THE EFFECT OF SOIL STRUCTURE ON WATER USE EFFICIENCY

EFFET DE LA STRUCTURE DU SOL SUR L'EFFICIENCE D'UTILISATION DE L'EAU

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ABSTRACT

Water use efficiency (WUE) is considered as the ratio of the crop yield per unit consumptive use of water (t yield / ML water). Since the transpired water is drawn from the soil by the plant root system, any factor that restricts the expansion and efficiency of the plant root system will reduce WUE. Given the number of interactive factors that influence transpiration, 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 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. 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.

Key words: *Soil structure, Water use efficiency, Sodic soil, Leaching fraction, Irrigation management.*

RESUME

L'efficience d'utilisation de l'eau (EUE) est considérée telle que le taux du rendement agricole par unité de l'usage combiné de l'eau (t rendement / ml eau). L'eau étant dérivée du sol par le système racinaire des plantes, aucun facteur qui limite l'expansion et l'efficience du

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système racinaire des plantes réduira WUE. Compte tenu de nombreux facteurs interactifs qui affectent la transpiration, la réalisation optimale de WUE, il n'est pas une tâche simple à aucun gestionnaire d'irrigation. Certains facteurs tels que les régimes d'irrigation (pour optimiser la performance par rapport à la structure du sol et aux profils de rétention d'eau) peuvent fournir aux irrigants les rendements immédiats.

Cependant, d'autres facteurs tels que la fraction de lessivage et l'efficience et les cations du sol sont les préoccupations plus stratégiques, comme la bonne gestion de ces facteurs est essentielle pour le contrôle des menaces à moyen et à long terme pour la viabilité de l'irrigation sur un endroit particulier. L'équilibre entre les besoins de la gestion à court terme et les préoccupations stratégiques à long terme est nécessaire non seulement pour les gestionnaires d'irrigation, mais aussi aux organisations impliquées dans la recherche d'irrigation et de développement. Les sols indiquent énorme hétérogénéité spatiale au niveau global et au niveau de la terre et sur les distances <1 m. Une partie de cette hétérogénéité structurelle est importante pour le fonctionnement du système racinaire et pour le mouvement de l'eau et du sel, et sa perte ou sa modification peut avoir des effets délétères sur le système racinaire des plantes et sur le transfert d'eau et de sel dans le profil.

Mots clés: *Structure du sol, efficience d'utilisation de l'eau, sol sodique, fraction de lessivage, gestion d'irrigation.*

1. INTRODUCTION

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 becoming 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.

The use of better quality irrigation water in sodic soils 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 development in 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 accumulates at the A/B interface where conditions become anaerobic. Under these circumstances, water use efficiency becomes low, and irrigation management becomes more difficult. An approach needs to be developed wherein subsoil conditions can be improved without inflicting significant damage to the vine root systems.

2. SOIL FACTORS INFLUENCING WATER USE EFFICIENCY, TOOLS AND TECHNIQUES TO IMPROVE WUE

2.1 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 (synonymous to the ratio: 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 towards the 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.

2.2 Tools and techniques required to improve WUE

There are two types of information that are relevant to irrigation managers who want to optimize their soil conditions for plant growth and maximize 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. GBut until these models become sufficiently accurate, visual-tactile methods are likely to dominate. 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.

The available tools are 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). 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).

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. (2004). The model relies upon 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.

3. EFFEECTS OF LONG-TIME IRRIGATION ON SOIL STRUCTURE

3.1 Deterioration of soil structure

Evidence suggests that soil (particularly subsoils) under irrigation (e.g. cotton) is slowly becoming richer in sodium nad magnesium. 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 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 out 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 (Fig. 1).

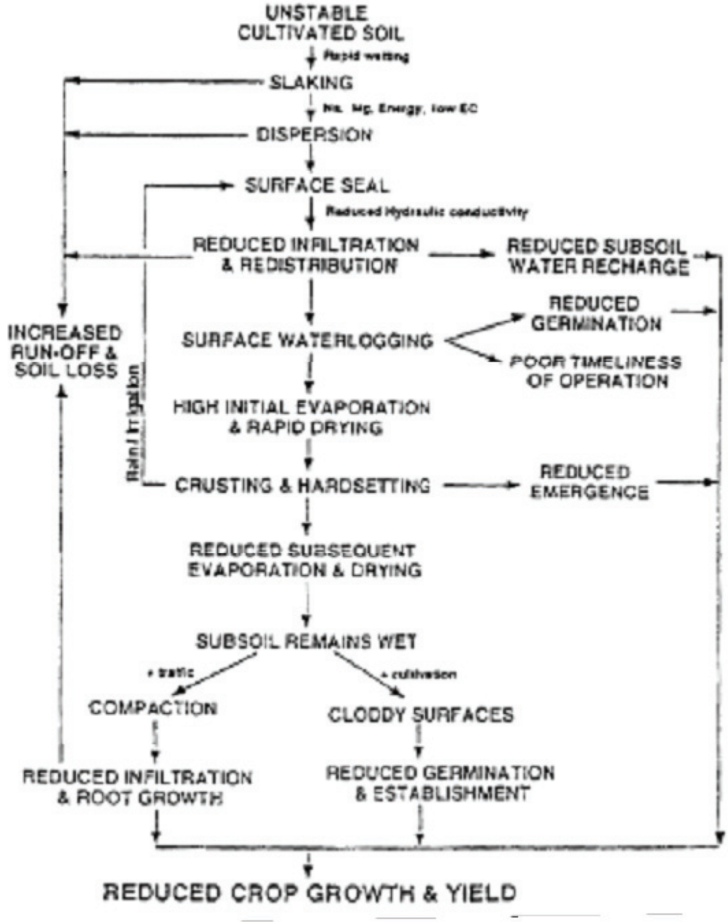

Fig. 1. Model showing the mechanisms by which slaking and dispersion may affect the soil physical properties and crop yield. (from So and Aylmore, 1993).

The knowledge about the effect of variable salt distributions within the root zone is to be substantially enhanced 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 deep) 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.

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, Personal Communication., 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. Reclamation of sodic soils is not a simple activity

(Mace & Amrhein 2001), but gypsum is one agent 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 (Wheaton et al. 2002).

There is evidence, to suggest that judicious surface application of gypsum under the drippers of irrigated vines can reduce the soil resistance by at least 1MPa throughout the soil profile even without tillage, deep-ripping or other soil disturbance (A James, Pers. Comm., Feb. 2005).

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 risk of subsurface cementation (a form of soil hardening) created by calcium carbonate (lime) precipitation.

3.2 Drip irrigation

There is ample evidence that poor quality irrigation water reduces soil organic matter (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 the wetted soil zone for 'onion' produced by irrigating this way (Clarke 2004). Soil structure can sometimes be improved by the application of organic matter. 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.

3.3 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 (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 is 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 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 root zone for more efficient uptake of water and nutrients.

3.4 Role of shrinkage cracks

It has been observed that when a salt tolerant species with deep roots 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-wetted via flood irrigation or during an intense 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 (e.g., 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. If Research on this topic is carried out, it should be linked to the 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 , 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.

4. RESULTS

4.1 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. 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. However, if we could understand 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 would 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.

4.2 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.

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