in-situ* resin method uses 'Plant Root Simulator' (PRS™) probes commercialised from the work of Schoenau and colleagues (Qian and Schoenau 1995, 2002; Qian et al. 1992; Schoenau and Huang 1991) and is now available through Western Ag Innovations in Saskatoon, Canada. These probes are based on ion-exchange membranes. They are buried in soil for a predetermined period, removed and transported to the laboratory for desorption of nutrient elements and assessment of soil nutrient supply characteristics.

Advantages of *in situ* resin techniques are that they account for both the factors of soil binding strength and also diffusive limitations to nutrient movement through soil. As the latter is highly dependent on soil water content, these techniques rely on the soil being moist to be effective. For Australia, a disadvantage of this requirement is that in southern grain cropping areas, where growers need to determine fertiliser nutrient requirements in the period January to April, soils are dry and therefore not suitable for assessment using such *in situ* resin techniques. In irrigated areas, however, there may be scope for soil nutrient assessment using these *in situ* resin methods, but extensive calibration, or correlations with existing calibrations, would be needed before widespread adoption.

For southern Australia, where predictions of soil nutrient requirements are needed at the end of summer when soils are dry, resin techniques are likely to be useful only as *ex situ* laboratory methods. Alternatively, these techniques could be used during the cropping season and analysed after harvest to provide general guidance on nutrient management in the next season.

3.5 Ion-selective field effect transistors

Principle and applications

Ion-selective field effect transistors (ISFETs) are integrated circuits with ion-selective membranes applied to the gate of the sensor. ISFETs can be used to measure concentrations of the relevant ions in a solution. ISFETs have small dimensions, rapid response times (milliseconds), low output impedance, high signal-to-noise ratio, require low sample volumes and have the potential for mass production (Birrell and Hummel 2001). When coupled with an automatic system for specimen preparation and a flow injection analysis system, they have the potential to be an effective real-time soil sensor (see Adamchuk et al. 2003).

ISFETs can be used for a range of determinations that reflect conditions in the soil solution. These include nitrate (Birrell and Hummel 2001), pH, lime requirement (Viscarra Rossel and McBratney 1998b), calcium, potassium, sodium and ammonium (see references in Birrell and Hummel 2001).

Implementation of the technology for real-time soil measurement is hindered by the need for a rapid specimen collection and difficulties in extracting the soil solution. This involves careful consideration of soil conditions, engineering design and the kinetics of reactions involved in the preparation of the sampled solution. Viscarra Rossel and McBratney (2003) consider the latter in relation to measurement of lime requirement. They reasoned that measurements for machinery travelling at 8 km/h would need to be taken every 9 seconds to ensure characterisation at 20 m intervals. They also demonstrated that measurements after 3 seconds could be used to satisfactorily predict equilibrium conditions at 12 minutes. This is sufficient for a soil pH and lime-requirement sensing system for field-based predictions of lime requirement and continuous liming. Issues relating to the speed of measurement are considered below.

Potential development

The major challenge for implementation of ISFET technology is construction of robust equipment for high-speed specimen collection and solution extraction. Several groups are developing such equipment and initial results are promising (McBratney pers. comm.), although considerable refinement is needed, particularly to deal with difficult Australian soils (e.g. hard-setting soils, sodic clays, non-wetting sands).

3.6 Electrical conductivity

Unlike the previous methods that rely on either spectroscopic principles or direct sensing of soil extracts, several geophysical methods can be used to determine the ease with which an electrical current can be made to pass through soil and deeper regolith. The methods rely on either electromagnetic induction or resistivity and they can be used to characterise large volumes of soil (with depths from less than 1 metre to several hundred metres), although the extent of measurement is often not specified with any great precision.

Electromagnetic induction

Principle and applications

This method involves using a varying magnetic field to induce currents in the ground in a way that ensures their amplitude is linearly related to the terrain conductivity. The magnitude of these currents is determined by measuring the magnetic field they in turn generate. Unlike resistivity measurement, these electromagnetic techniques do not require an instrument in contact with the soil. As a result, measurement and survey can be rapid. McNeill (1980) provides a good account.

Electromagnetic induction survey, or EM survey as it is widely known, has become very popular in Australia, particularly to support precision agriculture. Commercial instruments are available and, when coupled with Differential Global Positioning Systems, they provide a rapid mapping tool. When used appropriately (i.e. with thorough ground truthing), the method is invaluable for mapping selected soil properties. However, total reliance on EM survey as a surrogate for soil survey is unwise, as even a rudimentary understanding of the technique and natural soil variation will show.

Because most soil and rock minerals are very good insulators[4], the electrical conductivity sensed by an EM unit is electrolytic and it takes place through the pore-water system.

The following factors are therefore of importance:

- shape, size and connectivity of the pore system
- water content (i.e. degree to which the pore system is filled and inter-connected)
- concentration of dissolved electrolytes in the soil water
- temperature and phase of the pore water (frozen soil is rarely a consideration in Australia)
- amount and composition of colloids.

While clay content, electrical conductivity of the soil solution, and water content are often recognised as the controlling factors that must be accounted for when calibrating EM measurements (e.g. Williams and Baker 1982, Williams and Hoey 1987), it is not that simple. It is the pore system and its contents rather than the clay content *per se* that should be considered. Soils with significant clay usually have a pore geometry dominated by finer sized pores. In comparison to a sandy soil, greater proportions of these pores are filled and connected at comparable water contents, and this gives rise to the larger electrical conductivity. The bulk density of the soil should also be considered because it determines total porosity. Clay soils in most cropping areas usually have a substantial cation exchange capacity, and cations in solution are in equilibrium with the charged clay surface — these cations also contribute to the electrolyte concentration. Finally, colloids, particularly those associated with organic matter, may also contribute to the measured conductivity.

Most ground-based electromagnetic measurement in Australia is undertaken using one of the commercial units produced by Geonics Ltd. These units can be configured to measure conductivity in the immediate soil profile (to approximately 1.5 m for the EM38) or deeper layers (~6 m for the EM31, and down to 60 m with the EM 34). Using classical EM instruments, the depth of measurement is affected by coil spacing and frequency. The EM38 and other similar instruments have both of these fixed.

[4] Some exceptions include the iron minerals magnetite, maghemite and pyrite.

Potential development

- EM survey is more likely to be of value when combined with other sensors, particularly gamma radiometric survey.
- The use of EM units with rotating coils, variable spacing or several frequencies are all worthy of investigation. They have the potential to provide better information on the profile of soil water content. Spinning coil sensors (as used in WWII direction finders) can have useful side benefits, for example, if true reversal is obtained, then auto zero correction is possible (zero drift with time and temperature can be a limiting factor with high resistivity measurements).

Resistivity

Principle and applications

The resistivity of soil (i.e. the inverse of conductivity) can be measured by passing a voltage to electrodes placed in the soil. The technique has been used for a long time in geophysics, and various configurations of electrodes can be used to control the volume and depth of measurement. Resistivity measurements using conventional equipment are slower than electromagnetic induction and physical interpretation of results can be complex. The soil factors noted in the previous section affect resistivity measurements in the same way.

Several commercial systems are available including the VERIS EC Mapping System from the United States and the French ARP system. Both systems use rotating metal discs as electrodes. The discs either cut several centimetres into the soil (VERIS) or have small probes that push into the soil (ARP). Continuous recording of resistivity and conductivity is possible when the cart is towed across the landscape. Testing of a VERIS 3100 at the Australian Centre for Precision Agriculture has demonstrated its utility for routine measurement. The MuCEP is an earlier version of the ARP. Dabas and Tabbagh (2003) provide a good comparison between resistivity (Veris 3100, ARP) and electromagnetic systems (EM38). Not surprisingly, they conclude resistivity methods to be preferable because of better calibration and depth control.

Potential development

The VERIS EC Soil Mapping System uses a six-electrode disc system that makes soil contact and can map electrical conductivity at two apparent depths by means of the two electrode configurations used. The ARP has a configuration that allows measurement at three depths (0.5, 1.0, 2.0 m).

It would be useful to try a six-electrode device, at say 1MHz, to see if a measurement of soil moisture measurement could be obtained. The use of six electrodes would enable some interesting variations in admittance measurement methods. This may have been done and is not a trivial exercise if meaningful measurements are to be obtained.

3.7 Ground-penetrating radar

Principle and applications

Ground-penetrating radar (GPR) is a subsurface imaging technique that uses the reflection of very short pulses of electromagnetic energy from dielectric discontinuities in the ground to form an image of the subsurface. Almost any reasonably abrupt variation in material type will produce a reflection of energy and show up as an image. Since water has a high dielectric constant (~80) compared to most dry soil materials (~5), soil water content is important. However, slowly changing water contents are hard to detect with GPR and, in general, water profiling is not possible with traditional types of GPR. More rapid changes, such as wetting fronts, are easier to detect and this use of GPR is more appropriately applied in irrigated regions.

GPR is very material-dependent. Under good conditions, near-optical clarity of images is obtainable. However, in poor conditions (e.g. high clay and water contents), GPR may be near useless.

The high cost and complexity of GPR, coupled with the need for some expertise in operation and image processing and interpretation, mean that subsurface imaging is likely to be limited to particular investigations of subsurface features where the unique imaging capability can be of value.

GPR has also been used as a type of time-domain reflectometer in which the time-of-flight of an electromagnetic pulse between two antennae on the ground surface is used to measure soil water contents in the near subsurface. However, the cost, complexity and expertise required probably limit its use in this application to specific investigations carried out by consultants with the necessary know-how and equipment.

Potential development

Within the scope of this report, it is suggested that the main use of GPR will be for subsoil water content measurement. However, as indicated above, using expensive imaging radar to determine the magnitude only of a single variable would be a poor use of resources. A simpler version of GPR with lower initial cost, requiring no operational or interpretational expertise and giving a simple water content display, would be desirable. The ability to obtain a water content profile in real-time would provide an additional advantage. GPR has the added advantage of measuring soil water content of relatively large volumes of soil (compared to say time domain reflectometry) and this should be of greater relevance to plant growth.

