NATIONAL PROGRAM FOR
Sustainable Irrigation

Scoping study

Improving plants' water use efficiency and potential impacts from soil structure change - research investment opportunities

CRCIF technical report 3.14/1

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Executive Summary

Background

The Board of the National Program for Sustainable Irrigation commissioned this scoping document to assist in its research investment deliberations. The key questions addressed by this scoping study are:

1. *What understanding, techniques and tools require further explanation or development to improve water use efficiency?*
2. *How well do we understand the impacts of long-term irrigation on soil structure? What are the effects of soil structure change (within and around the root zone on the flow of water and rate of movement along various pathways of salts?*

Key issues which the NPSI Board requested should be addressed in the document were:

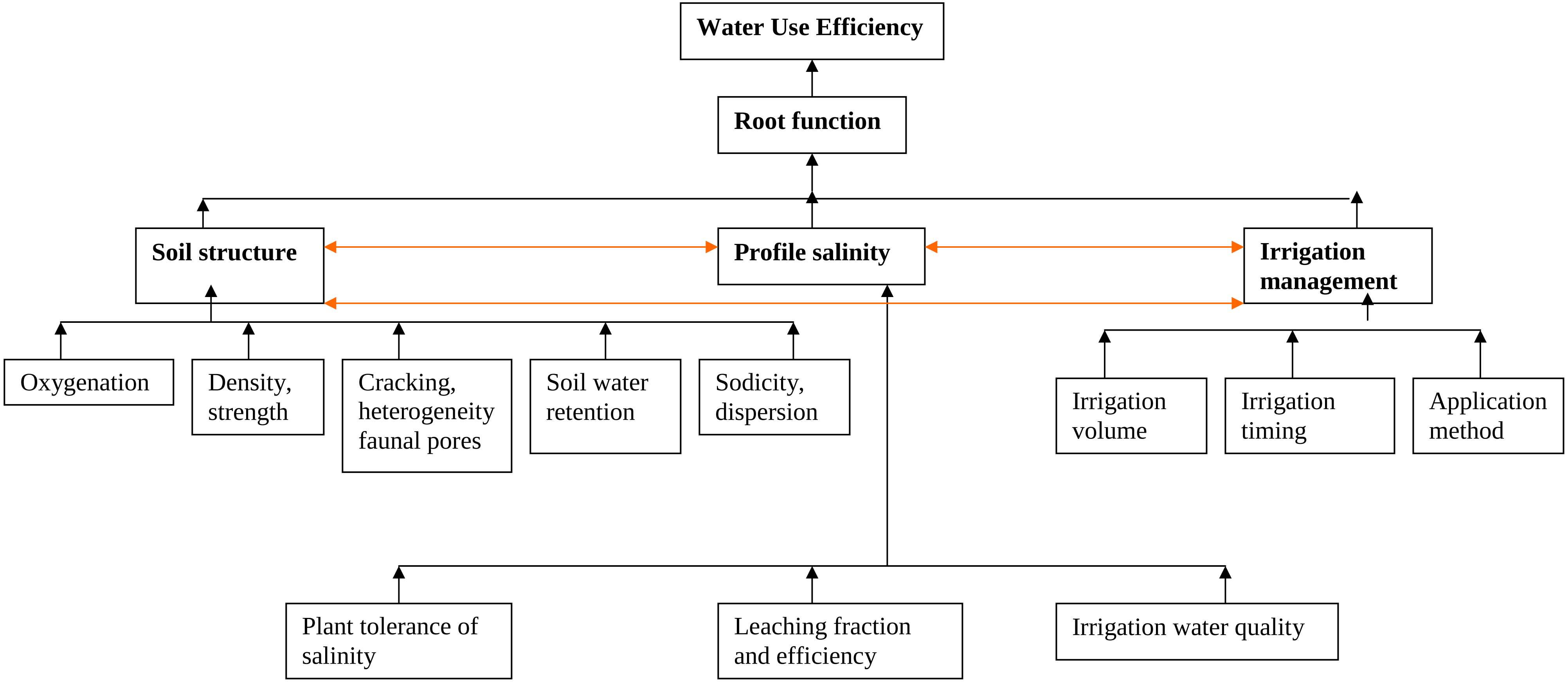
- Comment on the place that oxygenation may have in reducing the effects of water logging on production for various irrigation systems and secondary issues such as disease and pathogens at higher water temperatures.
- How much is understood on the impacts of soil structure on water use efficiency, and in particular, managing the leaching fraction requirements of various soils?
- Comment on the proposed work by Schrale to investigate issues associated with soil structure decline
- Other than leaching efficiency and leaching fraction, are there other issues we do not understand that limit plants' water use efficiency and salt disposal within the root zone?

Discussion

If *water use efficiency* (WUE) is considered as the amount of water transpired relative to the amount applied (t yield / ML water) then any factor that restricts the expansion and efficiency of the plant root system will reduce WUE. Given the number of factors shown in the following diagram (and the strong interrelationships between most of the factors at the more detailed two levels), achieving optimal WUE is not a simple task for any irrigation manager.

Some factors, such as irrigation scheduling (to optimise performance relative to soil structure and water retention profiles) can provide relatively immediate returns to irrigators. However, other factors such as leaching fraction and efficiency and soil cations are more strategic concerns, as their proper management is essential not for short-term advantage, but rather for the control of medium- to long-term threats to the viability of irrigation at a particular location.

The balancing of short-term management needs with longer term strategic concerns is obviously a requirement not only for irrigation managers, but also for organisations involved in irrigation research and development.



Linkages between the three broad areas impacting on root growth are shown. However, linkages at the most detailed level are too numerous and complex to be indicated on this diagram.

Soil structure and structural decline

Soils display enormous spatial heterogeneity at the aggregate and clod scale and over distances <1 m. Some of that structural heterogeneity is important for root system function and for water and salt movement, and its loss or modification can have deleterious effects on plant root systems and on water and salt transfer through the profile. Currently, there is little information on the spatial (particularly short distances) and temporal variation of soil properties.

Structural decline in many irrigated areas is associated with accumulation of sodium in the subsoil, leading to clay dispersion, increased soil strength, poor aeration and reduced hydraulic conductivity. Associated processes include precipitation of $CaCO_3$, and accumulation of Mg. Changes in exchangeable cations may not cause problems until heavy rain or improvements in irrigation water quality cause dilution of salts. In dealing with this form of structural degradation, tools needed include a suitable methodology for measuring subsoil degradation, better understanding of processes, and better information on options for remediation.

A general consequence of subsoil deterioration is a reduction in the overall volume and number of larger pores that contribute to deep drainage of water. As the number of preferred flow paths diminishes, leaching efficiency could be expected to reduce as well, but there is little information to directly relate leaching efficiency to various levels of structural decline (and, as noted above, a lack of methods for conveniently measuring structural decline, particularly in the subsoil).

A 1-page concept proposal to investigate soil structural decline under precision and saline irrigation has been developed from consultation between the existing NPSI project DEP15 project leaders and the NPSI Coordinator. **It is recommended that the core research related to soil structural decline and the subsequent agronomic responses be considered for funding but consideration be given to funding this work within a broader research program investigating the impacts of precision irrigation with saline water.**

Waterlogging and oxygenation are potentially significant issues for a number of crops. Air injection via subsurface drip irrigation systems has been found to give yield increases in plants subject to waterlogging. However, direct injection of air seems to be little used, and injection of air mixed into the irrigation water has difficulties with the air and water separating in the irrigation lines so that only short lines can be used. Alternatively, hydrogen peroxide has been added to irrigation water and soils, but at this stage there is little information on the operating conditions under which benefits would be obtained nor on the exact mechanism(s) of action. Land and Water Australia received a proposal under the Innovation Program on the delivery of oxygen to the roots through subsurface drip irrigation. The proposed research approach is sound and includes a combination of commercial field demonstrations/trials supported by glasshouse trials. Skills of the principal investigator and other identified team members are of international research standard. The major limitation of this proposal is its limited scope. **It is recommended that this research be funded and that the opportunity to expand the proposed research program to include other regions and crops be investigated.**

Irrigation management

Two types of information products can assist irrigation managers to optimise their soil conditions for plant growth and maximise water use efficiency. One is based on simulation modelling. The other relies on rapid field evaluation using procedures such as soil pit investigations to directly observe soil-water movement and deep drainage after an irrigation. Computer models that describe dynamic processes in irrigated soil may eventually be the main tool used by irrigators. However, until these models become sufficiently accurate, visual-tactile methods are likely to dominate.

