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THE IMPACT OF IRRIGATION ON SOIL STRUCTURE

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Summary/abstract

Good soil structure is an essential element of healthy and sustainable agro-ecosystems. It promotes the development of extensive plant root systems and efficient use of water and nutrients and, in doing so, buffers plants against drought and other adversity. Irrigation places a number of stresses on soil structure. This review examines the nature of soil structure, its role in plant growth, the nature of stresses on soil structure which come from irrigation and management approaches to irrigation-induced soil structural decline.

Introduction

In 2004-5 the area under irrigation in Australia (2.4Mha) represented only 0.5% of all agricultural land but produced 23% of the total gross agricultural commodity value ($40bn). Agricultural industries accounted for 65% of Australia's water use and the effective average water use over all irrigated land, whose area had doubled in the previous 40 years, was 506mm (ABS, 2006). These statistics underline the major contribution to the Australian economy of an industry established in a climate of relatively cheap land and water and largely in the absence of environmental accountability. The changing times invite discussion of the sustainability of irrigated agriculture in a future fraught with climate change, with environmental pressures from legislation and the public and with the demands of powerful produce buyers. These pressures for improved quality and yield, for the profitable and efficient use of water and for the minimization of other environmental impacts will constrain profitability and drive a good deal of future change in irrigated agriculture (Grant *et al.*, 2003).

One of these environmental impacts is, of course, upon the soil itself. Irrigation, even with water of high quality, often represents a large increase in the amount of water which would pass through a soil profile under natural conditions and has the capacity to accelerate mineral weathering, to transport and leach soluble and colloidal material, to change soil structure and to raise the local water table. It also has the capacity to reverse soil preparation measures such as the tillage which precedes planting. These effects depend upon the intensity of irrigation. Irrigation water of poor quality has the added capacity to inflict critical damage, especially upon soil structure. It need hardly be said that the pressure on irrigators to conserve water may increasingly lead to compromises on water quality such as reactivation of inferior groundwater sources and the increasing application of re-use water. Inevitably, soil will become one of the main environmental casualties.

The nature of Australia's soil resources also presents challenges. Irrigated soils in Australia are largely fine-textured. The major irrigated soils in Southern Australia are Red-brown earths (Chromosols), grey and brown soils of heavy texture (Vertosols) and solonized brown soils (Sodosols). In northern NSW and in Queensland, Black earths (Vertosols) are important and in north-eastern Queensland there are a range of duplex soils (Sodosols, Kandosols, Chromosols) (Smith *et al.*, 1983; Isbell, 2002). Red-brown earths, the largest group amongst these (Cockroft and Martin, 1981) are, for the most part red to brown in colour, hardsetting with a marked texture contrast between the A and B horizons (Northcote, 1981). Clay mineralogy is dominated by illite/kaolinite (Williams, 1981) which causes them to be more dispersive (Sumner *et al.*, 1998). The nature of the Red-brown earths makes them generally somewhat vulnerable to structural decline. Soil variability is a further major impediment to good management and there seems little doubt that it will become one of the central issues in the future development of sustainable irrigated enterprises. Grant *et al.* (2003) point to recent advances in precision viticulture by Bramley and his co-workers (e.g. Lamb and Bramley, 2001).

The aims of this work are to review the importance of soil structure to plant production, to examine the impact of irrigation on the structure of soil and to briefly discuss approaches to monitoring, avoidance and remediation of irrigation-induced soil structural decline.

Soil structure and its significance for plant growth

The phrase "soil fertility" is frequently associated with the chemical fertility of soil as determined by nutrients and pollutants; this view neglects the physical aspects of fertility which are embodied in soil structure whose importance has been recognized in numerous published reviews (e.g. Dexter, 1988; Hamblin, 1985; Horn *et al.*, 1994; Kay, 1990; Kay and Angers, 2000; Bronick and Lal, 2005). Soil structure is defined as "the arrangement of the solid particles and of the pore space located between them" (Marshall, 1962); a simpler, working definition is just "the size and arrangement of pores". Pores are arguably the most important soil physical feature because most soil processes that have immediate consequences for soil biological activity or soil conservation occur either within pores or on the surfaces of the particles that form their walls. It is not just the size and number of these pores which are important but also their continuity; obviously isolated pores will play a much less central role in soil processes. A broader view of soil structure is that it is the size and arrangement in space of soil properties in general, for example cohesion or strength. This broader definition fits in better perhaps with the popular perception of a soil with good structure as one which is soft, friable, readily yields the correct tilth and is stable towards water and traffic.

During soil formation weathering of the soil parent material generates particles of various shapes and sizes. The simple packing together of these particles gives rise to what is called *textural porosity*. However, these particles are then rearranged by, for example, swelling and shrinking, wetting and drying, root growth, dissolution and deposition of solids by water and the activities of soil organisms. The particles become bound together by cementing agents (e.g. iron oxides), by dead organic matter (e.g. biological exudates), by fine material like clay and silt and by roots and hyphae. The resulting size, shape and arrangement of aggregates which can separate along cracks and flaws are basic characteristics peculiar to each soil (Marshall *et al.*, 1996). In these ways, the coarser elements of soil structure, regarded as *structural porosity*, are then essentially superimposed on simple textural porosity. Soil structure requires a very long time to develop but can be changed rapidly by management. In this regard, large pores are the weakest and most vulnerable to soil management.
The range of pore sizes in soil is very large and effectively covers 7 or 8 orders of magnitude with pores in each size range serving different, useful purposes. These are summarized in Table 1 below.

Pore size	Pore description and function examples
10 mm	*Macro-pores* created by tillage, root growth, soil fauna or clay soil shrinkage. Rarely filled with water.
1 mm	Pores between aggregates in a finely tilled seed bed. Very fast draining.
0.1 mm	Smallest <u>rigid</u> pores that can be entered by roots. Filled with air most of the time.
0.01 mm	*Meso-pores* mainly within aggregates. Coarsest water storage pores.
0.001 mm = 1μm	Pores narrower than this are inaccessible to bacteria. Water storage pores.
0.1μm	*Micro-pores:* Finest water storage pores; water in smaller rigid pores is unavailable to plants.
0.01μm	Almost all pores between clay particles are smaller than this. Pore walls are cation exchange surfaces and so buffer pH and nutrient concentrations in soil water. Water-filled most of the time.
0.001μm	Smallest pores within a fine clay matrix that are about three water molecules wide. Pore walls are cation exchange surfaces. Water-filled all of the time.