Methods of measuring moisture profiles have been published; however, we are not aware of any practical implementations or commercial instruments based on these techniques (Keam et al. 1999). There is potential for further development in this area. Huisman et al. (2003) provide a useful review of measuring soil water content with GPR that reaches similar conclusions.

3.8 Gamma radiometric spectrometry

Gamma spectrometry for soil measurement can be undertaken using airborne or vehicle-mounted systems. Gamma spectrometry detects the natural radioactive decay of isotopes for several elements. Potassium, thorium and uranium are the only naturally occurring elements with radioisotopes that produce gamma rays of sufficient intensity and energy to be measured by airborne sensors. Gamma rays are strongly attenuated by rocks, soil, vegetation, air and water. As a consequence, most of the signal detected by above-ground measurement systems comes from the upper 0.3–0.5 m of the soil. Minty (1997) provides a thorough review of the fundamentals of airborne gamma-ray spectrometry.

Improvements in global positioning, detector technology, data analysis and intensity of survey flight lines have made gamma radiometric spectrometric data invaluable for regional-scale soil, land and geological survey (e.g. Cook et al. 1996b, McKenzie and Ryan 1999). The great advantage over remote sensing methods that rely on reflectance is that spectra can be related to soil materials rather than land surface reflectance alone (the latter being prone to the effects of surface cover and geometry).

The gamma radiometric signal is controlled by the mineralogy and particle size of soil along with the effects of attenuating materials. Soil parent material, the intensity of weathering and the geometry of near-surface soil layers are therefore of great significance. While sound physical interpretations of radiometric images are nearly always possible, careful field investigation and geomorphic stratification of the landscape are necessary — identical gamma radiometric signals can be generated by soils with a variety of combinations of particle size, degree of weathering and horizon configuration.

The relationship between gamma radiometric signals and key soil properties affecting crop production will nearly always be empirical and only locally applicable. For example, Bierwirth (1997) reports strong correlations between pH and radiometric potassium in the Wagga Wagga region. In this instance, low potassium signals were associated with highly acid soils on sandstone parent materials. Similar environments just to the east of Wagga Wagga conversely return very low potassium signals on soils derived from basalt but these would be expected to be well buffered and not strongly acid. A good understanding of field pedology and targeted field measurements are necessary for informed interpretation.

Gamma radiometric spectrometers can be mounted on field vehicles and commercial companies now provide this service in combination with electromagnetic induction to generate maps at paddock scales. This combination of sensors is particularly effective because the gamma radiometric data relate more to the solid mineral component of soil while the electromagnetic induction data relate to the electrolyte properties of the soil solution. Direct field measurement of soil properties is always required for calibration.

Potential development
Gamma radiometric survey has a well-developed technology for both airborne and ground-based measurement. Down-borehole units are used for mineral exploration and contamination investigations (e.g. USAEC 2000). Although there have been some recent and notable improvements in data acquisition and analysis, most benefit for cropping should come from encouraging operators to carefully interpret gamma radiometric survey results and promote the use of multiple sensing systems (e.g. in combination with EM survey). As with EM survey, an appreciation of the physical principles of measurement and field pedology is essential to avoid spurious correlations and interpretations.

3.9 Temporal remote sensing

Principle
Multi-spectral remote sensing is often limited by difficulties in relating measures of land surface reflectance to soil variables controlling crop performance. While the situation is changing to a degree with the increasing availability of hyperspectral methods, perhaps the greatest advance will come from temporal analysis of images collected either frequently or at key times of the year, or both. Daily multi-spectral remote sensing at a coarse resolution has been available for several decades (e.g. AVHRR images) and these data have been used to calculate regional-scale water balances (e.g. McVicar and Jupp 2002). The increasing resolution of satellite data in time and space should increase the relevance to crop production.

Temporal remote sensing should provide indications of growing season length and net primary productivity. Differences in the soil-water regime relating to both plant-available water capacity and waterlogging should be discernable but considerable research is required.

Potential development
Investigations are needed into the utility of temporal remote sensing for the identification of areas with contrasting crop performance associated with either limited plant-available water capacity or waterlogging, or both, across several landscapes typical of large areas in the graingrowing regions of Australia. These investigations need to address the reliability of temporal remote sensing for characterising the soil-water regime.

3.10 Terrain analysis

Local variations in terrain control the movement of sediments, water and solutes within the landscape. Soil formation is strongly influenced by these processes. As a result, detailed digital information on landform can be used to predict the distribution of many soil properties including soil depth, available water capacity, total carbon, total phosphorus and sodicity (e.g. Moore et al. 1993, Gessler et al. 1995, McKenzie and Ryan 1999, McKenzie et al. 2000), although the predictive power depends on the type of landscape, its history and the scale of variation.

A digital elevation model is simply a computer file with a grid of points defined by a location and elevation. Its real value arises from various indices of surface geometry that can be calculated from the simple grid (e.g. slope, aspect, various curvatures, wetness indices). Wilson and Gallant (2000) provide a comprehensive account of digital elevation models and terrain analysis.

While digital elevation models can be used to help predict the distribution of soil properties at various scales (Gessler et al. 1995, McKenzie and Ryan 1999, Cook et al. 1996a, Henderson et al. 2001, Bishop and McBratney 2002), they can also be used to define management units (e.g. Reuter et al. 2003).

Digital elevation models (DEMs), with a grid resolution of at least 25 m, are available for about half the cropping lands of Australia. More coarse models cover the remaining areas (approximately 200 m resolution) but these are of limited value for predicting soil distribution (Gessler 1996). More significant for precision agriculture is the generation of high-resolution digital elevation models from ground survey using differential GPS. Bishop and McBratney (2002) consider many of the issues associated with data from these surveys and confirmed the superiority of the ANUDEM software for digital elevation model production. Very high-resolution digital elevation models (i.e. vertical resolution of a centimetre and grid cells of a metre) are now being obtained for significant areas using LIDAR (e.g. some large areas in the Riverina). The resulting DEMs are ideal for precision agriculture particularly in low relief landscapes. New terrain variables suited to low relief landscapes are now available and they should be useful for delineating management zones and soil distribution (Gallant and Dowling 2003).

High-resolution terrain analysis also provides a local landscape framework for interpreting results from other sensors (e.g. EM survey and ground-based gamma radiometric survey). It should be viewed as a mandatory data layer.

Potential development
Two lines should be pursued. The first relates to the availability of high-resolution digital elevation data across Australia’s cropping lands. The feasibility of acquiring LIDAR data across these areas should be investigated. Consortia have been formed to acquire such data across irrigated areas at reasonable cost. Easy-to-use software for terrain analysis with algorithms suited to low relief landscapes is also needed to encourage combined use with other forms of data (e.g. EM survey).

3.11 Deeper measurement using core scanning or down-borehole technology

Most of the measurement technologies considered so far are better suited to near-surface or surface measurement (i.e. upper 0.30 m). However, deeper observations are needed to determine subsoil constraints to root growth, to characterise the soil-water regime or to assess potential off-site impacts. While some of the technologies provide insights about deeper layers (e.g. EM survey and, to a lesser extent, gamma radiometric spectroscopy), there is still an urgent need to develop rapid measurement systems to characterise the complete soil profile, at least to 1–3 m. *Farmers using soil testing require information that relates to the potential root zone and not just the top 0.20 m*.

Undisturbed soil cores spanning deeper layers can be readily collected with small drill rigs using either push-tubes or Proline samplers. There is an excellent opportunity to apply many of the methods considered above to an automated scanning system for soil cores.
Commercial units have been developed for sediment and rock cores (e.g. Geotek 2001) that include gamma density (attenuation of gamma rays provides a means for measuring water content and bulk density), natural gamma radiation, electrical resistivity, magnetic susceptibility, digital photography and seismic properties. The Geotek unit can be readily modified to include mid- or near-infrared sensors (Geotek pers. comm.). Rapid core measurement would allow soil surveys to be undertaken in a far more efficient manner and it would be a natural complement to vehicle-mounted sensor systems (see below).

Down-borehole sensor systems also provide a means for characterising soil and regolith. Measurements of electrical conductivity in particular can be made at a well-defined depth and the sensor can integrate over a realistic volume of soil to reduce the effects of short-range variation.

A range of other sophisticated sensors is also available. For example, the US Army’s Site Characterization and Analysis Penetrometer System is mounted on a 20-ton truck. Down-hole determinations are made to 50 m using a real-time video (100-times magnification), gamma ray spectrometer (radioactive waste detection), water content probe, pore water pressure sensor, liquid and gas sampler, laser-induced fluorescence (detects hydrocarbons), direct sampling ion trap mass spectrometer (detects volatile organic compounds), thermal desorption sampler, laser-induced breakdown spectroscopy (detects various metals) and X-ray fluorescence (metals). Eight SCAPS trucks are operated by three federal agencies in the United States and millions of dollars have been saved in site investigation and clean-up costs (USAEC 2000).

Potential development
An automated core scanning system designed for agronomic applications is clearly feasible. A unit should be developed and tested across a broad range of soils used for cropping with a view to rapid measurement of bulk density, water content, water retention, particle size distribution, organic matter, exchangeable cations/CEC, pH and lime requirement.
There should also be an assessment of geophysical measurement systems for down-borehole sensing to complement the core scanning system.

3.12 Telemetry

Commercial systems for monitoring soil water using telemetry are currently available. For example, capacitance probes linked to mobile telephone systems or radio networks are now routinely used in irrigated agriculture (e.g. http://www.sentek.com.au/). These systems have obvious applications for dryland systems and the main issue is cost. Charlesworth (2000) provides details about costs and operating options for the Adcon addIT system. These figures suggest it could be somewhat expensive to instrument a reasonable area. However, a significant fraction of the cost resides with the probes themselves rather than the telemetry system.