Information on soil-water retention curves and associated changes in unsaturated hydraulic conductivity could be used to optimise irrigation systems in terms of minimising plant water stress, controlling leaching of water and salts, and minimising impacts on soil structure. As the cost of measuring soil hydraulic properties directly is high, they are usually predicted from other soil properties that are easier to measure. Prediction of soil hydraulic properties using pedotransfer functions has met with limited success, but continued development is essential. The model recently proposed by Groenevelt & Grant (2004) appears promising. Methods are also needed for extrapolation of data on soil hydraulic properties up to paddock and whole-catchment scales.

Profile salinity

Plant root growth is impacted by the salinity of the soil-water solution, though plants respond to combined osmotic and matric stresses. Variations in plant responses to the combined stress indicate a need for greater data across a range of plant species. Irrigation management (eg. timing, volume, and possibly placement of irrigation water) also impacts on water use efficiency.

Drip irrigated systems create spatial and temporal variation of salts and sodicity. Some winegrape areas make use of a number of additives to the irrigation water, and the long-term effects of those additives are currently unknown.

Other issues of interest include the need to be able to predict temporal and spatial variations in distributions of water and nutrients, the importance of extending knowledge from a single irrigated area to consideration of catchment processes and the potential impact on soil structure of variability in solute distributions and root activity associated with alternate irrigation management practices such as partial root zone drying.

Recommendations for research

Apart from the two research proposals already receiving comment, higher priority recommended areas of research and their components are given in the following table. A wider range of topics (some of perceived lower priority) is given in a table in the accompanying text, together with greater information on the perceived structure of some of the research activities.

Some of those research areas will be appropriate for funding by NPSI, others may be more appropriate for other funding bodies or institutions. However, it is strongly recommended that coordination between potential funding bodies be sought to ensure the best possible coverage of the areas identified.

Development of tools characterising soil structural and soil-water properties to enable better water use efficiency and management of leaching fractions under irrigation			
Components	**Perceived priority (1-4, high-low)**	**Likely cost & duration**	**Relevant section in text**
Refine field (e.g. soil pit) methods to allow description of the soil-water properties including patterns of wetting and deep drainage under micro-irrigation systems.	1	$120,000-$150,000 1-2 years	1.2
Investigate the impacts of subsoil structural decline on deep drainage and leaching efficiency.	1	$200,000-$300,000 3 years	3.1
Develop a simple, robust methodology to characterise water retention curves for Australian soils, thereby producing more useful pedotransfer functions and optimal efficiency of irrigation scheduling.	1	$800,000 3 years	1.1, 1.2
Improve quantitative understanding of weighting functions to account for different limiting soil properties in calculating soil-water availability for different crops.	2	$300,000 3 years	1.2
Investigate the effects of soil biopores on drainage and leaching efficiency.	2	$100,000-$150,000 2 years	3.2

Tools for identification and remediation of soil structural decline under irrigation			
Develop tools and monitoring protocols for assessing soil structural stability under irrigated crops, and test under a broad range of soil types.	1	$60,000 1 year	2.2
Determine the extent to which subsoil structural stability varies according to proximity to zones where by-pass flow occurs (shrinkage cracks, old root channels) and where crop roots are most active	2	$500,000-$600,000 3 years	2.2

Expansion on Key Points

1. Soil factors influencing water use efficiency – current understanding, tools and techniques required to improve WUE.

1.1 Soil factors influencing water use efficiency

Restricting the meaning of *water use efficiency* (WUE) to the amount of water transpired relative to the amount applied (t yield / ML water) (Hillel 1998; Skewes & Meissner 1997a, b & c) focuses attention on soil factors that influence this ratio. In this context, any factor that restricts the root system reduces WUE.

For example, high soil strength due to compaction (e.g. van Huyssteen 1983) prevents plant roots from exploring the soil matrix for water and nutrients and can have a direct impact on WUE (Masle and Farquhar 1988). Roots encounter increasing difficulty entering regions of soil that have penetrometer resistances exceeding approximately 0.5 MPa (Young et al. 1997) and they generally stop growing altogether when soil resistance reaches 3.6 MPa (Masle 1999). Unless root systems can take advantage of crack networks or are established before the soil matrix becomes compacted, they must rely upon the unsaturated hydraulic properties of the soil to facilitate transport of water and nutrients down relatively modest gradients in water potential toward the immobile root system. However, soil strength is neither uniform nor static and root systems may have varying abilities to take advantage of spatial and temporal variations in soil resistance (Masle 1998). Nevertheless, we still do not yet understand the extent to which WUE is reduced when root systems expend their energy exploring complex channels, rather than more direct routes toward water and nutrients.

The aeration status of the soil matrix also has an impact on plant uptake of water and nutrients, although there are many interactions controlling plant responses (Saqib et al. 2004). However, most plants of commercial value do not use soil-water efficiently when it is anaerobic. Part of the plant response is caused by nutrient deficiencies due to changes in the redox status of the soil solution. Many plants, however, suffer physiological membrane damage and become less selective for critical and harmful solutes (Jackson 1990). Having said this, most soils are not completely immersed or anaerobic – they contain isolated regions of oxygen deficiency which plant roots generally avoid. The extent to which WUE is diminished by the presence of spatially variable anaerobic conditions is unknown.

Research is needed into the impacts of spatial and temporal heterogeneity in soil strength and anaerobic conditions (over quite short distances) on root system growth and efficiency. Research is also needed to understand how irrigation management can influence plant response to this variability. Despite a tendency to view a soil profile as a laterally homogeneous medium, in reality there is enormous lateral heterogeneity at the aggregate, clod, and <1 m scales. It seems likely that some of that heterogeneity is important for root system function and for water and salt movement, and that its loss or modification can have deleterious effects.

It is generally thought that soluble salts have a negative linear effect on plant response when they exceed threshold concentrations (e.g. Maas 1993; Sadeh & Ravina 2000). However, thresholds vary from species to species (e.g. Shainberg & Oster 1978;

Feinerman et al. 1982; Mizrahi & Pasternak 1985; Oosterhuis & Wullschleger 1990; Stevens et al. 1999) and with the timing of the stress in relation to flowering and fruit-set. The plant response is not simple, though (see Schmidhalter & Oertli 1990), because plants do not distinguish between water stresses due to soluble salts (osmotic head) and water stresses due to the pore matrix (matric head). Rather plants sense a combined osmo-matric head. It should also be noted that the effects of soluble salts do not vary linearly as the soil dries out (Groenevelt et al. 2004). In fact, the greatest effect on soil-water availability appears to occur when the soil is still relatively wet, somewhere around field capacity. This effect diminishes considerably in drier soils, where the effects of matric head become much more limiting to plant available water (Groenevelt et al. 2004). Work with tomatoes (Kütük et al. 2004) appears to corroborate this concept, which may have implications for the most efficient timing and amounts of irrigation for different crops depending on their sensitivity to osmotic stresses. Considerable work has yet to be done to evaluate the response of different plant species to osmo-matric stresses because each plant seems to have different root-cell reflection coefficients (Zimmermann et al. 2002). Research is needed to understand how different plants respond to irrigation water of differing quality in different soils.