Table 1: Scale in soil structure (adapted from Marshall and Holmes, 1988 and Marshall *et al.*, 1996)

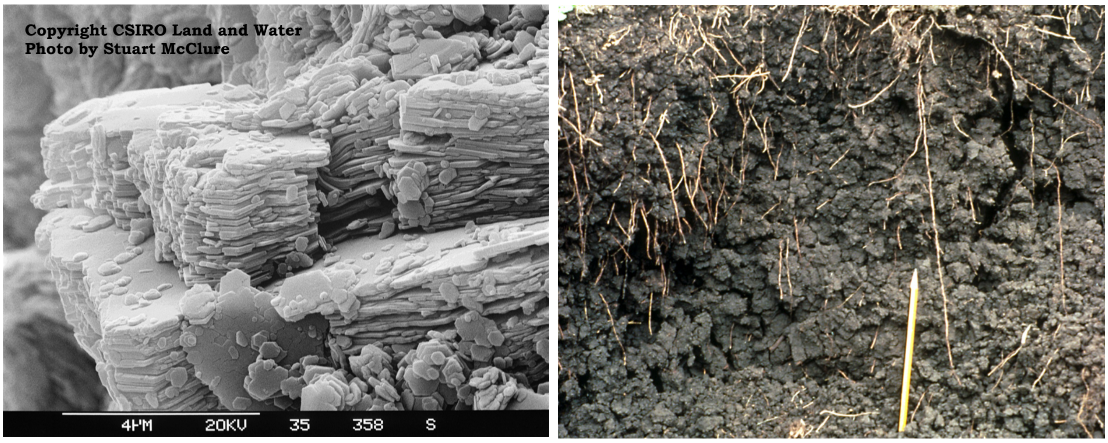

Figure 1: Soil structure at extreme scales. *Left:* textural porosity in the clay mineral kaolinite. The scale bar is 0.004 mm. Many of the pores visible are small enough to retain water that is not available to plants. *Right:* structural porosity in a "self-mulching" clay soil with well-defined aggregates and large pores that play a role in drainage, aeration, root growth and the activities of soil fauna.

The importance of soil structure to plant growth is readily appreciated by considering just three soil physical properties which depend critically upon it – permeability, pore size and strength.

- Permeability embodies the size, continuity and tortuosity of channels which control the movement of water, gases and organisms. This has a major impact upon run-off (and therefore soil erosion and water storage), aeration, salt leaching, nutrient movement and transformation, biological activity (root growth, fauna movement) and heat transfer.

- Pore size is important in its own right as the water available to plants is held within pores in a size range of about 0.2-30 μm[1]; the abundance of these pores in any soil is largely determined by its texture.

- Soil strength is critical during germination and root growth and in determining how a soil responds to tillage.

As a consequence of these factors, plants growing in structurally degraded soils are often constrained by water-logging and poor aeration when the soil is wet and by high strength, rather than by the availability of water, as the soil dries. Smith *et al.* (1983) refer to the rapid initial infiltration into flood-irrigated, fine-textured soils which have cracked on drying followed by slow drainage and prolonged periods of wetness and anoxia which retard crop growth. Cockroft and his co-workers (summarized in Murray, 2007) have promoted the use of raised beds to overcome such problems and to maximize root volume.

[1] 0.0002-0.03 mm

Passioura (1991) notes that the presence of continuous macropores increases the extent of the root system even in hard soils. However, what appear to be adequate root length densities may obscure the true picture of roots clumped together in occasional macropores that punctuate an otherwise hostile soil matrix; under these conditions the supply of nutrients and water is severely limited.

While soil structure is fundamental to plant growth, the *stability* of this structure is perhaps even more important; some features of good soil structure can be created by, for example, well-timed and appropriate tillage but can then be rapidly demolished by a heavy downpour or an irrigation event. While it is true that many soil properties such as clay content, mineralogy, pH and bonding agents (e.g. iron oxides) contribute to structural stability, from the point of view of practical soil management the stability of soil structure towards the effects of wetting, and to some degree traffic, is largely conferred by fresh organic matter, by exchangeable calcium, by electrolyte concentration[2], by roots and hyphae and by the quality of applied irrigation water.

Kay (1990) defines *structural resilience* as a further aspect of soil structure; this describes the ability of soil to recover its structure by natural processes such as, for example, by wetting and drying or by swelling and shrinking as occurs in the “self-mulching” soils. Kay *et al.*, (1994) have noted that soil structural stability and structural resilience may be combined to give a measure of *structural vulnerability*. This measures the overall inability of soil structure to cope with common stresses (e.g. rapid wetting), either because the soil is unstable towards those stresses or because there are no mechanisms for it to recover from the damage they inflict. This concept of structural vulnerability has obvious applications in sensible land use planning.

The impact of water on soil structure

Of the five factors that determine the course of soil formation (climate, vegetation, topography, parent material and time (Jenny, 1941), only vegetation would seem to be routinely changed by human intervention. However, the climate factor contains water (rainfall) as one of its principal components, one which has a major impact upon weathering, leaching, biological activity and, inevitably, upon soil structure; this component of climate is effectively changed by both vegetation removal and by irrigation, often dramatically. Irrigated

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[2] The dispersion of soil (see later) is independently suppressed by the concentration of electrolytes (salts) in solution regardless of the dominant exchangeable cation (e.g. calcium, sodium). The addition of gypsum to soil is used to increase *both* exchangeable calcium and electrolyte concentration.

crops routinely receive amounts of water that range from minor supplementation to amounts that dwarf the local rainfall. In Australian vineyards for example, applications range from practically zero in higher rainfall areas to more than 10 ML/ha (McCarthy, *pers. comm.*). Even with precision irrigation the amounts are deceptively large. As an example, the application of 1 ML/ha through drippers to what is commonly less than 5% of the area of a vineyard floor corresponds to 2000 mm of water through the soil profile directly under a dripper. The rate of application may also be deceptively large; Currie (2006) points out that a 4L/hr dripper wetting a 30cm disc of soil (sandy loam) represents an intensity of about 60 mm/hr which is in the realms of a tropical downpour.

Remarkably, there have been relatively few rigorous studies of the effects on soil structure, especially at depth, of such dramatic long-term changes in local hydrology under irrigation. Smith *et al.* (1983) refer to structural decline on a flood-irrigated, self-mulching grey clay after 10 years of intensive cotton production. Mullins *et al.* (1990) have reviewed the behaviour, occurrence and management of hardsetting in which structurally unstable soils collapse to a dense mass on wetting and then become stronger as they dry. Barber *et al.* (2001), noting a decline over several years in lateral and upward water movement from sub-surface irrigation in the Murrumbidgee Irrigation Area, found evidence of clay migration away from emitters and suggested that this translocated fine material may block pores. Artigao *et al.* (2002) found no evidence of physical degradation in a Spanish soil irrigated for 25 years. Salgado *et al.* (2004) observed very high bulk densities, under both furrow and drip irrigation, in 10 Chilean vineyards ranging from 4 to 12 years old. Cockroft and Olsson (2000) have identified the progressive hardening and loss of porosity of raised beds in irrigated orchards even though these were untrafficked and composed of water-stable aggregates, a phenomenon described as *coalescence*. Ricks Presley *et al.* (2004) noted several previous studies which concluded that irrigation caused no changes in soil physical properties but an equal number of studies that reported an impact of irrigation on soil physical properties. These same authors observed the effect of 30 years of irrigation (centre pivot sprinkler) with high quality water on two soils in Kansas and reported increased clay movement and mineral weathering but there did not appear to be any significant bulk density changes.