Another telemetry system is the Motorola platform for ad hoc wireless networking. It is suited to situations where low rates and small volumes of data exchange are required along with simplicity, reliability and efficiency. Various configurations are possible in a network (with each node measuring one or more soil properties *in situ*). The most useful for a farm or group of farms would involve nodes (Mini PAWNs) located within the management zones. These nodes would have to be within 1–2 km of each other and they connect to a gateway unit that controls data collection times and communication to the CDMA mobile telephone network.

4. Which soil properties should be measured?

4.1 Direct versus indirect methods of measurement

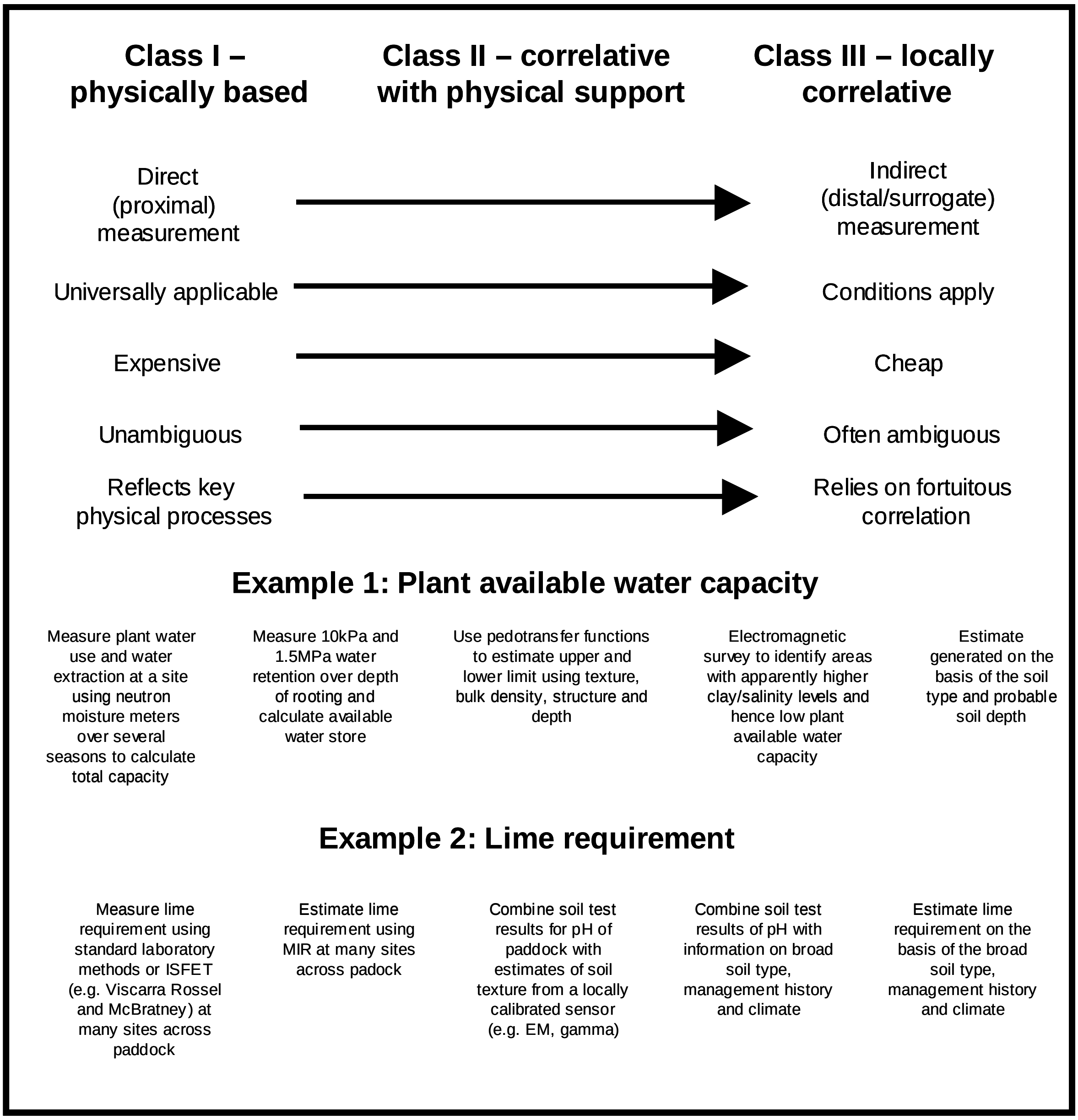
It will be evident from the following sections that measurements of most soil properties with a direct causal link to crop performance are currently both expensive and technically demanding. For most soil factors affecting crop performance, there is a progression of measurement options from exact methods with a sound scientific basis towards those that are less direct and less expensive. However, the latter are invariably more empirical, less accurate and prone to error. The sequence is shown in Figure 2.

Most but not all methods of soil measurement suited to real-time or near real-time operation fall towards the centre or right-hand side of Figure 2. These methods tend to work very well under a restricted set of conditions but they may fail under others. This conditional success is controlled in large measure by the type of soil and, in particular, its mineralogy, particle-size distribution, presence of certain segregations (e.g. iron oxides and oxyhydroxides), soluble salts, water content and organic matter abundance and composition.

The following sections disentangle some of these relationships to provide a clearer basis for identifying measurement technologies with potential for broad application. This task requires an appreciation of the correlation structure of soil properties within soil horizons, soil profiles and across landscapes. This is considered after an introduction to the main soil properties likely to be of benefit to crop management in Australia.

While this review focuses on soil measurement, it is recognised that, in most circumstances, an integrated program of soil and plant analysis is required, especially for micronutrients and nitrate.

Figure 2: The progression from direct to indirect soil measurement



4.2 Water content

Knowing the water content of a soil profile is invaluable for a range of management decisions including the timing of both planting and cultivation. In conjunction with seasonal weather forecasts, it can be used to guide fertiliser strategies. Water content profiles or, more precisely, water content and retention profiles are a key input to farming system models such as APSIM (Keating et al. 2003).

Several *in situ* systems for measuring water content have been developed and most applications have been directed towards irrigation scheduling: for example, neutron moisture meters, time domain reflectometers, drainage meters (Hutchinson and Bond 2001) and wetting-front detectors (Stirzaker 2003). These systems provide information on when to stop or start irrigation. Some of these sensors have considerable potential in dryland settings. For example, capacitance probes (either manually read or with telemetry) strategically located across the management zones of a farm provide a means for monitoring water content. This strategy is feasible now.

Alternative systems using vehicle-mounted sensors such as ground-penetrating radar have the potential to provide maps of soil water content but they need to be calibrated with point-based measurement.

4.3 Plant-available water and depth of rooting

Description and relevance to cropping

The water content of a soil profile by itself is insufficient — the proportion of the water content that can be extracted by the crop must also be known. This requires information on the soil water characteristic and root distribution. Profile-available water capacity has routinely been estimated from field texture, soil structure and the occurrence of layers that limit root growth. In some cases, these estimates are supplemented by measurements of volumetric water contents at potentials of either –1.0 m or –3.3 m (notional field capacity) and –150 m (notional wilting point). The available water capacity has been equated with the difference between the two water contents. The plant-available water capacity has been calculated for the soil profile by summing the available water capacity over either the depth of rooting or a standard depth. Estimates of soil water availability should take into account limitations to root growth associated with poor aeration and excessive soil strength — this is achieved using the *non-limiting* or *least limiting water range* (Letey 1985, 1991; Da Silva et al. 1994; Groenevelt et al. 2001, Section 4.10). Ideally, plant-available water capacity should be determined in the field by measuring differences between volumetric water content at the drained upper limit and the lower limit after complete extraction of water by the crop. Dalgliesh and Foale (1998) provide methods for measuring plant-available water capacity using such a field-based approach. The rapid adoption by farmers of these measurement methods and interpretation of the soil-water regime via the APSIM farming systems model (Keating et al. 2003) is achieving excellent results in various parts of Australia. Farmers are able to make more informed choices on crop type, planting times and fertiliser requirements.

Potential methods for rapid measurement

Automated core scanning has the potential to improve on the methods outlined by Dalgliesh and Foale (1998) but the level of farmer involvement would be less and this may be a significant disadvantage. In the right circumstances, EM survey can provide a good mapping tool for identifying soils with contrasts in plant-available water capacity, but careful local calibration is necessary. If improvements to EM survey are possible and profile water content can be mapped successfully, then there is the potential for regular monitoring of water availability. Again, local calibration would be necessary to confirm the relationship between water content and water retention.

4.4 Nutrient supply — nitrogen

Description and relevance to cropping

Availability of nitrogen exerts a major control on plant growth. Nitrogen available to plants at any given time is usually small (compared to both the demand and total store) but oversupply can also occur at times, leading to losses from the system. Characterising the nitrogen status of soil is complicated by a variety of connected processes.

Most nitrogen in surface soils is immobilised, bound as organic nitrogen associated with humus. A small proportion of this store is steadily turned into inorganic (mineralised) forms, although the resulting ammonium and nitrate compounds comprise less than 1–2% of total nitrogen — methods sensitive to total nitrogen may therefore be useless for nitrate (especially when the large spatial variability is also considered). A third and less significant form of nitrogen in soil is that incorporated or fixed into the structures of clay minerals as ammonium. Mineralisation involves a complex set of reactions with several participating groups of micro-organisms. It occurs most effectively in well-drained, aerated soils with good supplies of exchangeable cations. Mineralisation of organic nitrogen produces ammonium and most of this is then converted to nitrate by bacteria. Nitrifying bacteria are sensitive to a number of environmental factors including aeration, temperature, water content, ratio of carbon to nitrogen, and supply of ammonium. Another major role of bacteria is biological fixation. Several groups of micro-organisms can directly reduce atmospheric nitrogen gas to ammonia, which is then converted to proteins. Well known are the symbiotic bacteria of the genus Rhizobium and legumes.