Some of the dynamic aspects of water use efficiency are more difficult to predict. For example, soil-water is conventionally thought to be completely 'unavailable' until it reaches a state of gravitational equilibrium, called "field capacity" by agronomists (e.g. Gardner 1968) and the "drained upper limit" by horticulturalists (Harden 1988). This concept is completely arbitrary though, because plants under water stress do not wait to absorb water until the energy status of the irrigation water reaches 'field capacity' - they immediately start taking up water in response to the ambient vapour pressure deficit. Nevertheless, excessively large hydraulic conductivities do remove a considerable amount of water before plants can extract it. This explains the link between the availability of soil-water and an arbitrary matric head describing its energy status, even though this varies from 5 to 33 kPa depending on circumstance. Similarly, at the dry end, excessively low hydraulic conductivity limits the rate at which water can move toward plant roots. We know from experience (and limited experimental evidence – e.g. Gardner 1965) that unsaturated hydraulic conductivity declines precipitously with increasing matric head, and that this varies with soil type. We don't, however, understand how to manage irrigation water efficiently to prevent leaching of nitrogen and other soluble compounds in horticultural operations, even using trickle- or drip-irrigation (Thorburn et al 2003; Mmolawa and Or 2000). Our understanding of the way in which hydraulic properties of Australian soils change as they drain and dry out is also limited (Cresswell & Paydar 1996). Research is therefore needed to link our understanding of how soil hydraulic properties change during drying with irrigation management so that we minimize leaching, even with drip-irrigation.

1.2 Tools and techniques required to improve WUE

There are two types of information products that are relevant to irrigation managers who want to optimise their soil conditions for plant growth and maximise water use efficiency. One is based on simulation modelling. The other relies on rapid field evaluation using procedures such as soil pit investigations to directly observe soil-water movement and deep drainage after an irrigation. Both approaches are relevant and valid. Computer models that describe dynamic processes in irrigated soil may eventually be the main tool used by irrigators. However, until these models become sufficiently accurate, visual-tactile methods are likely to dominate.

Battam et al. (2000) described how drip irrigation emitters connected to a portable pump were used in conjunction with large soil pits to successfully investigate patterns of wetting and deep drainage in a hardsetting red soil under cotton. Suppliers of drip irrigation equipment are very keen to see widespread use of this type of measurement technology by soil surveyors and irrigation design engineers (Erez Cohen, pers. comm.). Funding is required to refine the soil pit method to allow rapid description of the patterns of wetting and deep drainage under micro-irrigation systems.

Managing irrigation water efficiently also requires an understanding of the fundamental hydraulic properties of our soils. However, the time and cost involved with existing methods of measuring these properties directly means that they are usually predicted from other soil properties that are easier to measure. Hence, there is a need to develop more rapid and robust measurements of soil hydraulic properties that can be used by practitioners under field conditions. The current push to predict soil hydraulic properties using pedotransfer functions, while laudable, has met with limited success (Kay et al. 1997; Paydar & Ringrose-Voase 2003; Regalado & Munoz-Carpena 2004), particularly for the hydraulic properties of swelling soils (Vervoort et al. 2003). The available tools are simply too crude to allow prediction of hydraulic properties at the paddock scale and are of little use to irrigators (Rawls et al. 1998; Minasny & McBratney 2000; Wosten et al. 2001). Nevertheless, better predictions are essential if scientists are to develop improved irrigation practices and have them adopted, as changing grower attitudes toward irrigation is not a simple task (Moore 2004). To improve prediction of soil hydraulic properties, better models for the soil-water retention curve are needed than those proposed by, for example, Brooks & Corey (1964), Campbell (1974), van Genuchten (1980) or Hutson & Cass (1987). Better ways to characterise the water retention curves for Australian soils would enable production of better and more useful pedotransfer functions. In this regard the model recently proposed by Groenevelt & Grant (2004), appears promising and needs to be exploited and tested on a range of different soils used for irrigation in Australia.

Methods are also needed for extrapolating information on soil hydraulic properties at one scale up to (more relevant) paddock and whole-catchment scales (Mubiru & Fairweather 2004). Two issues are common. The first relates to the management of soil spatial variability within an irrigation block, with growers frequently identifying the management of variable blocks as a considerable difficulty. The second is the need to be able to translate specific, detailed, soil information into guidelines for irrigation strategies that can be used by suppliers of equipment and by farm managers.

Better predictions of soil-water availability to plants are needed, to take into account more than simply the 'drained upper limit' and the 'refill point'. All soil properties that limit root growth and extraction of water and nutrients should be considered, including high soil strength, poor aeration, excessively high or low hydraulic conductivity, and high concentrations of soluble salts. A new model for soil-water availability that takes all these factors into account was recently proposed by Groenevelt et al. (2001 and 2004). The model relies upon having an understanding of the physical properties that limit water availability in a given soil. This understanding is used to develop weighting functions, which are then applied to moderate the soil- water capacity. The weighting functions differ for every soil and their effects may differ for different crops. Further research is therefore needed to develop a series of useful weighting functions to account for different limiting soil properties in calculating soil-water availability for different crops. This research would provide a basis for identifying opportunities to improve WUE by more accurately assessing irrigation requirements for specific soils and crops.

2. Impacts of long-term irrigation on soil structure

2.1 Overview

Cropping is widely recognised to have caused significant declines in soil structure and productivity for a considerable proportion of Australia's arable soils. This review has focussed on soil structural decline associated with irrigation practices, rather than the changes commonly associated with cropping.

The impacts of irrigation on soil condition may be positive or negative, depending on the actual soil requirements of the crop being grown. Effects of irrigation are more likely to be positive where the initial soil condition is very poor and amelioration is undertaken.

There is perceived to be no lessening of the impact of soil structure decline on the productivity of irrigated areas. We may be starting to manage our surface soils better (cover crops, gypsum) but there is a legacy of previous long-term use of saline irrigation water that is only now beginning to come apparent as subsoil degradation – which is not easily addressed by surface management activities. As subsoil degradation is largely due to sodicity and salinity of the water used in irrigation, recent improvements in surface management and irrigation application systems have not reduced the incidence of subsoil degradation.

The problem is particularly evident on irrigated texture-contrast soils in vineyards where the quality of irrigation water used has recently improved (as in the Barossa Infrastructure Ltd, BIL, Scheme – discussed in the following section). The better quality water has led to serious dispersion of sodic clays in both surface and subsurface soils. The dispersed clay has caused poor aeration and an increase in soil strength throughout the profile, especially at the interface between the A- and B-horizons. This appears to have reduced root exploration of the B-horizon and thus reduced water-use from this zone, which has meant that more water needs to be added to keep the sandy surface soils moist and more water sits at the A/B interface where conditions become anaerobic. Under these circumstances, water use efficiency is lower, and irrigation management is more difficult. An approach needs to be developed wherein subsoil conditions can be improved without inflicting significant damage to the vine root systems. While some work on this has been conducted during the last 20 years (e.g. slotting of gypsum and organic matter) this has not proved very successful to date, and other methods are required.

2.2 Deterioration of soil structure due to sodicity and other factors

Anecdotal evidence suggests that soil (particularly subsoils) under irrigation (e.g. cotton) is slowly becoming more sodic and magnesic. The unwanted sodium and magnesium are apparently derived from the leaching fraction after calcium carbonate becomes insoluble and precipitates in sub-surface soil where the pH often exceeds 8.5. The process tends to occur more rapidly where bore water is used rather than river water.