In each of the above studies, salt-affected soil and/or poor water quality either was not, or did not appear to be a major issue. Apart from the inevitable structural collapse during irrigation of soils with low structural stability, few other general conclusions can be drawn from these studies about the impact of long-term irrigation on soil structure, especially at depth. Many different soil types were involved in these studies and the nature and range of data presented makes objective comparisons difficult. However, notwithstanding variations in water quality, the impact of water on soil structure seems certain to be very soil-dependent. In the experience of the authors, such field studies of long-term effects are frequently hampered by the lack of continuous, reliable records. Such field observations need to be conducted under tightly controlled and recorded conditions (e.g. of water quality, irrigation management, rainfall etc) and in our opinion should be supplemented by laboratory or greenhouse observations designed to observe the progress of soil structural changes as they occur.

Quite apart from the direct effects of water alone, soil structure can be dramatically and rapidly degraded in other ways by irrigation; history has many examples of such degradation (e.g. Khan *et al.* 2006) and these largely arise from secondary salinization.

The depth of the local water table represents an hydrological steady-state or balance between the addition to, and removal of water from the landscape. This balance is disturbed by irrigation (or vegetation removal), often leading to a shallower water table. Where the water table remains several metres deep there are few local consequences but as it approaches the soil surface it may provide capillary access to an ancient reservoir of dissolved salts accumulated in the groundwater from mineral weathering and rainfall. Losses of water from this soil by evapo-transpiration then allow the salt to accumulate near the soil surface.

In addition to its direct impact on plants, salinity creates a sodic soil whose structure is much less stable than before and is quite vulnerable to structural decline. As this process is a consequence of the local hydrology and the *amount* of irrigation water applied, it may occur regardless of the quality of the irrigation water being used. Indeed, even in the complete absence of a naturally shallow water table, the use of irrigation water of poor quality has similar potential to inflict soil structural damage. In this regard, both adverse natural hydrology and poor irrigation water quality can independently degrade soil structure (and soil chemistry) by making the soil sodic.

When all these factors are considered it is clear that irrigation has the capacity to change soil properties. Soil structural decline is virtually inevitable where salinity is involved. However, some changes in the structure of irrigated soils are also to be expected even when water quality is good. Irrigated soils undergo less swelling and shrinking and less wetting and drying than their dryland counterparts; these are both important physical processes for the creation of soil structure. It follows then that in the complete absence of biological activity, most of the changes in soil wrought by irrigation would probably be negative ones. However, increased soil water content also generally increases the activity of soil fauna and of plant roots, both of which tend to have positive effects on soil structure. The structural state of irrigated soils reflects the balance between these processes.

The mechanisms by which soil structure is degraded by irrigation are examined below. Firstly the effects of water alone (i.e. good quality water) on soil structure are discussed then the effects of water of poor quality are considered.

The effects of water alone on soil

Soil strength decreases rapidly with increasing water content so that wet soil is generally more vulnerable to structural damage from mechanical stresses or disturbance. This loss of strength is due to the softening of cementing agents and the general weakening of cohesion between particles (Marshall *et al.*, 1996). Of course, irrigated soil spends more of its time wet and in a weakened state so that there is more opportunity for such damage to occur. Moreover, if the applied water has energy because of its movement (e.g. due to rapid flow or emission from overhead sprinklers), it has the capacity to destroy soil aggregates.

As water content increases, the consistency of soil changes. Dry soil is strong and *brittle* and generally only vulnerable either towards rapid wetting (*slaking* –see below) or to pulverisation by poorly-timed tillage. If the soil has a very high swelling clay content it may also shrink and crack extensively on drying causing it to disintegrate into small aggregates. An increase in water content reduces soil strength and produces *friable* soil which is widely regarded as its most desirable state; at this consistency soil can be productively cultivated but, paradoxically, is at its most vulnerable to compaction by traffic. Further increase in water content leads to even weaker soil of a *plastic* consistency which is easily smeared and remoulded leading to almost complete loss of structure and to high strength on drying. Finally, soil which is disturbed in the presence of excess water assumes the consistency of a *liquid* and may *disperse*. These consistency phases persist over ranges of water content which depend upon the soil texture. For heavy clays each of these phases is quite pronounced and persists over a substantial range of water contents; for sands, the phases are practically non-existent. Indeed, for very coarse-textured soils like sands, there is virtually no cohesion when they are either dry or else saturated with water; they acquire some cohesion, however, when moist because of the *matric suction*[3] in the water, a phenomenon referred to as *effective stress* and which is present in all moist soils.

[3] *Matric suction* refers to the tension present in soil water whenever soil is not saturated. It behaves rather like a membrane which holds a soil mass together. In pure sand it is usually the *only* source of cohesion.

The mechanical stresses or disturbances which lead to soil structural damage can be external ones such as traffic (machines and livestock), tillage and the impact of water droplets from rain or irrigation; these provide the energy to disrupt soil already weakened by its water content. However, structural damage can also result from "internal" processes such as the stresses generated by rapid wetting, by swelling and shrinking or simply by the mass (overburden) of the soil itself and also by the increased opportunities, in wet soil, for dispersion and migration of fine material.

Slaking: As stated above, dry soils are vulnerable to slaking; this is the process by which larger soil aggregates (macro-aggregates >0.25mm) disintegrate into much smaller ones (micro-aggregates <0.25mm) during rapid wetting. Indeed the rate of wetting is critical here and probably more important than the energy of subsequent drop impacts from rain or irrigation in causing aggregate breakdown (Loch, 1994). This disintegration occurs because the rapid entry of water drawn by capillary forces into aggregates leads to entrapment and compression of air and to differential clay swelling due to uneven wetting; both of these produce stresses that the wet soil is unable to contain (Marshall *et al.*, 1996). Slaking is greatest in soils of coarse-medium texture because the water enters aggregates quickly. If wetting occurs slowly, the soil is still weakened but the relief of destructive stresses has time to occur and is less damaging. From an irrigation viewpoint, spray application or the capillary wetting of hills from furrows are less destructive processes than simple flood irrigation. Kemper *et al.* (1975) have demonstrated the importance of wetting rate, as determined by irrigation method, in relation to crust strength and the persistence of large soil pores. Slaking is, of course, largely a surface phenomenon as soil at depth tends to become wet more slowly and is also "contained" by the surrounding soil.

Mechanical dispersion: A further problem which compounds the effect of slaking is dispersion; this is the process by which even smaller colloidal particles (<10μm) are detached from their neighbours either spontaneously, as occurs in sodic soils (see below), or mechanically by disturbances such as the impact of water droplets or the shear forces from water flow.