Nitrate nitrogen in soil can be formed by nitrification or through the direct addition of fertilisers; it is then either incorporated into micro-organisms or taken up by plants. Removal of crops can represent a significant nitrogen export from the system. Nitrates can also be readily leached because they are negatively charged and move freely with soil water. Both factors can cause a serious problem in maintaining a cropping system's nitrogen supply. Nitrates can be reduced (via denitrification) to produce nitrogen gases that are lost to the atmosphere. Denitrification is more common in poorly aerated wet soils and it can lead to significant losses in cropping systems.

The nitrogen supply system for a crop is clearly complex and microbial ecology is central — many factors control the availability of nitrate and ammonium, and short-range variation in space and time is commonplace. Measurement of nitrate using standard laboratory methods is involved and interpretation criteria for estimating crop requirements are prone to error because:

- it is difficult to specify target yields and, as a consequence, nitrogen requirements of the crop due to seasonal variations in weather and other factors
- crops acquire more soil nitrogen than is measured as nitrate because of the dynamic nature of mineralisation
- nitrate is highly spatially variable
- in wetter areas, nitrate can be leached beyond the root zone, and rainfall can stimulate nitrate production between measurement and sowing (Strong and Mason 1999).

While there have been some promising developments in rapid and direct measurement of nitrate, the uncertainties associated with each source of error may overwhelm the benefit gained from accurate determination of nitrate at a given time. The strong biological control of the nitrate suggests that correlative methods that sense soil materials (particle size, mineralogy, organic matter) are unlikely to provide robust measures of nitrate. Janik et al. (1998) do not consider mid infrared to be an appropriate method for estimating nitrate.
At least one commercial company in Australia is now providing rapid soil testing for nitrate (one-day laboratory turnaround). The key feature is the streamlined system for sampling and laboratory analysis.

Potential methods for rapid measurement

The dramatic increase in nitrogen fertiliser use and improvements in yield are forcing better measurement, if only to avoid profligate use. Measurement to depth is necessary (i.e. more than 0.5 m). While routine methods are available, the development of a core scanning system has potential. Again investment in systems for rapid soil sampling and preparation is worthy of consideration.

In summary, the only Class I method (Figure 2) with potential for rapid measurement of nitrate at this stage would be ion-selective field effect transistors. Possible Class II methods in some special circumstances are near infrared and mid infrared (e.g. Shibusawa et al. 2001, 2003). These sensors should provide acceptable predictions of total nitrogen.

4.5 Nutrient supply — phosphorus

Description and relevance to cropping

Deficiencies of phosphorus often limit crop growth, particularly on the strongly weathered soils found across large parts of Western Australia and South Australia. The chemistry of phosphorus is complex; both inorganic and organic forms of phosphorus occur in soil and their relative proportions vary considerably. Organic phosphorus can form 20–80% of the total. Micro-organisms have a significant demand for phosphorus and they compete with plants for it.

The availability of inorganic phosphorus is strongly controlled by pH and different forms of phosphate occur with increasing pH. The presence of soluble iron or aluminium in acid conditions, and calcium at high pH, greatly reduces the availability of phosphorus. Maximum phosphate availability occurs in the pH range 6.0–7.0.

Three broad categories of phosphorus can be recognised. First are the readily available phosphates that occur in soil solution. Second are the slowly available, or labile, phosphates. These occur as freshly precipitated forms or as anions that can be readily removed from positively charged sites on clay and organic surfaces. Third are the very slowly available, or less labile, phosphates.

Many plants have developed mechanisms to deal with low phosphorus environments. Most notable are the associations between fungi (mycorrhiza) and plant roots. Mycorrhiza increase the surface area available for phosphorus uptake and provide a temporary store for the crop to draw on during periods of deficiency. Measurement of the phosphorus status of a soil is clearly an involved process.

Several rapid measurement technologies are sensitive to total phosphorus because they sense aspects of mineralogy and organic matter. For example, airborne gamma radiometric survey can be used to map total phosphorus across forested landscapes (McKenzie and Ryan 1999). However, available phosphorus is another matter altogether. Again, availability to crops is strongly mediated by biological processes that involve population dynamics influenced by short-term variations in temperature, water availability and flows of nutrients and energy. Correlative methods of soil measurement can be expected to return only relatively inaccurate and imprecise results (e.g. Janik et al. 1998).

Potential methods for rapid measurement

Mid infrared is a Class II method that gives good results for phosphorus sorption but not available phosphorus (Janik et al. 1998). There are no other obvious near real-time or real-time methods for measuring available phosphorus.

4.6 Nutrient supply — potassium

Description and relevance to cropping

While many Australian soils have adequate levels of potassium, deficiencies have been reported in many regions, particularly those with strongly weathered and light-textured soils. Generalised assessments of farmgate nutrient balances indicate a net loss of potassium from cropping lands in all states except Tasmania (NLWRA 2001). Increased awareness of deficiencies in Western Australia is redressing the balance there to some extent.

The quantity of potassium in soil is a function of its parent material (particularly the feldspar content), degree of weathering, clay mineralogy (illite is a good source of potassium), particle size distribution, organic matter and land-use history. With these factors, it would be reasonable to assume that mid-infrared spectrometry provides a useful rapid sensing technology, at least for total potassium. Results to date are mixed. Exchangeable potassium can be predicted but the results for available potassium are poor (Janik et al. 1998, Table 2). As with nitrogen and phosphorus, only a very small percentage of the potassium reserve is in solution and the supply to plants depends on the rate of potassium replacement in the soil solution (i.e. potassium buffering capacity) (Gourley 1999). A large number of conventional laboratory methods exist for exchangeable or extractable potassium but there is no standard method.

Potential methods for rapid measurement
Ion-selective field effect transistors are a Class I method that can be used for potassium, but again the major issue is development of a rapid specimen collection and extraction system. Airborne or ground-based gamma radiometric spectrometry may provide an indication of potassium status but the method responds to total rather than available potassium.

4.7 Nutrient supply — pH

Description and relevance to cropping
pH is a measure of the activity of the hydrogen ion (H^+) — its effective concentration in the soil solution. It exerts strong control on the soil chemical environment and to a large degree determines the availability of nutrients to crops.

Acid soils are found in areas of high precipitation because particular exchangeable cations (base cations) — mainly calcium, magnesium, potassium and sodium — are leached from the soil and acid-forming factors produce an increase of adsorbed hydrogen and aluminium. When organic matter decomposes, various acids are formed, the most common being carbonic acid (the result of the reaction of carbon dioxide and water). Stronger acids — such as sulphuric and nitric acid — in conjunction with organic acids are necessary to produce moderately to strongly acidic conditions. Sulphuric and nitric acid can be generated from reactions involving some fertilisers such as ammonium sulphate. In very acid soils, the exchangeable cations of hydrogen and aluminium dominate the exchange sites.

In drier climates, calcium, magnesium, potassium and sodium occupy a greater percentage of the exchange sites and soils are neutral to alkaline at depth. The presence of soluble salts in the soil solution (e.g. carbonates) contributes to alkalinity and can cause very high pH (pH 9–10) when sodium carbonate is present. High levels of calcium, magnesium, potassium and sodium can be also be generated through weathering of primary minerals.

Regional significance
Surface and subsurface acidity affects cropping areas mostly in the wetter parts of Western Australia, Victoria and New South Wales. While lime use has increased over the past decade, there is still a major gap between required and current rates of application (NLWRA 2001).

Potential methods for rapid measurement
Direct methods for rapid measurement of soil pH or, better still, lime requirement require sensors that respond to the soil solution, or state variables that control soil solution composition and concentration. Ion-selective field effect transistors are most promising at this stage (Viscarra Rossel and McBratney 2003, Adamchuk et al. 2003). Mid infrared has returned good results for pH buffering capacity (Table 3) but the results come from a restricted set of soils from the Adelaide Hills.

Locally correlative methods (i.e. Class III) including gamma radiometric spectroscopy and electromagnetic induction can provide estimates of pH in selected environments because they are detecting soil properties related to the leaching and weathering regime (e.g. Beecher and Dunn 2002). For example, sandy and strongly weathered acid soils in wetter environments usually have a low radiometric K signal (e.g. Bierwirth 1997). Conversely, alkaline soils with limited weathering are often associated with accumulations of sodium salts and elevated electrolyte levels, so electromagnetic induction can sometimes provide predictions of pH.

4.8 Other nutrients

Various other nutrients are required for crop growth. Sulphur has parallels with nitrogen in that most occurs in organic forms and these are slowly mineralised by microbial decomposition. Again, the released form is only weakly held by the soil and is prone to leaching. Of the 17 elements known to be essential for plant and micro-organism growth, eight are required in minute quantities: these so-called micronutrients are boron, chlorine, cobalt, copper, iron, manganese, molybdenum and zinc. Most micronutrients in soil are derived from the parent materials. Micronutrients can be harmful if there are large amounts in available forms (e.g. boron). Deficiencies, on the other hand, are more common in highly leached sands, organic soils and soils with very high pH; they can also develop on intensively cropped soil that has been fertilised only with macronutrients. Micronutrient deficiencies can usually be corrected quite economically on the basis of conventional soil testing and subsequent fertiliser addition. The demand for rapid soil measurement is not strong compared to other soil properties considered in this review.

4.9 Salinity and sodicity

Description and relevance to cropping
In free-draining soils and where rainfall does not greatly exceed evaporation, salt accumulates at the bottom of the active root zone or at the depth of effective wetting. The quantity of salt accumulated depends on the degree of leaching, which is controlled by soil permeability, rainfall and evaporation.

The soluble salt content, or salinity, within a given soil horizon is routinely measured by determining the electrical conductivity of a suspension of soil and water. A soil-to-water ratio of 1:5 is most common, although a 1:1 ratio or saturation pastes are more informative but more tedious to measure. Methods exist for converting between the two measures, and there are comprehensive criteria for interpreting the tolerance to salinity of a range of crops and other plants. Tolerance depends on clay content as well as electrical conductivity. Electrical conductivity can be measured rapidly using several geophysical techniques.