The adverse effects of exchangeable sodium and magnesium on soil structural stability are usually masked by the build-up of soluble salts in the root zone during periods of low rainfall. However, a return to high rainfall conditions or the use of alternative low EC water sources tends to dilute these salts and flush some of them from the soil. This reduction in root zone salinity apparently induces excessive swelling (Batey & McKenzie 1999) and perhaps dispersion, resulting in structural decline which makes the root zone more prone to waterlogging (Figure 2.1).

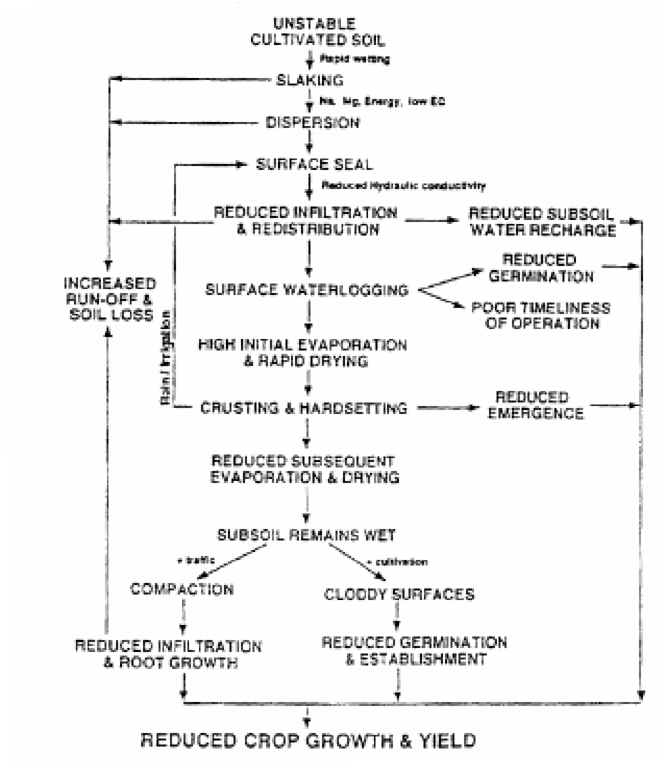


Figure 2.1 Model showing the mechanisms by which slaking and dispersion may affect the soil physical properties and crop yield. (from So and Aylmore, 1993).

Much more needs to be learned about the effect of variable salt distributions within the root zone so that irrigators can monitor their soil in an appropriate manner, and then apply management techniques (eg. gypsum application and opportunity cropping to utilise the rainfall before it drains too deeply) to minimise potential adverse impacts on soil structural stability and crop performance.

Calcium carbonate (lime) is imported via irrigation water, and is sometimes used as a soil ameliorant by irrigators to counteract soil acidification. Very little is known about the risk of cementation in clay soil following lime precipitation. Cementation has the potential to greatly restrict soil-water movement and root growth.

Similar concerns have emerged in the grape industry. For example, after 20 years of vineyard irrigation in the Barossa Valley with moderately saline bore water (EC = 3.5 dS/m), the Barossa Infrastructure Ltd (BIL)-scheme, was introduced in 2001 to supply water from the Murray River system with an EC of only 0.5 dS/m (Ruralfunds 2003). The BIL-scheme was widely adopted by irrigators, but little thought was given to the long-term consequences of a change in water quality on the hydrologic properties of the already sodic duplex soils (Clarke 2004). The growers simply didn't appreciate that without careful management of the new water, swelling and dispersion of the sodic clays would cause serious problems with soil physical properties (Clarke et al. 2002).

Soil penetrometer resistance in the Barossa Valley increased throughout the soil profile, particularly in the B-horizon where resistances of 5 and 6 MPa are now encountered (Kienzler 2002). The hydraulic properties at the interface of the A and B horizons have also changed dramatically, with saturated hydraulic conductivities in the order of 10^{-12} m/s (D Currie, Pers. Comm., Jan 2005), which is considered suitable for use in dam-liners. The implications for root growth in the hard, impermeable and anaerobic B-horizons are obvious, and the consequences for water use efficiency are catastrophic – virtually none of the stored water in the B-horizon is available to plants. Virtually all irrigation in the Barossa Valley is conducted with drip irrigation of some sort, and this is not a problem that can be solved simply by changing the type of irrigation system (e.g. from surface to sub-surface drip irrigation).

Reclamation of sodic soils is not a simple activity (e.g. Mace & Amrhein 2001), but gypsum is one tool that can be used, particularly where thorough mixing can be achieved. This is not easy to implement in established vineyards and orchards without damaging the root systems, and so most gypsum is surface-applied (e.g. Wheaton et al. 2002). Thorough mixing is little easier to achieve under broadacre cropping where the target zone may be at 0.5-1.0 m depth. There is evidence, however, to suggest that judicious surface application of gypsum under the drippers of irrigated vines can reduce the soil resistance by at least 1 MPa throughout the soil profile even without tillage, deep-ripping or other soil disturbance (A James, Pers. Comm., Feb. 2005). The reason for this is not yet understood. It is not known, for example, whether gypsum reduces soil resistance simply by increasing water entry into the B-horizon or whether it changes the structure of the soil in some other way that reduces soil resistance. Similarly, it is not known whether the lower penetrometer resistance coincides with improvements in other soil properties (e.g. aeration) and whether vine roots take advantage of these better conditions to extract more water and nutrients from the subsoil. Also, penetrometer data do not indicate that the gypsum has had any impact on the hydraulic properties of the B-horizon.

For dealing with situations where subsoil properties have drastically deteriorated, information is needed on:

- a monitoring protocol for subsoil structural stability under irrigated crops, tested under a broad range of soil types.
- the extent to which subsoil structural stability varies according to proximity to zones where by-pass flow occurs (shrinkage cracks, old root channels) and where crop roots are most active.
- the extent to which applied gypsum and opportunity cropping can maintain subsoil electrolyte concentrations when large amounts of low-electrolyte rainfall are applied to soil that has been made more sodic and magnesic by prolonged irrigation.
- the risk of subsurface cementation (a form of soil hardening) created by calcium carbonate (lime) precipitation.

2.3 Drip irrigation (emphasis on winegrape production)

Irrigation with sodic and/or saline water (e.g. bore water) is to be avoided where possible. There is ample evidence that poor-quality irrigation water reduces soil organic matter (e.g.

Nelson et al 1998), diminishes soil structural stability; and impacts negatively on soil hydraulic properties and plant performance (Cass & Sumner 1982). Nevertheless, irrigation with saline/sodic water is widely practiced in many Australian vineyards, with serious consequences for production and WUE (Cass et al. 1996).

In recent years there has been a significant move from furrow toward drip irrigation, and while this has reduced water application volumes, it has also generated greater variability in soil properties as a function of distance from the dripper (Stevens & Douglas 1994). Typically salt is leached from the root zone directly under the dripper but it accumulates toward the periphery of a wetted 'onion' produced by irrigating this way (Clarke 2004). In doing so, the root system becomes restricted in its exploration of the potential root zone. Any concentration of salt leads to sodic conditions and structural degradation when water of higher quality is applied (eg. winter rainfall). Postgraduate research is currently being funded by the GWRDC and CRC for Viticulture at the University of Adelaide (Mr D. Currie, Mr D. Smith) to understand the impact of this kind of structural degradation on soil-water availability and plant response. It will also evaluate the role of cover crops in ameliorating subsoil damage caused by irrigation.

There is anecdotal evidence to suggest that surface drip systems create more problems with surface salinity/sodicity/pH imbalance than buried drip systems, particularly when the latter are placed to one side of the vines. However, buried drip systems can also have problems, eg. piping and clay illuviation.