Acting together, slaking and dispersion generate a large amount of fine material which blocks useful pores at the soil surface and seals it against water entry; Loch (1994) has shown that drop impact "sorts" this fine material and generates a thin, dense surface layer. The fine material also effectively acts as a cementing material leading to the formation of surface crusts. These crusts severely retard water infiltration and germination and enhance runoff and erosion. This degradation of surface soil structure is promoted by irrigation methods where the applied water arrives suddenly and has a good deal of energy due to its velocity or turbulence; this energy is expended in the destruction of soil aggregates and the loss of surface soil structure. Even if the soil structure at depth is good, the loss of soil structure at the surface may severely constrain the productivity of the soil.

Apart from the damage to surface soil structure by water there is also a good deal of potential for structural damage at depth. As discussed earlier, irrigated soils spend more of their time wet and therefore weaker than their non-irrigated counterparts. This reduced strength threatens the existence of the larger continuous pores in the soil that are essential features of good soil structure. These larger pores are necessary for good drainage, gas exchange and extensive root penetration but are the most vulnerable features of soil structure.

Hardsetting soils: These are soils that slump when wet under their own weight and then set to a hard, dense mass with little or no structural porosity as they dry but then soften again on re-wetting. This behaviour affects the soil to a greater depth than the simple surface crusting discussed above which only occurs in the top few millimetres. Mullins *et al.*, 1990 have reviewed this behaviour and point out that about 13% of Australian soils have duplex profiles with a hardsetting A_1 horizon. They also point out that this behaviour probably extends to any soil that has an unfortunate particle size distribution (allowing for dense packing of particles), no significant shrink-swell potential (that might generate cracking) and that has unstable aggregates either because it lacks organic matter or cementing agents or because it is sodic (see below). In these soils irrigation or rainfall after tillage and sowing causes the surface soil to collapse again; Gusli *et al.* (1994) showed that beds of soil aggregates collapse on wetting and draining because of slaking and the suction (effective stress) of the water as it drains. After this collapse the soil strength then increases and prevents germination as the drying occurs from the surface, or prevents root elongation as roots dry the soil. Mullins *et al.* (1990) suggest that a major contribution to this increased soil strength during drying arises from effective stress (see above). These soils may also display a rather narrow water content "window" for productive tillage; by the time they are dry enough to support traffic, cultivation may yield a tilth that is too cloddy or dusty. Mullins *et al.* (1990) rightly point out that the word "compaction" is often loosely applied to any process that causes soil to become denser and that a clear distinction must be made between processes such as hardsetting on the one hand, and true compaction which is produced by the external stress of traffic on the other; this is essential for sensible management of soil problems associated with increased bulk density.

Coalescence: Or and Cockroft and their respective co-workers (e.g. Or, 1996; Teamrat *et al.*, 2000; Cockroft *et al.*, 1996; Cockroft and Olsson, 2000) have identified a process of "aggregate welding"; they have named this process coalescence. In the field Cockroft and Olsson (2000) have observed a progressive hardening of well-prepared, untrafficked, irrigated raised beds composed of water stable aggregates of a red-brown earth. Grant *et al.* (2001) have observed similar behaviour in a self-mulching, heavy grey clay. This phenomenon differs from hardsetting in that it occurs gradually, rather than abruptly. While macro-pores are still present so that infiltration and drainage remain good, root growth is constrained. This progressive "welding together" of soil aggregates appears to proceed with wetting and drying cycles (Lanyon *et al.*, 2000). Its absence in some soils appears to be associated with amounts of soil organic matter well in excess of the amounts required for aggregate stability in water. Nevertheless, the distinction between coalescence and hardsetting is not a sharp one. The word "coalescence" has been used to describe processes that involve at least some hardsetting behaviour (e.g. Teamrat *et al.*, 2000; Bresson and Moran, 1995). The extremes of behaviour would seem to be complete collapse of soil to a dense, structureless mass (hardsetting) on the one hand, and "aggregate welding" with no significant bulk density change on the other (coalescence). It seems more probable that different soils respond to wetting by a mixture of these two processes depending on their composition and the water-stability of their aggregates.

Compaction: This is the increased density that soils develop as a result of transient external stresses such as agricultural machinery traffic and which may affect soils to considerable depth. Compaction is cumulative and difficult to reverse as it affects the whole soil volume whereas attempts to remove it by tillage generally only fragment the soil into large clods which are themselves compacted (Koolen and Kuipers, 1983). While the degree of compaction depends on soil texture, and on organic matter and water contents, irrigated soils are clearly more at risk here because of their perennially moist and therefore weakened state. The increased density and preferential loss of large pores associated with compaction increases both the penetration resistance of soil and the time during which the soil remains water-logged after rain or irrigation.

Salt-affected soils: The structural stability of soil is degraded dramatically by sodicity[4], a soil condition which promotes dispersion. Sodicity and its management have been comprehensively reviewed by numerous authors (e.g. Gupta and Abrol, 1990; Naidu *et al.*, 1993; Rengasamy and Olsson, 1993; Jayawardane and Chan, 1994; Sumner and Naidu, 1998; Levy, 2000). Australia has an abundance of naturally sodic soils and the secondary salinization associated with irrigation and land-clearing has added to these. It is generally

[4] Sodicity is the extent to which the cation exchange capacity (CEC) of a soil is occupied by sodium, most of the remainder being occupied by calcium, magnesium and potassium. In Australia an exchangeable sodium percentage (ESP) above 6 defines a sodic soil; in the U.S. it is 15.

commonplace to observe a tendency for salinity, sodicity and exchangeable magnesium to increase with depth due to plant water uptake, leaching and increased access to the products of mineral weathering at depth (Isbell *et al.*, 1983; Tucker, 1983)

Most non-saline soils are able to be dispersed to some degree when mechanically disturbed in the presence of water; this is a common phenomenon at the soil surface where traffic and the impact of water disturb the soil. However, sodicity reduces the energy required to disperse soil and, in severe cases, dispersion occurs quite spontaneously in the presence of good quality water without the need for any mechanical disturbance. Furthermore, in soils where the amounts of exchangeable magnesium or potassium have increased at the expense of exchangeable calcium, dispersion may be enhanced further, even at the same sodicity level. Although mechanical dispersion of soil can be minimized by very careful management, spontaneous dispersion is quite another matter and poses a major threat to soil structure. It allows fine material to be easily mobilized throughout the soil profile, not just near the surface; these dispersed particles progressively block the voids essential to good soil structure. As an example, Kyei-Baffour *et al.* (2004) have shown that strength increases in a leached saline soil can pervade the whole profile. Kienzler (2001) observed markedly increased penetration resistance to depth in a salt-affected irrigated vineyard. Currie (2006) observed increased penetration resistance and lower permeability under or near drippers at the boundary of the A and B horizons in irrigated vineyards.