A consequence of widespread salt accumulation in soils, either now or in the past, has been the formation of sodic soils. These are soils where sodium occupies an appreciable percentage of the exchangeable cations. Sodic soils are not necessarily saline and, as a result, they may be poorly characterised using electromagnetic or resistivity methods. In sodic materials with low soluble salts, clays tend to swell and disperse, producing a soil with very low permeability and porosity. Resulting soil structural units are often large and conditions for root growth are usually poor. The adverse physical effects of sodicity are reduced in more saline soils but the high salt content severely limits root growth.

There are various definitions of sodic soils and most use the Exchangeable Sodium Percentage (ESP) as a criterion — this is simply the exchangeable sodium concentration expressed as a percentage of the cation exchange capacity. An ESP of 6 has been widely used in Australia as a limit above which sodicity has adverse effects.

The effect of ESP on clay dispersion is also influenced by other soil properties such as organic matter content, clay mineralogy, cation composition, iron and aluminium oxide content and, particularly, electrolyte concentration of the soil and of any applied irrigation water. Measurement of ESP using standard chemical methods is relatively slow and involved, and only broad recommendations on gypsum application rates are feasible.

More specific recommendations must take into account electrolyte concentration, mineralogy and organic matter. Precise laboratory methods that take account of these factors have only become available recently (e.g. Rengasamy 2002) and there is not a large database for evaluating less direct measurement technologies.

Regional significance
Sodic and saline features are common throughout the grain-producing areas of Australia. They tend to be more common in drier areas and in landscape settings where salts are effectively trapped, for example, on the very flat riverine plains with clayey soils in Queensland, New South Wales and Victoria, and in regions where salt inputs over long periods have been substantial, for example, in southern cropping areas in Western Australia and South Australia, particularly those nearer to the coast.

The depth to sodic materials down the profile is a key determinant of whether sodicity is a problem or not. While EM survey is often useful for detecting sodic materials, resolution of the depth is more problematic. As an indication, high sodicity at 0.5 m will present problems in many cropping areas but high sodicity at 1.0 m will be far less significant.

4.10 Soil strength

Soils with a narrow non-limiting water range (Section 4.3) are common across the cropping lands of Australia and they are difficult to manage. Windows of opportunity for tillage and trafficking are small, risks of compaction are high, waterlogging is common, and crop growth is often poor. Such soils are often very strong. Several tine-mounted sensors for measuring soil strength profiles have been developed (Andrade et al. 2002). Careful measurement of water content is necessary to account for the strong relationship with strength. Such sensors are research tools at present but load cells mounted on tillage implements should be quite feasible with existing technology. If soil strength can be disentangled from field water content, then rapid measurement should assist in identifying problem areas and should guide strategies for amelioration.

4.11 Other soil properties

This review has been restricted to readily measured soil properties of immediate relevance to crop production. A number of other soil physical properties would be useful if they could be readily measured. The permeability of a soil, in conjunction with its water storage capacity, has a strong control on the soil-water regime. Hydraulic conductivity is a measure of permeability. Soils with a slow hydraulic conductivity at or near the soil surface (e.g. less than 30 mm/h) cannot transmit water from heavy showers of rain and this can lead to excessive run-off and erosion. Run-off also represents a loss of water that would otherwise be available to plants.

Subsoil layers are nearly always less permeable than surface layers because of the lower rates of biological activity. Soils with strong texture contrasts often have a sharp reduction in hydraulic conductivity with depth, so that drainage of water is often impeded. As a result, periodic saturation can occur.

Hydraulic conductivity is largely controlled by the texture and structure of a soil layer. Sandy soils are nearly always very permeable but the converse is not always true. Some clay soils can be more permeable than sands (e.g. Red Ferrosols) because of their strongly aggregated structure. Other clay soils (e.g. most Vertosols and the B horizons of Sodosols) are very impermeable. While general rules of thumb for estimating hydraulic conductivity have been published (see McKenzie and Cresswell 2002), predictions are still imprecise.

Some other soil properties, such as soil erodibility, are of great significance but other avenues for measurement and prediction are available and they will not be considered here.

5. From potential soil sensors to practical measurement systems

5.1 ‘Measure more less well’

A key principle for providing better spatial information to support farm management is to ‘measure more less well’. This principle arises from the very large short-range spatial variability in soil properties. A few accurate and precise measurements will return minimal information on the broad patterns of soil variation. The effort devoted to obtaining higher accuracy and precision will be overwhelmed by the spatial variation. However, ‘measuring more less well’ provides more information on the patterns of variation and it gives a better basis for defining management zones or guiding variable rate technology. There is a sound statistical basis for the strategy (e.g. Gundersen and Østerby 1981). It also highlights why technologies such as mid infrared have so much potential for rapid soil measurement.

5.2 How rapid and frequent should measurement be?

A key issue for setting investment priorities for research and development in rapid soil measurement is defining the required speed of measurement. As noted earlier, a real-time measurement system mounted on a tractor with variable rate technology (e.g. for fertiliser, herbicide, sowing etc) requires measurement intervals within 10 seconds. Apart from spectrometers mounted either on tines or above the ground, a measurement system needs to have a robust system for specimen collection and extraction (e.g. to implement ISFETs) or specimen collection, drying and grinding (e.g. for mid infrared). Several systems for the former are under development and initial results are promising.

If the measurement system is required to return results for a paddock within days or weeks, then different opportunities arise. For example, one option for implementing mid-infrared measurement is to develop a rapid and automated specimen collection and preparation system.

Such a system may involve:

- a small drilling rig or hydraulic system for collecting many spatially referenced specimens across a paddock
- an automatic system for specimen drying and sieving that delivers prepared materials in trays
- trays that are compatible with a moving stage and automated mid-infrared scanning system.

Likewise, the opportunity for rapid core scanning is feasible when the time constraint is in days and not seconds.

It is logical to invest in both types of measurement system. If they work well, some of the methods that provide timely information for zone farming (i.e. time scale of days) may progress to real-time measurement with supporting variable rate technology.

In the overwhelming majority of instances, a farmer is unlikely to act within a few hours of receiving a soil test. Even with rapid sensing in real time, it is much more likely that the decision will be made several days or weeks after analysis. The need for rapidity, therefore, has much more to do with cost and laboratory throughput. A focus on sampling systems is therefore appropriate because far more samples need to be taken and processed than hitherto, and the cost of sampling needs to be minimised. Given the time delay before the use of information, the capacity of the laboratory to deal with the analysis and the perception of value for money provide the next reason for needing rapidity — there is a need for abundant and cheap analyses (this is the virtue of calibrated mid infrared).

In summary, the need for rapidity is logistical and at the laboratory and sampler stage of the information system, not at the user end.

5.3 Tine-mounted sensors

The best example of a tine-mounted sensor is the real-time spectrophotometer developed by Shibusawa and colleagues (Shibusawa et al. 2001, 2003). The unit is a research tool in its current configuration. While the results are promising, they have been achieved on Andisols used for rice production. These soils are virtually unknown in Australia because they form from volcanic ash. They are unusual soils because of the very low bulk density (often less than 1.0 Mg/m^3), excellent structure and large organic carbon contents (often over 5%). These soils are nearly always moist, friable and readily ploughed.

The cropping lands of Australia contain large areas that are hard-setting, abrasive, sodic or dense. Wear and tear on machinery can be severe and conditions during field operations are often hot and dusty. These factors mean that tine-mounted sensors would have to be very rugged. The accompanying instrumentation is not insignificant so the apparatus would, in the near future, most likely be single purpose (i.e. not incorporated into existing machinery). The measurement of soil strength using tine-mounted sensors is more feasible (e.g. Andrade et al. 2002).

5.4 Who does the measurement?

Measurement systems that can be applied by farmers or local agricultural consultants have some significant advantages:

- Farmers have a rich local context for interpreting results (e.g. a detailed knowledge of seasonal conditions, rotational history, prevalence of disease).
- Farmers will usually be able to judge whether further information acquisition reduces uncertainty in decision making.
- Farmers learn first-hand about the resource base for their enterprise.

However, measurement systems have to be:

- well developed and require minimal training
- relatively cheap per unit
- robust across a range of conditions.

If measurement systems are to be used by technical specialists, then less mature technologies can be applied. It is also feasible to utilise systems with large capital costs but high throughputs.

6. Moving from point measurement to maps of paddocks, farms and landscapes

6.1 The correlation structure of soil properties

Soil is a three-dimensional mantle with varying degrees of internal organisation. The organisation is lateral, vertical and through time. As the previous sections have shown, soil can be characterised using a range of morphological, physical, chemical, mineralogical and biological variables. The degree to which these variables correlate with each other is embodied in the concept of *orderliness* (Butler 1980).

Mapping is simple when a district has a soil mantle with highly correlated variables and zones exist where rapid change occurs over short distances — measuring one or two variables (e.g. using EM survey) produces a map that forms a good base for estimating other soil properties. Unfortunately, the complexity of landscape processes in many parts of Australia makes this the exception rather than the rule. Many soils bear the imprint of different environmental conditions and unusual combinations of soil properties occur; for example, formerly leached profiles may have subsequent inputs of carbonate. These unusual combinations of properties play havoc with calibrations for measurement systems that rely on a correlative basis.

It would be ideal to directly measure the soil properties relevant to crop production. Clearly, we have to rely in most instances on indirect methods of measurement. The fundamental control on the success of soil measurement is then determined by strength of correlation between the direct and indirect properties.

There has been a large amount of work on the correlations between soil properties and the following generalisations can be made.

- Soil properties are often poorly correlated, although in some landscapes they may be very strongly correlated.
- The pattern and strength of correlations between individual soil properties often change across a landscape and between broad soil types.
- Soil properties mediated by biological processes (e.g. nitrate) are unlikely to have simple relationships with more invariant soil properties (e.g. particle size, cation exchange capacity).
- Soil physical properties (e.g. water storage, permeability) tend to be more closely correlated to readily observed properties than are nutritional properties.
- Correlations are more robust when there is a physical basis to the relationship.
- Many active or passive methods for rapid measurement respond to soil properties that are indirectly related to the functional attributes controlling crop growth. The logical connection between many of these attributes (e.g. dielectric constant, gamma ray emissions, electrical conductivity, reflectance spectra across a range of wavelengths) is poorly documented for many soil materials across the cropping lands of Australia.