Soil structure can sometimes be improved by the application of organic compounds. However, water repellency may become a problem with organic additions where the soil has been dried strongly. Water repellence can make clay-rich soil behave more like a sand in terms of sorptivity – with the subsequent beading and run-off of drip-applied water leading to poor spatial uniformity of infiltration and potentially low water use efficiency. This problem was observed at a vineyard near Orange where a large number of young vines were lost apparently because of poor sorptivity in a Red Dermosol (light clay subsoil) using a buried drip irrigation system under very hot and dry conditions. In overseas research, Pietola et al. (2003) showed that soil with clay content as high as 70% can display water repellency. The hydrophobicity was associated with high organic matter content and strong drying of the soil. These observations are relevant to local irrigators interested in using PRD techniques.

Many compounds are applied to vines and horticultural crops via drip irrigation systems. The handbook entitled: Nicholas P (ed.) (2004) Grape Production Series Number 2: Soil, Irrigation and Nutrition. (SARDI: Adelaide) discusses some of the chemicals used routinely in drip irrigation systems. They include biocides such as sodium hypochlorite and chlorine to prevent blockages by microbial growth, pesticides such as Trifluralin to kill roots that block buried drip lines, acids to prevent/remove calcrete blockages in the drippers and compounds such as sodium hexametaphosphate to prevent iron precipitation in the drip lines. A cocktail of dissolved nutrients also is applied via fertigation. A survey of the additives used by irrigators for a range of water qualities and soil types would be valuable, in conjunction with short-term and long-term assessments of soil biological, physical and chemical conditions under drippers, between drippers, and in the inter-row (topsoil and subsoil).

2.4 Impacts of low suctions

Another form of structural degradation that occurs under irrigated cropping systems is aggregate coalescence (soil hardening), which is the gradual increase in soil strength with no increase in bulk density (Grant et al. 2001). This can occur as soil organic matter contents decline (eg. Cockroft & Olsson 2000), but it has been observed in relatively stable soils and can also occur simply by exposing soils to irrigation water at small suctions (Ghezzehei & Or 2000). The extent to which the soil-water suction can be managed by applying irrigation water at very low rates has yet to be evaluated. There is evidence that living root systems and large amounts of particulate organic matter are crucial factors to resist aggregate coalescence (Lanyon & Cass 1998). In addition, methods to apply irrigation water at rates <2 mm/h are required because anecdotal evidence from Bruce Cockroft indicates that soil hardening occurs whenever soils become too wet. If methods could be developed to apply irrigation water at extremely low rates, this could reduce the total amount of water required and improve conditions in the rootzone for more efficient uptake of water and nutrients.

3. Effect of soil structural change on the flow of water and salt movement along various pathways

3.1 Role of shrinkage cracks

Much of the soil used for irrigated crop production in Australia has the ability to shrink when dry. Subsoil deterioration under irrigation (as noted previously) drastically reduces permeability and increases soil strength, reducing subsoil drainage or water extraction by plants. If the subsoils remain wet for extended periods, subsoil cracking is greatly diminished, and clay dispersion could be expected to block many permanent macropores.

A general consequence of subsoil deterioration is likely to be a reduction in the overall volume and density of larger pores that contribute to deep drainage of water. As the density of preferred flow paths diminishes, leaching efficiency is reduced because water flowing through the soil profile contacts increasingly smaller proportions of the total soil mass. Leaching, under these circumstances is very difficult, and relies upon management techniques that avoid soil structural damage, such as intermittent leaching with suitable electrolytes (*cf.* Al-Sibai et al. 1997; McNeal 1968; Quirk & Schofield 1955). Direct information linking leaching efficiency to changes in soil structure appears to be scarce, due in part to the lack of suitable method to characterise changes in subsoil structure. Recent research (Stevens et al. 2004) found a mean leaching efficiency of 63% for twenty irrigated grape and citrus sites in the Riverland and Sunraysia regions.

It has been observed that when a salt tolerant species with deep roots (eg. safflower, Oldman saltbush) is encouraged to root deeply into cracking clay soil, the soluble salts accumulate on crack faces in response to direct evaporation of the subsoil water. When such a soil is quickly re-wet via flood irrigation or during an intense downpour of rain, the accumulated salt on the crack faces are apparently quickly leached deeper into the subsoil. The quantitative effect of this bypass flow and salt flushing on leaching efficiency under drip and two dimensional (eg furrow) irrigation practices is not understood. Work on dryland salinity has certainly included focus on using salt-tolerant species to provide productive use of saline land and to assist with its regeneration, but there appears to have been little investigation of impacts of such plants on cracking and potential for enhanced salt leaching. Research on this topic if carried out should be linked to existing dryland salinity investigations.

Where pockets of saline subsoil occur, root density and function are diminished. Because shrinkage cracks form where the soil is weakest (i.e. where it is wettest), the most saline sections of the root zone should develop more crack faces onto which salts accumulate (via evaporation), and be in a position where they can be leached readily, provided some way can be found to cause subsoil drying. Research on this issue is needed to improve understanding of the extent to which deep inter-connected shrinkage cracks (with and without deep ripping) can be used by irrigators to accelerate deep leaching of unwanted soluble salts using only a small amount of deeply draining water. This study would also need to quantify the extent to which this approach modifies the short-range patterns of distribution of subsoil sodicity, carbonate concretions and boron toxicity. Interactions of these shrink/swell salt accumulation processes with raised beds (mounded systems) appear to be understood poorly, and research to define optimal raised bed profiles would be useful..

Methods likely to be useful for this type of study are described in: Rimmer & Greenland (1976), Bui & Mermut (1989), Chorom & Rengasamy (1997), McKenzie & McBratney (2001), McKenzie et al. (2001), and Vervoort et al. (2003).

3.2 Role of soil fauna in soil structural improvement under drip irrigation

The work of Bruce Cockroft (e.g. Cockroft and Olsson 2000) is not widely published but it leads the way in soil management for irrigated orchards as well as vegetables. The long-term objective is to grow something in the soil at all times to replenish soil organic matter continuously and maintain soil structure in an ideal state for regular cropping (possibly annual). To achieve this, large quantities (eg. 1% by weight) of calcium (gypsum or lime) are mixed into the soil along with fertilizer and ryegrass seed to be grown for at least one year. The ryegrass is then sprayed-off or cultivated into raised beds on which trees or vegetables are planted and irrigated carefully (rates <2 mm/h) through to harvest. After harvest, the soil is immediately re-seeded with ryegrass to maintain a bed of actively growing roots during winter.

Where these techniques are not applied, anecdotal evidence suggests that the activity of beneficial soil fauna such as ants and earthworms is poor in drip irrigated vineyards and citrus orchards. Some growers are attempting (at great expense) to overcome this challenge by importing mulches and composts. The effects of these treatments on soil biological activity, soil structural condition as well as water and solute movement are poorly understood.

Given the great variation in management approaches noted above, it would be valuable to have quantitative information on the extent to which biopores can be used by irrigators to accelerate leaching of unwanted soluble salts using minimal water. It would also be valuable to have information on the extent to which such leaching modifies the short-range distribution of subsoil sodicity, alkalinity and boron toxicity.

3.3 Use of salt tolerant perennial plants to biologically remove sodium salts imported via irrigation water

In the 1930s, British research workers in Sudan (Greene & Snow 1939) demonstrated the feasibility of using harvested saltbush as a rotation crop to remove unwanted sodium salts that were entering irrigated cotton fields via the irrigation water. The saltbush rotation crop apparently also created large shrinkage cracks and root channels which improved soil structure. It would be useful to investigate the feasibility of using salt-tolerant deep-rooted perennial plants (eg. 'Oldman saltbush) to reduce rootzone salt concentrations and improve subsoil structure under crops such as cotton, though current dryland salinity research may have already addressed many of these issues and the most useful approach may be to link to existing studies.