Although sodicity is often a consequence of a salinity episode; sodic soils are not necessarily saline; in Australia sodic soils are far more common than saline ones. Salinity may be removed relatively easily by leaching but sodicity may persist (Oster, 1994). Indeed, in soils with a high cation exchange capacity, sodicity may be somewhat buffered or slow to change. While a soil remains both sodic *and* saline, dispersion is reduced. However, as the soil becomes even more sodic at a given salinity level or the salinity decreases due either to winter leaching or a change to better irrigation water source, the structure of the soil becomes increasingly unstable. The finest soil particles, the soil colloids, become much easier to detach from their neighbours. The clay in the soil swells more readily and this swelling closes pores which conduct water; when the soil dries, the swelling is largely reversed. At the same time, mechanical dispersion of the soil colloids by soil disturbance becomes more pronounced and when the soil becomes severely sodic, dispersion becomes quite spontaneous in the presence of water of low salinity. The dispersion process, however, is not reversed as the soil dries since the dispersed particles do not return to their original locations but remain behind the retreating water meniscii and ultimately lodge in positions that reduce the permeability of the soil and increase its density and strength.

The general behaviour of soil in relation to salinity and sodicity is illustrated by the graph in Figure 2 below. The area below the broken line represents salinity and sodicity conditions where dispersion is modest or non-existent and the soil structure is more or less stable. As sodicity increases, at any given level of salinity, the energy required to disperse soil particles is reduced until ultimately, when sodicity is high, dispersion becomes spontaneous. Alternatively, at any given sodicity level, the soil becomes more prone to dispersion as salinity is reduced. This is particularly relevant to irrigation or the arrival of rain where the leaching of salt from a soil profile that is both saline and sodic may trigger a dispersion event that degrades soil structure.

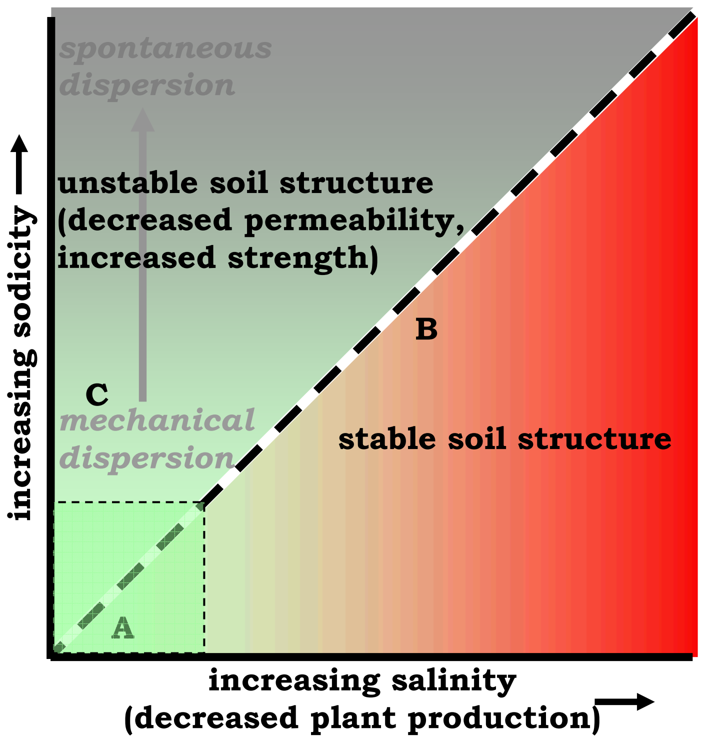

Figure 2: Effect of salinity and sodicity on the stability of soil structure (adapted from Quirk and Schofield, 1955). Points A, B and C are discussed in the text below.

The permeability of soil is of critical importance in irrigation and drainage and the broken line in Figure 2 can represent the salinity levels, for any given level of sodicity, at which the permeability of the soil is significantly reduced below its stable value at high salinity levels. This salinity level or salt concentration is referred to as the *threshold electrolyte concentration* (TEC) for that soil at a given sodicity (Quirk and Schofield, 1955). Salinity and sodicity scales have deliberately not been included in Figure 2 because this threshold concentration line is not universal and depends on texture, clay mineralogy and other aspects of soil composition. In a review paper Shainberg and Letey (1984) noted that the TEC concept has been applied to many soils as a tool for managing their permeability when irrigated; this is a critical issue governing the successful leaching of accumulated salt. Rengasamy *et al.* (1984) have applied a similar concept to the dispersive behaviour of red-brown earths in Australia.

In practical terms, if the salt concentration falls below the threshold concentration for any given sodicity level, there will be a significant drop in soil permeability and a perched water table may be created on an impermeable subsoil (Rengasamy and Olsson (1993). The maintenance of good soil permeability is essential for the provision of adequate leaching and for the avoidance of water-logging.

Although we are considering the effect of water alone on soil in this section it is useful to consider the consequences of a change in water quality. As an example, a soil of stable structure (point A in Figure 2) may originally have low sodicity and salinity. Irrigation with a saline water source (or saline groundwater accession), increases both salinity and sodicity (point B). Winter rainfall or a change to high quality irrigation water leaches the salinity but a good deal of the sodicity remains (point C). This soil now has a more unstable structure. As Figure 2 suggests, the structure of a soil which is very sodic is really only stable when the soil is also saline. This may place an unacceptable constraint on plant production and means that soils of vulnerable structure growing plants that are sensitive to salinity require close management to maintain them in a state represented by the small dotted square in Figure 2.

The extent of swelling, dispersion and subsequent migration of clay in a soil profile depends upon the quality and amount of applied water (rain/irrigation) and upon many soil properties. Soil texture and structure, clay mineralogy, particle size and shape together with the many soil chemical properties that determine swelling and dispersion such as exchangeable cations, pH, organic matter and cementing agents all contribute to this behaviour. Accordingly, the dispersive behaviour of salt-affected soils is quite soil-specific and perhaps the only generalization that can be made is that increases in exchangeable sodium have a generally negative impact upon soil structure and that this effect is reduced by increasing salinity.

In summary the discussion above demonstrates that water is, on the one hand, a powerful agent for soil structural decline, it is also, on the other hand, essential for the biological processes which generate soil structure. Soil which is moist also has lower resistance to penetration. If this increased water content is persistent and does not occur at the expense of good aeration or of excessive nutrient leaching, then roots and soil organisms will tend to congregate under these conditions. This increased biological activity contributes to good soil structure as the growth and decay of roots and the activities of soil fauna generate a network of coarse pores. The increased concentrations of organic matter from these processes will also stabilize soil structure. It might well be said that the art of good irrigation is a compromise in which the soil is maintained in a moist but not wet condition in which the constructive, largely biological processes and the destructive, largely physical processes at work on the soil structure are neatly balanced.