Most systems for mapping involve segmenting the landscape into units that can be more readily described or measured in the field and subsequently represented on maps. Segmentation of the three-dimensional landscape into horizons, profiles and land management units (e.g. for zone farming) presupposes a degree of correlation between soil and sometimes landscape properties. This is necessary to allow simplification and prediction. The approach assumes that there are better locations than others for drawing boundaries both laterally and vertically. The advent of digital technologies and quantitative methods has created opportunities for representing the landscape continuum in a manner that more realistically depicts natural variation. In zone farming, all that is presupposed is a relationship between soil variation (or whatever data layers are used for definition of zones) and yield or variation in profitability.

Our view is that methods for mapping should recognise that low levels of orderliness are common. Soil properties have varying levels of correlation and natural modalities may or may not occur. As a result, soil measurement systems for mapping should aim to:

- measure and describe the continuum in terms of individual properties
- classify later into soil types or map units if it is required for practical purposes.

6.2 Mapping — management units or continuous surfaces or both?

The pattern and scale of soil variation largely determine whether uniform management, zone farming or variable rate technology is needed. On the basis of patterns in yield data, Pringle et al. (2003) provide a means for determining the opportunity for each approach. Rapid soil measurement will be of greater value when zone farming or variable rate technology is the best approach. The optimal choice also depends on the response function for various management inputs. If response functions are reasonably flat, then only a few rates of inputs may be needed (e.g. low and high fertiliser additions).

6.3 Linking farm-scale mapping to the broader landscape

Assessing the environmental impacts of farming requires a much broader view of landscape processes than that afforded by detailed soil maps of individual farms and paddocks. The nutrient and water balances of broader landscape units have to be known to understand the impacts on groundwater and surface water quality. It would be advantageous to ensure on-farm measurement and mapping feeds into broader scale mapping programs and databases (see Section 8).

7. The challenge of monitoring soil change

Soil water content can be monitored on a seasonal basis and a range of measurement methods is available (e.g. Dalgliesh and Foale 1998).

However, monitoring of most other soil properties is challenging for several reasons.

- A large proportion of soil variation occurs over surprisingly short distances (up to half the variance within a paddock may already be present within a few square metres).
- Different soil properties have contrasting scales of variation in space and time.
- Some properties change slowly (e.g. pH) while others may be episodic (e.g. bulk density increases due to cultivation when the soil is too wet).

The large short-range spatial variability of most soil properties has several major implications for monitoring.

- Most measurements of soil properties involve the collection of a specimen — sampling is destructive and subsequent measurements are undertaken on separate specimens. The short-range spatial variability can be easily confused with change over time unless there is careful sampling and sufficient replication.

- The large magnitude of variability means that an equally large effort in measurement is necessary to detect trends — the signal-to-noise ratio is typically low.

- Some soil properties can be readily monitored (i.e. those that are less spatially variable (e.g. pH and organic carbon), responsive to management and easy to measure), while others are impractical because of the large spatial variability and high cost of measurement. Selecting tractable soil properties is crucial to the success of a monitoring program.

- It is practical to monitor soil change at local and regional scales. However, it is essential to repeat measurements over time at the *same* site and then to analyse differences between individual sites over time (a site being an area of ~25×25 m rather than a paddock). The alternative of comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time is an inefficient and ineffective method for detecting change.

- Monitoring soil change relies ultimately on very good quality measurement at representative field sites often over extended periods (i.e. decades).

- Information on land management is critical for interpreting the results of direct soil monitoring.

Strategies for monitoring soil change over time are usually at odds with those for soil mapping. For a set level of resources, monitoring soil change over time is best served by accurate and precise measurement at a few representative locations. In contrast, mapping is best served by measurements with lower accuracy and precision at many locations.

These technical issues explain to some degree why soil monitoring is not widely undertaken — see McKenzie et al. (2002) for a review. However, in cropping systems there are other strategies that can provide early warnings on changes in soil condition (the crop being chief amongst these). Measuring the imports and exports of water and nutrients can provide a good basis for estimating soil change and it may be considerably more efficient. This is because some of these terms can be measured at a level that integrates short-range variation. This highlights the need for a combined approach to soil and crop measurement.

8. Building the soil information base for Australian agriculture

There is a lack of reliable and useful soil information across large parts of Australia's cropping lands. Developing rapid soil measurement technologies is a critical step but the more general solution involves action on several fronts.

- There should be a minimum standard of land resource survey coverage (with supporting extension programs and well-characterised sites) if only to increase the appreciation in each district of the range of soil conditions and potential limitations to crop production, along with some basic data to allow the initial parameterisation of farming system models.

- The well-characterised sites are needed to provide reliable pedotransfer functions for estimating hydraulic properties (e.g. PAWC), and other rules of thumb for local conditions.

- There is an excellent opportunity to integrate farmer-based measurement (e.g. profile-available water capacity measurements collected as part of the FARMSCAPE program) with the broader survey coverage. This provides a rational framework for comparing crop performance and management within and between regions.

- It is essential for the grains industry to gain a broader landscape perspective to deal with issues of sustainability. For example, having a sound knowledge base in relation to issues that may arise in relation to nutrient management (e.g. nitrate accession to groundwater in areas with heavy fertiliser use), excessive deep drainage and salinity, and the fate of herbicides and pesticides. There needs to be a sound basis for managing land at the fine spatial scale (e.g. paddocks, farms, even cost centres), so the collective sum of management units has a benign or beneficial impact across the broad landscape.

The existing land resource survey coverage for Australia will be available on-line during the next few years. It is logical for the grains industry to take full advantage of this development as a means for providing better soil information to farmers.

Building an adequate soil information base for Australian agriculture requires an effective partnership between individuals, groups and agencies in the private and public sectors. There are several technical, commercial and institutional issues that need to be addressed to create such a partnership but a consideration of these is beyond the scope of this review.

9. Priorities for development and testing

We have identified the following areas to be worthy of investment.

Specimen acquisition and preparation

- Rapid geo-referenced sampling systems are necessary for collecting soil specimens from the field (disturbed soil and undisturbed cores) for near-surface and deeper soil characterisation.
- Automatic preparation equipment (drying, grinding and homogenising) is needed to supply these specimens in prepared batches for analysis using various rapid sensors (e.g. mid infrared, near infrared).
- Likewise, rapid coring systems are necessary for deeper soil characterisation.
- The implementation of ion-selective field effect transistors requires further development of automatic sampling and extraction systems.

Measurement platforms

- The potential for automatic core scanning using a range of sensors should be investigated — options for down-borehole scanning should also be considered.
- There is potential for improving mid-infrared data acquisition (e.g. automatic staging and batch analysis) and combining these with other spectral ranges in the near infrared and visible.
- There is merit in developing integrated ground-based measurement systems that include a full set of sensors.

Sensors and measurement systems

- Increasing the scanning area of mid-infrared instruments will improve predictions of soil properties. This requires the involvement of instrument manufacturers.

- Several improvements to EM survey instruments are feasible and these should be investigated as a means for obtaining soil water content profiles and information on electrolyte concentrations.

- Ion-selective field effect transistors have considerable potential both for real-time measurement and low-cost batch measurement. Confirmation of the robustness of these sensors would be beneficial.

- Cheap telemetry systems are opening up new and cost-effective possibilities for monitoring soil water content across the landscape. Opportunities for these systems in dryland farming should be investigated.

- Resin-based soil measurement systems will probably never achieve real-time reporting, but laboratory and *in situ* assessment of soil nutrient status using multi-element capability resins is worth further evaluation. In particular, their potential use during the cropping season needs to be assessed.

- A watching brief should be maintained on measurement technologies that at present are either very expensive (e.g. field-based X-ray fluorescence, laser luminescence) or at a very preliminary stage of development (e.g. chemiresistors, ‘electronic noses’, ‘labs-on-a-chip’, nano-technology).

Integrated soil and crop measurement

- Temporal remote sensing with a frequent return interval during the growing season has the potential to identify differences in crop water use and soil hydraulic properties. Further investigation is needed to determine whether these methods can be of assistance to farmers.

- Analysis is needed of the potential for balanced soil and plant analysis systems to ensure targeted and effective measurement — direct soil measurement is not always the best option for identifying soil-related problems (e.g. nutrient deficiencies, waterlogging).

Key data sets

- Calibration data sets for mid-infrared measurements are needed across the major soils used for cropping in Australia.

- Soil hydraulic property measurements are needed on representative soils across the cropping lands of Australia to provide a better basis for estimation using rules of thumb and more formal pedotransfer functions (e.g. for plant-available water capacity, permeability).

- High-resolution digital elevation models are invaluable and steps should be taken to ensure that a better coverage is obtained for the cropping lands of Australia.

- A basic level of land resource survey is required across the cropping lands of Australia to ensure greater awareness of soil-based limitations to crop production and to provide basic data sets (e.g. for hydraulic property estimation). Such a survey framework can provide a first approximation of likely soil properties limiting production along with remedies.

Training and protocols

- Effective application of new and existing technologies for soil measurement requires training programs for technical groups, consultants and farmers.
- Protocols are needed for site-specific rules of soil-test interpretation.

10. References

Adamchuk, V.I., Lund, E., Dobermann, A. and Morgan, M.T. (2003). On-the-go mapping of soil properties using ion-selective electrodes. In *Precision Agriculture: Proceedings of the 4th European Conference on Precision Agriculture*. (J. Stafford & A. Werner, eds). Wageningen Academic Publishers: Wageningen.

Andrade, P., Upadhyaya, S.K. and Jenkins, B. (2002). Development of a compaction profile sensor. In *Proceedings of the Sixth International Conference on Precision Agriculture*. (P.C. Robert, ed.). ASA-CSSA-SSSA: Madison.

Baumgardner, M.F., Silva, L.F., Biehl, L.L. and Stoner, E. (1985). Reflectance properties of soils. *Advances in Agronomy* **38**: 1–44.