4. Impact of oxygenation on effects of waterlogging on productivity for various irrigation systems

4.1 Waterlogging in irrigated systems

Excess water in the root zone results in depletion of oxygen, leading to reduced root respiration and the production and accumulation of phytotoxic compounds, such as ethylene, in plant roots and soil. Saturated soil conditions also change the soil's redox potential, increasing the loss of nitrogen and production of ions that may be toxic. These factors combine to hamper plant growth and may cause significant yield losses. Excess water stress is greatest under conditions of rapid respiration (summer), and on soils with smaller drainable pore space (i.e. lower hydraulic conductivity), which is characteristic of clay soils. The main factors that influence waterlogging are the:

- intensity and duration of the applied water,
- structure (pore size distribution and connectivity) of the soil material, and
- potential for drainage out of the root zone.

The potential for root zone waterlogging occurs under irrigated conditions because of the relatively frequent and large volumes of water applied.

Transient waterlogging refers to short term (normally hours to days in length) saturated conditions, often within only a part of the root zone. It is commonly found where redistribution of water within the profile is limited, and is often associated with irrigation systems where the water is applied at a rate in excess of the soil infiltration rate. Hence, this form of waterlogging is most likely to occur with either surface irrigation systems (e.g. furrow/border check/bay) or drip irrigation systems (either surface or sub-surface). It is not commonly found with either micro-sprinkler or high pressure sprinkler irrigation.

Irrigation-induced waterlogging is apparent near the inflow end of many surface-irrigated fields and is normally associated with periods of irrigation in excess of 8-12 hours. Waterlogging may also occur at the tail end of surface-irrigated fields due to poor surface drainage and excessive tail-water flows backing up over the crop. The ability to reduce irrigation-induced waterlogging in surface irrigation is significant when measurements are taken during irrigation (e.g. Hodgson, 1982; Hodgson and Chan, 1982; Thongbai et al, 2004) and anecdotal observations suggest that inappropriate surface irrigation strategies commonly account for losses of up to 1 bale/ha/season for cotton and could be as high as 2-3 bales/ha/season under adverse conditions.

Transient waterlogging may also be found around the emitters of sub-surface drip irrigation systems, particularly in clay or structurally degraded soils. In these cases, the emission rate of the dripper is greater than the hydraulic conductivity of the soil and a zone of saturation is formed (Figure 4.1). Saturated zones around drip emitters are commonly blamed by farmers for an increase in root disease incidence and impacts on root distribution and nutrient uptake. However, there are few reported studies demonstrating the impact on crop production of transient waterlogging around drip emitters. This suggests that this issue is not a major problem for a significant proportion of the industry, perhaps because the majority of drip irrigation is conducted on highly cultivated, free draining soils in annual horticultural production systems. It is likely to be more of a problem in areas of heavy clay soils (eg. SDI of cotton) and where perennial cropping is conducted on structural degraded soils. Hence, Stevens and Walker (2002) found that vines at Loxton experienced transient waterlogging which increased their uptake of both Na^+ and Cl^-, and increased the rate of Na^+ uptake relative to that of Cl^-. In this case, transient waterlogging was probably caused by a combination of soil sodicity, small excesses in irrigation, and the combination for part of the season of low electrolyte concentration and high sodium adsorption ratio in the soil solution.

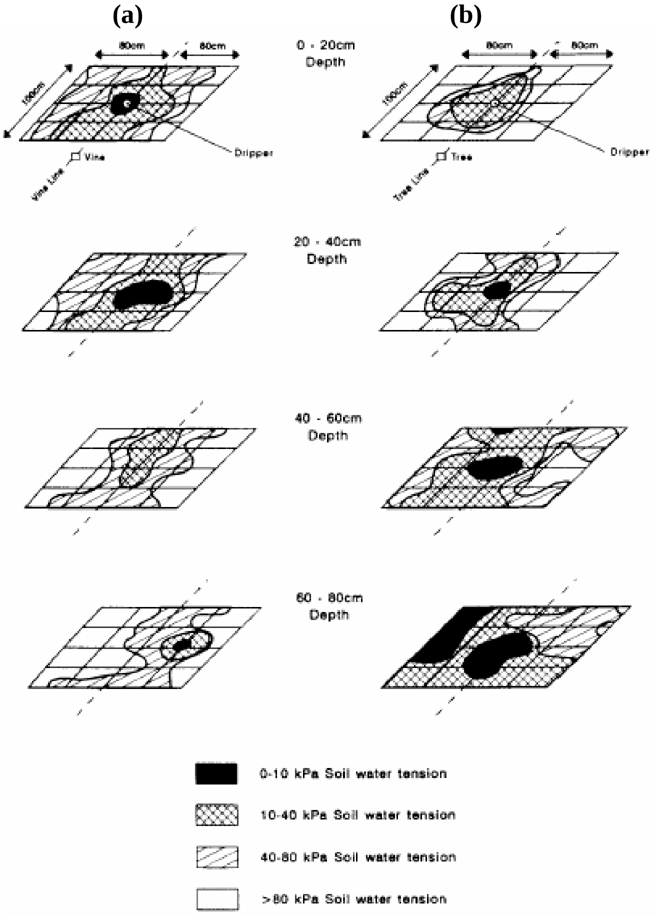


Figure 4.1 Measured zones of soil moisture under 4 l/hr drip emitters at a spacing of 1 m in (a) clay and (b) sandy loam (from Mitchell and Goodwin, 1996)

4.2 Strategies to overcome the effects of transient waterlogging in irrigated systems

4.2.1 Air injection

There are two main forms of air injection system using existing sub-surface drip irrigation. Where the air and water are not distributed simultaneously, a compressor can be used to inject air either after irrigation or during periods of rainfall. This type of system has previously been used in the Hawaiian pineapple industry to reduce disease incidence during periods of high rainfall and has been previously promoted by Groaire Irrigation (Denver, Colorado) but does not seem to be in current widespread use The alternative is to inject air into the water stream during irrigation. The most common form of this system is the Mazzei (ToroAg) venturi injector system.

Goorahoo *et al*. (2001) found under field conditions that injecting air using a Mazzei venturi produced a 33% increase in bell pepper count and 39% increase in total weight for the season. Similarly, Bhattarai *et al.* (2004a) found that aerating drip irrigation significantly enhanced growth of waterlogged field-grown zucchini (by 25%) and glasshouse-grown cotton and vegetable-soybean under field capacity and saturated soil conditions by up to 25% and 90%, respectively. Bhattarai and Midmore (2004) also found that salt exclusion and tolerance to salinity were improved by aeration.

Air has a very much lower viscosity than water, and drip lines are designed for water viscosity. When air replaces water in a long drip lateral, even with pressure-regulating emitters, the air flow through the first and last emitters will be enormously different. Trying to pump a mixture of air and water into typical laterals is of little help, because the air bubbles move to the top of the tube, and the water flows on underneath. While manufacturers (Mazzei) of the venturi injectors claim that the air is injected as micro-bubbles that do not coalesce, evidence presented in the patent application indicates that air entrapment does occur and needs to be vented at strategic locations in the pipeline. Problems with the emission uniformity of injected air have also been observed in the field. For example, Goorahoo *et al*. (2001) found that the location along the drip tape positively affected production in the first 50 m of lateral but that there was no difference between the control and treated crops at greater lengths. This suggests that the majority of bubbles were being discharged closer to the field inlet and that the non-uniformity of air discharge from the laterals may be a limiting factor within large-scale field installations.