Water quality issues

The stresses that irrigation places on soil structure are amplified considerably when the irrigation water itself is of poor quality. Water is a vehicle for the movement of vast amounts of salt in the landscape and irrigation has the capacity to transform a structurally stable soil into a salt-affected one. Against a background of water conservation, it seems almost inevitable that irrigation water quality might generally decline. In 2004-5, 12% of the total water used in Australian agriculture was groundwater[5] and 2% was re-use water (ABS, 2006). The uses of irrigation water from both of these sources seem likely to increase in the future and this poses a major long-term threat to soil structure. Over two thirds of the groundwater resources of Australia contain more than 500 ppm of solids (Rengasamy and Olsson, 1993); Ricks Presley *et al.* (2004) have demonstrated that long-term use of water of this quality can significantly raise exchangeable sodium percentage (sodicity) throughout soil profiles. More recently, Hamilton *et al.* 2005 have discussed the potential for the use of reclaimed water in the Australian horticultural industry and Wetherall *et al.* (2006) reported substantial increases in the use of recycled water in Australia over 5 years. While the pressure to use water several times rather than just once is laudable it comes at a price when used for irrigation. There is practically no use to which water is put that does not increase its salinity. Although it is treated to remove pathogens, salinity is never reduced unless the water is subjected to a very expensive process such as reverse osmosis. While the use of inferior water for irrigation represents an excellent measure to conserve water, the cost of such water conservation may be soil integrity. Example discussions of these issues can be found in Halliwell *et al.* (2001) who have reviewed the impact of wastewater on soil physical properties and in Surapaneni and Olsson (2002) who have reviewed the impact and potential management of conjunctive water use in irrigating pastures and crops.

The principal water quality factors which determine how irrigation water will affect soil structure and its stability are total salinity (frequently characterized by the electrical conductivity (EC) of the water), sodium adsorption ratio (SAR) and carbonate/bicarbonate concentrations. Shainberg and Oster (1978) have discussed these water quality factors in some detail. Other common water quality factors which have a less direct effect on soil structure are nutrients (mainly nitrogen, phosphorus and boron) and non-nutrient

[5] Substantially higher in N.T. and S.A.

concentrations (mainly chlorine) which impact on plant growth and soil biology generally. However, Magnesan *et al.* (1999) have shown that wastewater with high carbon:nitrogen used for irrigation can cause microbial blockage of the pores that conduct water even in freely draining soil. More general guidelines for irrigation water quality, including the factors that influence soil structure are presented in the National Water Quality Management Strategy (2000) The factors discussed below will be confined to those that have a direct effect upon soil structure via sodicity.

Salinity: This has a direct, adverse effect upon plant growth and soil biology, both of which normally generate and stabilize soil structure. However, as discussed above, salinity has a much more direct physical effect on soil structure as it is almost always due to high concentrations of sodium so that the cation exchange capacity of soil irrigated with saline water becomes populated with sodium creating a sodic soil. As noted previously, the salinity may be removed by leaching but sodicity is not so easily removed. It is generally true then that all saline soils are sodic but that sodic soils may or may not be saline.

Sodium Adsorption Ratio (SAR): The common "bases" calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) generally comprise almost all of the exchangeable cations in soil. Ideally, the exchangeable cation suite is dominated by calcium with lesser amounts of magnesium and potassium and little or no sodium. This composition ensures that these plant macro-nutrients are available and that soil structural stability is good, essential features of any productive soil. However, relatively small amounts of exchangeable sodium (~10%) can degrade soil structure. The capacity of irrigation water to transform a non-sodic soil into a sodic one depends upon a number of factors including soil type, management, time and water quality. The most important water quality factors in this regard are the total salinity and the sodium adsorption ratio (SAR) given by:

$$\mathrm{SAR} = [\mathrm{Na}^{+}] \ / \ \sqrt{([\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}])} \qquad (1)$$

where $[Na^{+}]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ refer, respectively, to the concentrations (in milli-moles/L)[6] of sodium, calcium and magnesium in solution[7]. SAR and total salinity are quite independent of one another and in principle it is possible to have any combination of the two (see Table 2)

[6] Concentrations in milli-moles/L are calculated by dividing concentrations in mg/L (or ppm) by atomic mass (Na=23; Ca=40; Mg=24). As an example, a sample of irrigation water containing 115 mg/L Na, 5 mg/L Ca and 3 mg/L Mg has SAR=10.

[7] Traditionally potassium has been omitted from SAR calculations because its concentration in environmental water samples was regarded as quite low; the author's own experience has not always supported this but it is now an established convention. Potassium has a negative effect on soil structure but it is much less than that of sodium.

but generally, for environmental water samples, when one is high so is the other. In relation to soil structural stability, SAR is an expression of the balance between the concentration of an undesirable cation (Na) and those of more desirable ones (Ca, Mg). In simple terms soils irrigated with water of high SAR become progressively more sodic; this process is accelerated if the water is also saline. As an example, Table 2 shows two water samples of the same SAR but very different salinity. The water of higher salinity could make most soils quite sodic (and possibly saline) if used for irrigation; the water of lower salinity would have negligible effect on most soils.

sodium (ppm)	calcium (ppm)	magnesium (ppm)	SAR	EC (dS/m)
45	0.2	0.1	20	0.2
700	50	25	20	3.5

Table 2: Two water samples with the same high sodicity (SAR) but very different salinity (EC)

The impact on a soil of water with a high SAR also depends upon the cation exchange capacity (CEC) of the soil, the time over which this irrigation water has been applied and management (e.g. mulching). Fine textured soils or those with high organic matter content generally have high CEC and are heavily “buffered” against most chemical changes including changes in sodicity. Time is an important factor in any soil changes but the irrigation-induced sodicity of soil is complicated by the fact that irrigation with saline/sodic water in spring/summer may alternate with leaching by good quality water during autumn/winter rainfall. This may reduce soil salinity dramatically but have a lesser effect upon sodicity, especially in soils of finer texture where the “chemical inertia” or buffering of a large CEC comes into play; this means that the dispersion “hazard” for soil structure is at its worst just before the irrigation season commences. Crop transpiration and the management of irrigation and the surface soil also influence the impact of saline/sodic irrigation water on soil. SAR is increased whenever water alone is removed from the soil by transpiration or evaporation. Accordingly, management strategies that enhance evaporative losses such as no mulching, frequent small irrigation events or the use of fine sprays all tend to increase both SAR and salinity.

Carbonate/bicarbonate:

When they exist in surface waters, carbonate and bicarbonate always occur together in solution in equilibrium with one another, with the pH and with atmospheric carbon dioxide. At low concentrations in irrigation water there are generally no problems but at higher concentrations, evident from elevated pH, carbonate becomes problematic. This is because, although all bicarbonates are soluble, calcium carbonate is relatively insoluble so that irrigation with this water tends to enhance the SAR of the soil water by removing calcium from solution so that sodium and magnesium dominate. Below the soil surface where the respiration of organisms is at work, concentrations of carbon dioxide in the soil atmosphere may be 100 times higher than in the greater atmosphere; this lowers the concentration of carbonate in favour of bicarbonate. However, near the soil surface carbonate concentration is higher and may become even more elevated as transpiration and evaporation of water occurs. In extreme cases where pH and the concentration of carbonate in irrigation water are high, the soil will progressively become alkaline as well as sodic so that nutrient availability is also impaired.