Beckett, P.H.T. and Webster, R. (1971). Soil variability: a review. *Soils and Fertilizers* **34**: 1–15.

Bierwirth, P.N. (1997). The use of airborne gamma-emission data for detecting soil properties. In *Proceedings of the Third International Airborne Remote Sensing Conference and Exhibition*, Copenhagen, Denmark.

Birrell, S.J. and Hummel, J.W. (2001). Real-time multi ISFET/FIA soil analysis system with automatic sample extraction. *Computers and Electronics in Agriculture* **32**: 45–67.

Bishop, T.F.A. and McBratney, A.B. (2002). Creating field extent digital elevation models for precision agriculture. *Precision Agriculture* **3**: 37–46.

Blakemore, L.C., Searle, P.L. and Daly, B.K. (1987). *Methods for Chemical Analysis of Soils*. New Zealand Soil Bureau Scientific Report 80.

Bramley, R.G.V., Cook, S.E., Adams, M.L. and Corner, R.J. (1999). *Designing Your Own On-farm Experiments: How precision agriculture can help*. Grains Research and Development Corporation: Canberra.

Bramley, R.G.V. and Cook, S.E. (2000). Some comments on the utility of soil test data for fertility management and resource assessment. *ACLEP Newsletter* **7**(2), Australian Collaborative Land Evaluation Program: Canberra.

Bramley, R.G.V., Evans, T.E. and Proffitt, A.P.B. (2002). Digital elevation models and EM38 survey — useful tools in the assessment of constraints to vineyard productivity. *Proceedings of the 11th Wine Industry Technical Conference*, Australian Wine Research Institute.

Bramley, R.G.V. and Janik, L.J. (2003). Precision agriculture demands a new approach to soil and plant sampling and analysis — examples from Australia. *Communications in Plant and Soil Analysis* (in press).

Burrough, P.A. (1993). Soil variability: a late 20th century view. *Soils and Fertilizers* **56**: 529–562.

Butler, B.E. (1980). *Soil Classification for Soil Survey*. Clarendon Press: Oxford.

Charlesworth, P. (2000). Soil water monitoring. *Irrigation Insights* No. **1**. Land and Water Australia: Canberra. http://www.npird.gov.au/projects/finalrep_pdf/index.html

Cook, S.E., Corner, R.J., Groves, P.R. and Grealish, G.J. (1996a). Use of airborne gamma radiometric data for soil mapping. *Australian Journal Soil Research* **34**: 183–194.

Cook, S.E., Corner, R.J., Grealish, G.J., Gessler, P.E. and Chartres, C.J. (1996b). A rule based system to map soil properties. *Soil Science Society of America Journal* **60**: 1893–1900.

Cook, S.E. and Bramley, R.G.V. (1998). Precision agriculture — opportunities, benefits and pitfalls of site-specific crop management in Australia. *Australian Journal of Experimental Agriculture* **38**: 753–763.

Cook, S.E. and Bramley, R.G.V. (2000). Coping with variability in agricultural production — Implications for soil testing and fertilizer management. *Communications in Plant and Soil Analysis* **31**: 1531–1551.

Cook, S.E. and Bramley, R.G.V. (2001). Is agronomy being left behind by precision agriculture? *Proceedings of the 10th Australian Agronomy Conference*, Hobart.

Dalgliesh, N. and Foale, M. (1998). *Soil Matters*. Cranbrook Press: Toowoomba.

Da Silva, A.P., Kay, B.D. and Perfect, E. (1994). Characterization of the least limiting water range of soils. *Soil Science Society of America Journal* **58**: 1775–1781.

Dobermann, A., Langner, H., Mutscher, H., Yang, J.E., Skogley, E.O., Adviento, M.A. and Pampolino, M.F. (1994). Nutrient adsorption kinetics of ion exchange resin capsules: a study with soils of international origin. *Communications in Soil Science and Plant Analysis* **25**: 1329–1353.

Dunn, B.W. and Beecher, H.G. (2002). The estimation of soil sodicity and pH using NIR spectroscopy has potential for precision agriculture. In *Future Soils: Managing soil resources to ensure access to markets for future generations. Australian Society of Soil Science National Conference*, Perth, Western Australia. (D. Williamson, C. Tang, A. Tate, eds). Australian Society of Soil Science: Perth.

Dunn, B.W., Beecher, H.G., Batten, G.D. and Ciavarella, S. (2002). The potential of near-infrared reflectance spectroscopy for soil analysis — a case study from the Riverine Plain of south-eastern Australia. *Australian Journal of Experimental Agriculture* **42**: 607–614.

FIFA (2001). *Cracking the Nutrient Code: Guidelines for developing a Nutrient Management Code of Practice for your industry, region or farm*. Fertiliser Industry Federation of Australia: Canberra.

Gallant, J.C. and Dowling, T.D. (2003). A multi-resolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research* (in press).

Geotek (2001). *Multi-Sensor Core Logger*. Geotek: Daventry, United Kingdom.

Gessler, P.E. (1996). Statistical soil-landscape modelling for environmental management. PhD Thesis, Australian National University.

Gessler, P.E., Moore, I.D., McKenzie, N.J. and Ryan, P.J. (1995). Soil-landscape modelling and spatial prediction of soil attributes. *International Journal of Geographical Information Systems* **4**: 421–432.

Glendinning, J.S. (1999). *Australian Soil Fertility Manual*. CSIRO Publishing: Melbourne.

Gourley, C.J.P. (1999). Potassium. In *Soil Analysis: An interpretation manual* (K.I. Peverill, L.A. Sparrow and D.J. Reuter, eds). CSIRO Publishing: Melbourne.

Groenevelt, P.H., Grant, C.D. and Semetsa, S. (2001). A new procedure to determine soil water availability. *Australian Journal of Soil Research* **39**: 577–598.

Gundersen, H.J.G. and Østerby, R. (1981). Optimizing sampling efficiency of stereological studies in biology: or ‘Do more less well!’ *Journal of Microscopy* **121**: 65–73.

Henderson, B., Bui, E., Moran, C., Simon, D. and Carlile, P. (2001). *ASRIS: Continental-scale soil property predictions from point data*. CSIRO Land & Water Technical Report 28/01.

Hill, J. and Schütt, B. (2000). Mapping complex patterns of erosion and stability in dry Mediterranean ecosystems. *Remote Sensing of Environment* **74**: 557–569.

Huisman, J.A., Hubbard, S.S., Redman, J.D. and Annan, A.P. (2003). Measuring soil water content with ground penetrating radar: a review. *Vadose Zone Journal* (in press).

Hummel, J.W., Sudduth, K.A. and Hollinger, S.E. (2001). Soil moisture and organic matter prediction of surface and subsurface soils using an NIR soil sensor. *Computers and Electronics in Agriculture* **32**: 149–165.

Hutchinson, P.A. and Bond, W.J. (2001). Routine measurement of the soil water potential gradient near saturation using a pair of tube tensiometers. *Australian Journal of Soil Research* **39**: 1147–1156.

Janik, L.J., Skjemstad, J.O. and Raven, M.D. (1995). Characterization and analysis of soils using mid-infrared partial least squares. I. Correlations with XRF-determined major element composition. *Australian Journal of Soil Research*. **33**: 621–636.

Janik, L.J. and Skjemstad, J.O. (1995). Characterization and analysis of soils using mid-infrared partial least squares. II. Correlations with some laboratory data. *Australian Journal of Soil Research*. **33**: 637–650.

Janik, L.J., Merry, R.H. and Skjemstad, J.O. (1998). Can mid infrared diffuse reflectance analysis replace soil extractions? *Australian Journal of Experimental Agriculture* **38**: 681–696.

Keam, R.B., Holdem, J.R. and Schoonees, J.A. (1999). Soil moisture profile estimation from surface measurements at multiple frequencies. *Australian Journal of Soil Research* **37**: 1107–1121.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D.P., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, K., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**: 267–288.

Letey, J. (1985). Relationships between soil physical properties and crop production. *Advances in Soil Science* **1**: 277–294.

Letey, J. (1991). The study of soil structure: science or art. *Australian Journal of Soil Research* **29**: 699–708.

McBratney, A.B. and Pringle, M.J. (1999). Estimating proportional and average variograms of soil properties and their potential use in precision agriculture. *Precision Agriculture* **1**: 125–152.

McBratney, A.B., Mendonça Santos, M.L. and Minasny, B. (2003). On digital soil mapping. *Geoderma* (in press).

McKenzie, N.J. (1991). *A Strategy for Coordinating Soil Survey and Land Evaluation in Australia*. CSIRO Division of Soils, Divisional Report No. 114.

McKenzie, N.J. and Ryan, P.J. (1999). Spatial prediction of soil properties using environmental correlation. *Geoderma* **89**: 67–94.

McKenzie, N.J., Isbell, R.F., Brown, K. and Jacquier, D.W. (1999). Major soils used for agriculture in Australia. In *Soil Analysis: an interpretation manual*. (K.I. Peverill, L.A. Sparrow and D.J. Reuter, eds). CSIRO Publishing: Melbourne.

McKenzie, N.J., Gessler, P.E., Ryan, P.J. and O'Connell, D. (2000). The role of terrain analysis in soil mapping. In *Terrain Analysis: principles and applications* (J.P. Wilson and J.C. Gallant, eds). John Wiley: New York.

McKenzie, N.J. and Cresswell, H.P. (2002). Estimating soil physical properties using more readily available data. In *Soil Physical Measurement and Interpretation for Land Evaluation*. Australian Soil and Land Survey Handbook Series, Vol. 5. (N.J. McKenzie, K. Coughlan and H.P. Cresswell, eds). CSIRO Publishing: Melbourne.

McKenzie, N.J., Henderson, B. and McDonald, W.S. (2002). *Monitoring Soil Change. Principles and practices for Australian conditions*. CSIRO Land & Water Technical Report 18/02, Canberra.