4.2.2 Injection of hydrogen peroxide

The production benefits of applying hydrogen peroxide to waterlogged soils have been known for some time. For example, Hodgson (1982) reported that peroxides supplied to waterlogged maize, soybeans and sugar beet in glasshouse studies (Melsted *et al.* 1949; Wiersma and Mortland, 1953) ameliorated waterlogging damage either partially or completely. However, until recently there was little evidence of benefits under field conditions. Hodgson (1982) found no benefit from applying peroxide to the soil surface prior to surface irrigating.

The reaction time for hydrogen peroxide in the subsurface is usually seconds to minutes, with occasional reactions being completed within minutes to hours (Jacobs, n.d). Therefore, close spacing of the injection ports is generally required due to the short reaction period of hydrogen peroxide. There is little understanding of the active mechanisms associated with benefits noted from the addition of peroxide. While the claimed benefit in studies looking at waterlogging is generally through direct availability of increased oxygen levels, the addition of hydrogen peroxide would also be expected to potentially impact on the breakdown of organic carbon, soil-water pH and/or affect nutrient availability within the root zone.

There is little understanding of the active mechanisms associated with benefits noted from the addition of peroxide. While the claimed benefit in studies looking at waterlogging is generally through direct availability of increased oxygen levels, it seems equally likely that the peroxide may be acting to breakdown organic carbon, change pH and/or affect nutrient availability within the root zone.

4.2.3 Soil and water management options

In many cases, prevention of waterlogging may be a more practical and reliable way to reduce waterlogging damage.

Options include compaction control, landforming to steepen irrigation fields and remove low points, increased slope to improve surface drainage, higher raised beds, increased flow rates, shorter field lengths, and reduced periods of inundation, gypsum application to overcome sodicity and improve drainage, and extra nitrogen fertiliser, have all been used to reduce the incidence of waterlogging in irrigated cotton. We don't yet understand, however, what the optimal dimensions are for raised beds in furrow irrigated cotton for different soils, field slopes and water application rates.

4.3 Review of existing LWA proposal on oxygenation

Land and Water Australia received a proposal under the Innovation Program on the potential to deliver oxygen to the roots through subsurface drip irrigation. This work proposed to investigate the benefits associated with the addition of either (a) hydrogen peroxide or (b) injected air into sub-surface drip irrigation systems growing horticultural crops. The new idea/innovation in this proposal is that there have been production and water use efficiency benefits observed with increasing air/oxygenation levels in the root zone of irrigated soils which would not normally be regarded as lacking in air/oxygen. In particular, this project proposes to develop an understanding of the *"specific mechanisms by which plant growth and yield are favoured under these soil conditions"*. An improved understanding of these mechanisms could provide the basis for developing irrigation strategies to increase yields and crop water use efficiency across a broad range of soil conditions and/or crops.

The combination of the field and glasshouse trials provides an appropriate mechanism to obtain both the fundamental information relating to soil microbial and plant response data, difficulties associated with the implementation of the technology under commercial conditions and the potential benefits arising under commercial production systems. While some previous overseas research has been conducted into the benefits of root zone aeration/oxygenation there is no research on this topic currently being conducted in Australia outside of the applicant's research group. The proposed research approach is sound and includes a combination of commercial field demonstrations/trials supported by glasshouse trials. The collection of detailed soil-water, plant and microbial response data under a range of conditions should provide a sound basis for the identification of the processes operating in response to increased aeration/oxygenation.

The skills of the principal investigator and other identified team members are of international research standard. The potential input from specialists in instrumentation and gas analysis, and mycology are noted. However, the time contribution of these particular staff is not identified in the host organisation support (section 10.4 in the proposal) and access to these staff would need to be confirmed. Similarly, the primary staffing resource involved in the delivery of this project is the postgraduate student. This student does not appear to be identified at present and there may be some concerns regarding attracting an appropriate student within a suitable timeframe.

The project activities related to investigating the benefits of aeration/oxygenation under surface drip irrigation (SDI) and developing appropriate application system technologies/guidelines are regarded as low-medium risk. If shown to be successful, this technique may provide benefits to sub-surface irrigated crops grown on soils with low hydraulic conductivities (e.g. structurally degraded or heavy clays). It should be noted that except for some specific crops and locations (ie. cotton on heavy clay soils) relatively little sub-surface irrigation is practiced under these conditions. However, the high risk components of this research are (i) the identification of the soil/microbial/plant processes and (ii) the potential production benefits arising from increasing the aeration/oxygenation in root zones not suffering conditions normally regarded as inadequately aerated. It is this high risk area of the research which is likely to provide greater returns due to the potentially broader applicability of the benefits.

A major limitation of the proposed research is its relatively small size and narrow local focus which raises some concerns regarding the ability of this project to undertake the breadth of research and develop the momentum required to make a significant difference to this area of research. Hence, it is recommended that the activities proposed in this research be funded and that the opportunity to expand the proposed research program to include other regions and crops be supported. Priority industries/areas for expansion of the investigations into aeration and/or peroxide addition benefits include:

- sub-surface drip (particularly using saline water) irrigation in southern Australia to determine the extent to which aeration can increase salt tolerance of various crops; and
- sub-surface drip irrigated cotton on heavy clay soils in central and southern cotton growing areas.

5. Soil structural decline under precision and saline irrigation

This one-page concept proposal was received by the NPSI Board at its meeting in November 2004 and arose out of consultation between the existing NPSI project DEP15 project leaders and the NPSI Coordinator. The proposal is for additional DEP15 project funding to address new research gaps identified during Stage 1 of DEP15. The project proposal is predicated on anecdotal evidence of soil structural decline under precision irrigation systems using saline water in the South Australian grape industry. The major knowledge gap identified in the proposal is the lack of understanding in relation to the impact of water quality and point source application of water on the soil physico-chemical properties in the root zone particularly in relation to the possible impact on structural decline, soil-water movement and leaching efficiency.

The proposed core research into the impact of precision irrigation with saline water on soil structure is a logical extension to the existing DEP15 project work. It also mirrors several research issues (Table 5.1) raised within the NPSI scoping study into soil-water and salt movement associated with precision irrigation systems (Raine *et al*. 2005).

Table 5.1 Linkages between key research investment opportunities identified in Raine et al. (2005) and the objectives outlined in the "Soil structural decline under precision and saline irrigation" proposal

Priority research investment opportunities identified in Raine et al. (2005)	Relevant objectives in proposal
Development of simple and robust techniques for soil characterisation	• Validate existing tools for quick detection of structural stability and field test for Riverland & Sunraysia
	• Identify the causal factors (physico-chemical/mechanical) of soil structural decline
Management of soil-water and solutes in precision irrigation systems - Development of irrigation management guidelines based on agronomic responses	• Scope current impacts of horticultural practices including water, soil and crop management on soil structural decline

However, the focus and outcomes of the other proposed objectives are not immediately clear. For example, the evaluation of soil structure on irrigated and adjacent undisturbed lands will provide a comparison that is unlikely to be particularly useful. Structural differences observed may be due to soil treatment during crop establishment (eg. deep ripping, cultivation, compaction), agronomic management practices (eg. mulching, surface cultivation, wheeled effects) or irrigation impacts. Similarly, this comparison would provide little guidance with respect to appropriate management practices to slow down or ameliorate structural impacts. It would be more appropriate to consider compare structural breakdown under alternative irrigation management and/or water quality regimes under paired site conditions so that both (i) an understanding of the causal mechanisms is developed and (ii) the effect of alternative management practices on the rate and nature of structural decline can be identified.

It is also not clear that the proposed use of satellite imagery to delineate "hotspots" associated solely with soil structural decline will be effective. There is no doubt that satellite imagery will be able to identify stressed areas but the crop and soil reflectance (presumably the indicators used in this analysis) will be affected by a range of crop (e.g. crop variety), irrigation (e.g. method of application, scheduling frequency, water quality) and soil (inherent soil salinity, texture, structure) factors which would make it difficult to specifically separate out structural decline issues.