Irrigation method

In non-saline soils where the quality of irrigation water is good, the impact of irrigation on soil structure is generally confined to the extent that wetting occurs; in flood irrigation the entire field is affected but in precision irrigation the effects are largely localized beneath the emitter. In precision-irrigated soils the shape of the wetting "envelope" is determined by soil texture and the rate of application. In soil with a sharp texture-contrast between the A and B horizons, dramatically reduced permeability in the subsoil will cause water to spread laterally at the A-B boundary so that the shape of the wetting "envelope" is more complex than it is in a uniform soil.

From the earlier discussion it is clear that methods, such as flood irrigation, that permit sudden wetting, especially of soil with poor structural stability, will encourage the formation of crusts at the surface and hardsetting at depth. Wetting of mounds from furrows occurs under tension so that the rate of wetting is slower. The impact of water drops from sprinklers also have an immediate impact on unprotected surface soil; Lehrsch and Kincaid (2006) have suggested that irrigators should reduce drop energy to minimize surface structural damage.

Smith *et al.* (1983) discussed irrigation methods briefly but do not discuss precision irrigation. They noted the importance of maintaining soil water content between an upper limit, above which the soil is anoxic, and a lower one, below which water is unavailable and strength is high. They point out that in older systems, the upper limit is frequently exceeded and that maintaining these limits requires modern, automated irrigation systems where frequent irrigation is possible. It is clear from previous discussion in this review that irrigation methods and management that maintain the soil in a wet condition for long periods will encourage hardsetting and coalescence and create more opportunities for compaction.

As discussed in the introduction, the enormous variability of soil in the field presents formidable challenges to sensible management and it is quite clear that the management of soil structure is no exception to this. The current treatment of an irrigated field as though it were a uniform soil means that, regardless of the irrigation method used, there will inevitably be soil that remains wet for periods that compromise the structure.

Where water quality is poor, the impact of irrigation can extend beyond the wetting zone as salts are re-distributed more widely by rainfall. Clark (2004) investigated seasonal excursions in both salinity and sodicity, in a vineyard drip-irrigated with bore water and then leached by winter rain, and mapped the two-dimensional distribution of soil properties. Salinity was leached to depth directly beneath drippers where the roots congregated. Salinity and sodicity accumulated during the irrigation season at the outer rim of the wetting envelope from drippers. The salinity was then leached and re-distributed during winter creating the necessary conditions for clay dispersion and soil structural damage. This damage was observed as increased bulk density at depths up to 1.2 metres.

Monitoring, avoidance and remediation of irrigation-induced soil structural decline

It is no less true in soil management than elsewhere that prevention is far better than cure; many approaches to the reversal of structural decline in soil, especially at depth, are costly and time-consuming at best and completely ineffective at worst. Cass *et al.*, (1993) noted that soil preparation measures for new, permanent, irrigated horticulture and viticulture plantings were largely ineffective. In particular they observed that proper procedures for deep ripping, application of calcium amendments and mounding of soil are largely ignored; they also regarded the installation of drippers rather than sprays as deleterious to soil structure. Olsson *et al.* (1995) have further discussed the improvement and management of subsoil structure in some detail. Grant *et al.* (2003) have discussed the management and avoidance of root-zone constraints in relation in relation to horticulture and viticulture. Much of the work of Cockroft and his colleagues has dealt with soil preparation ahead of horticultural plantings; these are summarized by Murray (2007). Tisdall and Adem (1988) have also described an integrated system (the "Tatura System") which produces excellent soil structural features. Hansen (2005), however, has cautioned that the need for such preparations should, if possible, be established in advance. He observed that vine responses to deep ripping and mounding of soil may be absent when no substantial limitations to root growth are present.

Again it must be stressed here that ignorance of soil variability is likely to compromise such preparations and soil survey is essential. The common practice of conducting a preliminary soil survey by excavating soil pits, say on a 75 metre grid, seems to these authors to be unnecessarily time-consuming and destructive when more or less intact soil cores to 2 metres can now be more easily and rapidly retrieved by small machines[8], examined and archived for future reference.

There is little doubt that root systems that are not constrained by poor soil structure will support the growth of productive plants that are buffered against adversity, promote soil and water conservation and allow growers a full "window" of management options." Even in cases where plant stress might lead to improved quality, the imposed stress ought to be an option not an unavoidable product of poor soil management.

Monitoring soil structure

In the authors' experience in irrigated vineyards it is quite difficult to know how much, if any, soil structural change has occurred since establishment because no soil structural measurements have been made over time and there is usually no reliable, non-irrigated "control" site to refer to. Soil variability, the absence of reliable data and the often daunting task of gathering such data make sound soil management an aspiration rather than a reality. However, there is no doubt that the statement "if you can't measure it, you can't manage it!"[9] applies here.

As discussed earlier, soil structure is, for practical purposes, largely described by three soil physical properties: permeability, pore size distribution and strength. Unlike soil texture and many soil chemical properties (EC, exchangeable cations, CEC, pH, nutrients etc) where careful sampling is the only major obstacle to otherwise reliable laboratory assessment, the measurements of these soil physical properties are not simple matters and generally require time, equipment and expertise. Moreover, they must either be measured in the field or on undisturbed samples so that measurements at depth require excavation rather than simple withdrawal of samples using soil augers.

- Soil permeability is normally characterized by the infiltration rate of water into the soil. Measurements of infiltration rate are relatively straightforward; in their simplest form they require a metal ring to be partially inserted into wet soil, filled with water

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[8] e.g. by the "Dingo"/"Ezi-Probe" combination as used by these authors for soil sampling in vine rows.
[9] Peter Drucker (1909-2005)

and the rate at which the water enters the soil measured. However, great care must be taken not to damage the measurement surface as the pores which transport most of the water are also most vulnerable to damage. In texture-contrast soils, the structure of the subsoil may be far more important so that careful excavation and preparation of the surface for measurement are essential.

- Soil pore size distribution measurement requires that an undisturbed soil sample is taken to the laboratory where its water release curve is measured with specialized equipment.

- Soil strength, especially as it relates to root growth, is generally characterized as penetration resistance which is critically dependent on soil water content (Marshall *et al.*, 1996) For this reason penetration resistance is usually measured when the soil is at field capacity; for practical purposes this is when penetration resistance is at its lowest. In many cases field capacity water contents are only attained in the field during the wet season. An alternative approach is to gather small undisturbed soil in sampling rings, establish a known soil water matric suction in the laboratory and measure penetration resistance with a laboratory micro-penetrometer.