McLaughlin, M.J., Lancaster, P.A., Sale, P.W.G., Uren, N.C. and Peverill, K.I. (1994). Comparison of cation/anion exchange resin methods for multi-element testing of acidic soils. *Australian Journal of Soil Research* **32**: 229–240.

McLaughlin, M.J., Lancaster, P.A., Sale, P.W.G., Uren, N.C. and Peverell, K.I. (1993). Use of cation/anion exchange resins for multi-element testing of acidic soils. *Plant and Soil* **155/156**: 223–226.

McNeill, J.D. (1980). *Electrical Conductivity of Soils and Rocks*. Technical Note TN-5, Geonics Limited, Mississauga, Ontario, Canada.

McVicar, T.R. and Jupp, D.L.B. (2002). Using covariates to spatially interpolate moisture availability in the Murray–Darling Basin: A novel use of remotely sensed data. *Remote Sensing of Environment* **79**: 199–212.

Minty, B.R.S. (1997). Fundamentals of airborne gamma-ray spectrometry. *AGSO Journal of Australian Geology and Geophysics* **17**: 39–50.

Moore, I.D., Gessler, P.E., Nielsen, G.A. and Peterson, G.A. (1993). Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal* **57**: 443–452.

NLWRA (2001). *Australian Agricultural Assessment 2001*. National Land and Water Resources Audit: Canberra.

Ozanne, P.G. and Shaw, T.C. (1967). Phosphate sorption by soils as a measure of the phosphate requirement for pasture growth. *Australian Journal of Agricultural Research* **18**: 601–612.

Pannell, D.J. and Glenn, N.A. (2000). A framework for the economic evaluation and selection of sustainability indicators in agriculture. *Ecological Economics* **33**: 135–149.

Pringle, M.J., McBratney, A.B., Whelan, B.M. and Taylor, J.A. (2003). A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. *Agricultural Systems* **76**: 273–292.

Qian, P. and Schoenau, J.J. (1995). Assessing nitrogen mineralization from soil organic matter using anion exchange membranes. *Fertilizer Research* **40**: 143–148.

Qian, P. and Schoenau, J.J. (2002). Practical applications of ion exchange resins in agricultural and environmental soil research. *Canadian Journal of Soil Science* **82**: 9–21.

Qian, P., Schoenau, J.J., Greer, K.J. and Liu, Z. (2002). Assessing plant-available potassium in soil using cation exchange membrane burial. *Canadian Journal of Soil Science* **82**: 191–194.

Qian, P., Schoenau, J.J. and Huang, W.Z. (1992). Use of ion exchange membranes in routine soil testing. *Communications in Soil Science and Plant Analysis* **23**: 1791–1804.

Rayment, G.E. and Higginson, F.R. (1992). *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press: Melbourne.

Rengasamy, P. (2002). Clay dispersion. In *Soil Physical Measurement and Interpretation for Land Evaluation*. (N.J. McKenzie, K.J. Coughlan and H.P. Cresswell, eds). Australian Soil and Land Survey Handbook Series, Volume 5. CSIRO Publishing: Melbourne.

Reusch, S., Link, A. and Lammel, J. (2002). Tractor-mounted multispectral scanner for remote field investigation. In *Proceedings of the Sixth International Conference on Precision Agriculture*. (P.C. Robert, ed.). ASA-CSSA-SSSA: Madison.

Reuter, J.I., Wendroth, O., Kersebaum, K.C. and Schwarz, J. (2003). MOSAIC: Crop yield observation — can landform stratification improve our understanding of crop yield variability? In *Precision Agriculture: Proceedings of the 4th European Conference on Precision Agriculture*. (J. Stafford and A. Werner, eds). Wageningen Academic Publishers: Wageningen.

Rooney, D.J., Norman, J.M. and Grunwald, S. (2001). Soil-imaging penetrometer: a tool for obtaining real-time in-situ soil images. Paper No. 013107, *Proceedings American Society of Agricultural Engineering* annual meeting, Sacramento, California, August.

Saunders, W.M.H. (1964). Extracton of soil phosphate by anion-exchange membrane. *New Zealand Journal of Agricultural Research* **7**: 427–431.

Schoknecht, N. and Tille, P. (2002). Soil-landscape mapping in south-western Australia — an overview. Western Australian Department of Agriculture. http://www.agric.wa.gov.au/progserv/natural/assess/PDF_files/mapping_overview.pdf

Schoenau, J.J. and Huang, W.Z. (1991). Anion-exchange membrane, water, and sodium bicarbonate extractions as soil tests for phosphorus. *Communications in Soil Science and Plant Analysis* **22**: 465–492.

Shibusawa, S., I Made Anom, S.W., Sato, S., Sasao, A. and Hirako, S. (2001). Soil mapping using the real-time soil spectrophotometer. In *ECPA 2001: 3rd European Conference on Precision Agriculture*. (S. Blackmore and G. Grenier, eds). Ecole Nationale Superieure Agronomique de Montpellier, France.

Shibusawa, S., I Made Anom, S.W., Hache, C., Sasao, A. and Hirako, S. (2003). Site-specific crop response to temporal trend of soil variability by the real-time spectrophotometer. In *Precision Agriculture: Proceedings of the 4th European Conference on Precision Agriculture*. (J. Stafford and A. Werner, eds). Wageningen Academic Publishers: Wageningen.

Shonk, G.A., Gaultney, L.D., Schulze, D.G. and Van Scoyoc, G.E. (1991). Spectroscopic sensing of soil organic matter content. *Transactions of the American Society of Agricultural Engineers* **34**: 1978–1984.

Sibbesen, E. (1978). An investigation of the anion-exchange resin method for soil phosphate extraction. *Plant and Soil* **50**: 305–321.

Skogley, E.O. (1992). The universal bioavailability environment/soil test unibest. *Communications in Soil Science and Plant Analysis* **23**: 2225–2247.

Skogley, E.O. and A. Dobermann (1996). Synthetic ion-exchange resins: soil and environmental studies. *Journal of Environmental Quality* **25**: 13–24.

Skogley, E.O., Georgitis, S.J., Yang, J.E. and Schaff, B.E. (1990). The phytoavailability soil test—PST. *Communications in Soil Science and Plant Analysis* **21**: 1229–1243.

Solie, J.B., Stone, M.L., Raun, W.R., Johnson, G.V., Freeman, K., Mullen, R., Needham, D.E., Reed, S. and Washmon, C.N. (2002). Real-time sensing and N fertilization with a field scale GreenSeeker™ Applicator. In *Proceedings of the Sixth International Conference on Precision Agriculture*. (P.C. Robert, ed.). ASA-CSSA-SSSA: Madison.

Stirzaker, R.J. (2003). When to turn the water off: scheduling micro-irrigation with a wetting front detector. *Irrigation Science* (in press).

Strong, W.M. and Mason, M.G. (1999). Nitrogen. In *Soil Analysis: An interpretation manual* (K.I. Peverill, L.A. Sparrow and D.J. Reuter, eds). CSIRO Publishing: Melbourne.

Sudduth, K.A. and Hummel, J.W. (1993a). Portable near-infrared spectrophotometer for rapid soil analysis. *Transactions of the American Society of Agriculture Engineers* **36**: 187–195.

Sudduth, K.A. and Hummel, J.W. (1993b). Soil organic matter, CEC, and moisture sensing with a portable NIR spectrophotometer. *Transactions of the American Society of Agriculture Engineers* **36**: 1571–1582.

Thompson, C.H. and Beckmann, G.G. (1959). *Soils and Land Use in the Toowoomba Area, Darling Downs, Queensland*. CSIRO Australia, Division of Soils, Soils and Land Use Series No. 28.

USAEC (2000). *The Tri-service Site Characterization and Analysis Penetrometer System—SCAPS*. United States Army Environmental Center Report No. SFIM-AEC-ET-TR-99073.

van Raij, B. (1998). Bioavailable tests: alternatives to standard extractions. *Communications in Soil Science and Plant Analysis* **29**: 1553–1570.

van Raij, B., Quaggio, J.A. and da Silva, N.M. (1986). Extraction of phosphorus, potassium, calcium and magnesium from soils by an ion-exchange resin procedure. *Communications in Soil Science and Plant Analyses* **17**: 547–566.

Viscarra Rossel, R.A. and McBratney, A.B. (1998a). Soil chemical analytical accuracy and costs: implications from precision agriculture. *Australian Journal of Experimental Agriculture* **38**: 765–775.

Viscarra Rossel, R.A. and McBratney, A.B. (1998b). Laboratory evaluation of a proximal sensing technique for simultaneous measurement of soil clay and water content. *Geoderma* **85**: 19–39.

Viscarra Rossel, R.A. and McBratney, A.B. (2003). Modelling the kinetics of buffer reactions for rapid field predictions of lime requirements. *Geoderma* **114**: 49–63.

Viscarra Rossel, R.A., Walter, C. and Fouad, Y. (2003). Assessment of two reflectance techniques for the quantification of the within field spatial variability of soil organic carbon. In *Precision Agriculture: Proceedings of the 4th European Conference on Precision Agriculture*. (J. Stafford and A. Werner, eds). Wageningen Academic Publishers: Wageningen.

Wilding, L.P. and Drees, L.R. (1983). Spatial variability and pedology. In *Pedogenesis and Soil Taxonomy. I Concepts and interactions*. (L.P. Wilding, N.E. Smeck and G.F. Hall, eds). Developments in Soil Science 11A. Elsevier: Amsterdam.

Williams, B.G. and Baker, G.C. (1982). An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. *Australian Journal of Soil Research* **20**: 107–118.

Williams, B.G. and Hoey, D. (1987). The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. *Australian Journal of Soil Research* **25**: 21–27.

Wilson, J.P. and Gallant, J.C. (2000). *Terrain Analysis: Principles and applications*. John Wiley and Sons: New York.

Yang, J.E. and Skogley, E.O. (1992). Diffusion kinetics of multinutrient accumulation by mixed-bed ion-exchange resin. *Soil Science Society of America Journal* **45**: 408–414.

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