There is no detail on the composition of the proposed research team, so it is unclear whether an adequate depth and breadth of skills exists to undertake this work. It will be important to ensure the team has access to expertise is soil physics, soil chemistry, and plant physiology. Similarly, there are no details on the nature of the in-kind contribution from partner organisations. The value of this work will be enhanced by ensuring it is conducted within a broader scientific framework that ensures the results and outcomes are transferable across regions, crops and irrigation systems. The amount of LWA funding requested is not excessive for the proposed research work. **Hence, it is recommended that the core research related to soil structural decline and the subsequent agronomic responses be considered for funding but consideration be given to funding this work within a broader research program investigating the impacts of precision irrigation with saline water.**

6. Other issues

6.1 Spatial and temporal variation of water and nutrients

Because water and nutrients are spatially concentrated in drip irrigation, the distribution and extraction of water and solutes varies in time and space (Mmolawa & Or 2000). The distribution of solutes in the root zone becomes particularly important when irrigation water of relatively low quality is used – industrial wastewater, recycled water, sewage water, etc. Plant toxicities can result when root systems are exposed to low quality water at critical stages in growth, and soil permeability can decline when water quality changes.. Furthermore, until the timing and placement of water and solutes in soils can be precisely controlled, ameliorative techniques will be needed to mop up any water and solutes that pass through the root zone. Intercropping of deep-rooted species along with shallow-rooted commercial crops appears to be one strategy for managing excessive leaching (Stirzaker 1999), but these cropping systems are not simple to manage. However, if we understood how to predict the spatial and temporal distribution of water and solutes in relation to root distributions in different soils under different irrigation systems, we could save a lot of water and nutrients and avoid the accumulation of salt in the root zone. The tools currently available to predict water and solute transport in irrigated soils are still not very reliable (Skaggs et al. 2004), and much work needs to be done in the modelling area.

6.2 Issues of scale

Deep drainage of water and solutes is an issue that continues to plague most irrigation areas, which struggle to combat rising water tables (Willis et al 1997). The extent of deep drainage relates to the application of inappropriate irrigation practices on different soils in the landscape. This is rarely appreciated by irrigators who tend to focus their management expertise at the paddock-scale, not the catchment scale. Research is required to help growers understand that irrigation practices at a paddock scale have potentially serious implications at catchment scales and thus on the sustainability of their own operations. To some extent, this is an extension and technology transfer operation, but there is a great deal of work to be done to verify the utility of various models (e.g. *WetUp* – Cook et al. 2003; Thorburn et al. 2003), and the way in which plants interact with the wetted regions of the soil (Philip 1997). Verification of these models would be greatly assisted by the collection of data on the inputs and outputs of water in various catchments.

6.3 Partial root zone drying

The utility of *partial root zone drying* (PRD) technology (Loveys et al. 2002) in reducing water requirements in irrigated vineyards has been proven beyond doubt. The physiological mechanisms appear to be well understood (Dry and Loveys 1998) and this method appears to be superior in grapes to comparable strategies to reduce water use, such as *regulated deficit irrigation* (RDI) (Loveys et al. 2002). Furthermore, the cost in yield and fruit quality is minimal in comparison to the savings made in water use (Dry et al. 2002). What is not yet understood with PRD irrigation is whether long-term vine-vigour is gradually sacrificed by forcing the vine to continually invoke stress responses. Similarly, there is a need to investigate whether the differences in soil wetting regime between various PRD strategies has an impact on soil structure due to the effect on the solute concentrations and distributions, the potential for changed soil cracking with extended drying or due to effect on microbial activity and root growth. To some extent, this can be evaluated by a simple survey of vines that have practiced PRD and other irrigation methods over the last 5-10 years.

7. Overview of potential research projects

The following tables list potential research projects to address the lack of knowledge/management tools identified above. Priority listings are given, together with **tentative** estimates of cost. Where possible, comments on the form of the work and potential linkages to other work are noted.

Some of the projects represent quite basic soil science issues that will not be addressed quickly or easily, and may well be outside the scope of the NPSI charter. Nonetheless, those areas are indicated as there may be potential for NPSI to encourage funding of those more fundamental research areas by other bodies.

Development of tools characterising soil structural and soil-water properties to enable better water use efficiency and management of leaching fractions under irrigation			
Components	**Perceived priority (1-4, high-low)**	**Likely cost & duration**	**Relevant section in text**
Refine field (e.g. soil pit) methods to allow description of the soil-water properties including patterns of wetting and deep drainage under micro-irrigation systems. (Initial review followed by field verification and testing).	1	$120,000- $150,000 1-2 years	1.2
Develop a simple, robust methodology to characterise water retention curves for Australian soils, thereby producing more useful pedotransfer functions and data interpretation to assist irrigation managers to achieve optimal efficiency of irrigation scheduling. (Method development involving 2 researchers for 3 years, followed by work on interpretation of data to provide management guidelines/advice.).	1	$800,000 3-4 years	1.1, 1.2
Investigate the impacts of subsoil structural decline on deep drainage and leaching efficiency. (Work to be aligned with, and value-add to, the project proposed by Schrale.)	1	$200,000- $300,000 3 years	3.1
Improve quantitative understanding of weighting functions to account for different limiting soil properties in calculating soil-water availability for different crops. (Basic research.)	2	$300,000 3 years	1.2
Investigate the effects of soil biopores on drainage and leaching efficiency. (Review of existing information, followed by field evaluation of effectiveness and practicality of existing approaches.)	2	$100,000- $150,000 2 years	3.2
Develop methods to extrapolate point-source information on soil hydraulic properties up to paddock and whole-catchment scales. (Possible alignment with CSIRO catchment studies?)	3	$200,000 2 years	6.2
Improved understanding of plant responses to spatial variations in soil-water, strength, oxygenation, and solute concentrations – for a range of soils. (Basic research.)	3	$500,000 3 years	6.1
Define the point at which soil hydrological properties (surface infiltration rate & sorptivity, water holding capacity, subsoil drainage) for sub-sections of a drip irrigation development are sufficiently different to require their own Irrigation Management Units. (Desktop study followed by field evaluation of output.)	4	$100,000 1 year	1.2, 6.2

Tools for identification and remediation of soil structural decline under irrigation			
Develop tools and monitoring protocols for assessing soil structural stability under irrigated crops, and test under a broad range of soil types. (Review of existing information and brief field validation)	1	$60,000 1 year	2.2
Determine the extent to which subsoil structural stability varies according to proximity to zones where by-pass flow occurs (shrinkage cracks, old root channels) and where crop roots are most active. (Basic research.)	2	$500,000- $600,000 3 years	2.2
Review of the possible adverse impacts on soil structure and root growth of compounds currently applied either individually and in combination to the soil via drip irrigation systems. (Review and in-field evaluation.)	3	$100,000- $150.000 1-2 years	
Assess the risk of subsurface cementation (a form of coalescence or soil hardening) created by calcium carbonate (lime) precipitation. (Field sampling and laboratory study.)	4	$50,000- $80,000 1 years	2.4
Determine the extent to which applied gypsum and opportunity cropping can maintain subsoil electrolyte concentrations in sodic and/or magnesic subsoils under drip irrigation. (Desktop evaluation/review, followed by some field testing.)	4	$200,000 2 years	2.2, 2.3
Identify the potential to use highly salt-tolerant crops to dry and crack subsoils to aid leaching of salt. (Align with work on dryland salinity management; proposed research would evaluate existing trials.)	4	$100,000 1 year	3.3

APPENDIX 1: References

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