Another soil property which is routinely used to assess soil structure is bulk density. Although this soil property is not directly significant, high values infer poor aeration and drainage and high penetration resistance. It is usually measured by taking an undisturbed sample of known volume with a metal sampling ring or a soil clod, whose volume must be determined, and determining the dry soil mass.

Of the soil measurements described above, only the field measurements of surface infiltration rates (permeability) and soil penetration resistance lend themselves to routine use without the need for special equipment and/or extensive training. Most soil can be viewed as a matrix punctuated by occasional macro-pores. In this regard, penetration resistance and permeability are complimentary measurements since the former is largely a function of the soil matrix properties while the latter is determined by the abundance and continuity of macro-pores. As mentioned previously however, surface infiltration rates, although easy to measure, have limited value when the structure of the subsoil is the major concern.

Other less direct methods of soil structural assessment use soil pits to examine soil structure and root behaviour at depth; these are invasive and difficult to quantify. Similarly, root length density measurements at depth, although much less invasive are tedious. While these direct observations of root behaviour are useful and can indicate, for example, that soil penetration resistance is not a problem, they may be affected by factors unrelated to soil structure such as salinity or chemical toxicity.

Currie (2006) argues that effective monitoring of soil water offers more direct assessment of drainage and water-logging than more tedious subsoil infiltration measurements. In this regard and more generally for the future of irrigation management, there is a pressing need for simple, reliable, inexpensive devices for measuring soil water content or matric suction.

The structural stability of soil is somewhat more amenable to monitoring as the measurements can be conducted with minimal equipment. Emerson (1991) has discussed a modified scheme of simple observations which allow soil aggregates to be classified in terms of their stability towards wetting and mechanical disturbance. Cochrane and Aylmore (1992) have developed a simple on-farm measure of structural stability and potential for gypsum response. It seems clear from the discussion above that equally convenient measures of soil structure itself are needed. Grant *et al.* (2003) express similar concern at the lack of on-farm assessments of soil structure.

Prevention of irrigated-induced soil structural decline

In soils that are not salt-affected and where water quality is good, the prevention of soil structural decline is largely one of maintaining high soil structural stability towards the effects of wetting together with the avoidance of soil disturbance, traffic, rapid wetting and excessive soil wetness. A good deal of the discussion below is taken from the work of Cockroft and his co-workers (summarized by Murray, 2007) except where reference is made elsewhere.

As indicated earlier the stability of soil structure towards wetting is largely conferred by fresh organic matter, exchangeable calcium, electrolyte concentration and by roots and hyphae. Fresh organic matter is largely supplied by microbial and root exudates and so the maintenance of an extensive living root system is the key to this supply. However, these useful accumulations of organic matter in soil are reversed by, amongst other things, intensive tillage. At the microscopic level, organic molecules provide bonding between soil particles while at the macroscopic level roots and fungal hyphae link small aggregates into larger stable units. Cass *et al.* (1993) note that the practice of using plants with extensive fibrous root systems such as ryegrass in irrigated enterprises is minimal. They point out that fibrous root systems stabilize pores and create new pores in the winter and that plants can be sprayed off in spring with a herbicide which leaves seeds intact for regeneration to create a population of living or dead roots in the soil at all times. Many irrigated enterprises are comparatively free of root activity other than that of the (seasonal) crop so the opportunities to create and maintain soil structure are limited. Certainly there is resistance to the use of cover crops in close proximity to crop plants because of concerns about weed management and water use efficiency. However, it can be argued that the progressive removal of root-zone constraints by plant roots may deliver long-term gains in soils with poor structure at depth and that these gains may include improved water-use efficiency. While organic matter from other sources such as a slashed mid-row cover crop can be applied to the soil and serve as a mulch, this does not offer the range and depth of soil improvement afforded by dense living roots. A similar consideration applies to imported waste organic material which may contain undesirable inorganic materials that are toxic, dispersive or add to the soil salinity.

As discussed previously structural stability at the microscopic level is also enhanced by exchangeable calcium and by the total electrolyte concentration in soil water; both of these suppress dispersion. Addition of a suitable, soluble calcium source to soil is ideal for this purpose as it maximizes exchangeable calcium and increases electrolyte concentration in the soil water. A negative effect, however, is that added calcium may also displace exchangeable potassium, an important nutrient. Unless the soil is acid, gypsum is the most appropriate source of calcium and may be broadcast at rates of a few tonnes per hectare or added to irrigation water (solubility is about 2 g/L). Shanmuganathan and Oades (1983) have recommended that annual smaller additions of gypsum are better than infrequent large applications in maintaining an adequate electrolyte concentration.

As previously discussed, rapid wetting of soil maximizes the stresses of wetting. Most methods of irrigation, even drip irrigation as shown earlier, cause at least localized sudden wetting. Perhaps the only exception to this is sprays which allow soil to wet more slowly. The use of mulches may effectively reduce wetting rates by increasing the antecedent water content of soil before irrigation.

Soil disturbance near the surface occurs routinely because of machinery and tillage, the impact of water drops from rain and irrigation, the flow of water and the activities of livestock. Soil disturbance at depth is largely due to occasional deep tillage and to the un-intended consequences of the passage of heavy machinery. When extensive plant coverage is absent, mulches offer the best protection against drop impact (and water loss by evaporation) and crust formation. However, for the other more energetic forms of soil disturbance, abstention is the only sensible strategy. In relation to agricultural machinery, Cass *et al.* (1993) suggest that no-till technology developed in the fruit industry needs appropriate application to viticulture. This is a particularly important issue because, as mentioned previously, soil compaction at depth is extremely difficult to reverse.

From the discussions in previous sections of this review, it is clear that long periods of soil wetness contribute to soil structural decline. Here again, soil variability and reliable water monitoring are central issues. As discussed previously, good management lies in the ability to furnish water in amounts and at rates that allow profitable plant growth and provide adequate leaching but that minimize the periods where the soil is wet enough to present a structural hazard. There is obvious potential for conflict here and other strategies are essential; these should seek to continuously maximize structural stability and to remove external stresses on the soil structure (e.g. traffic).

Salt-affected soils are even more vulnerable to structural decline and adequate leaching and supply of calcium are essential measures to suppress dispersion in addition to all of the above measures.

Amelioration of irrigated-induced soil structural decline

Poor soil structure needing rehabilitation will generally require some physical disturbance to create pores. The only agents available for this purpose are swelling and shrinking, tillage and the activities of roots and soil fauna[10]. Most of these agents can act near the soil surface but at depth, swelling and shrinking is reduced and soil fauna may be minimal so that substantial subsoil amelioration can only be achieved by deep tillage or over longer periods by root invasion. There is little evidence that poor structure at depth is improved by dissolved chemical ameliorants alone such as gypsum; such materials are only useful to stabilize pores once they have been created.

Mechanical disturbance at depth is invariably provided by deep tillage and, as noted above, Cass *et al.* (1993) and Olsson *et al.* (1995) have pointed out serious shortcomings in the way this is practised in relation to choice of tines, speed, number of passes, soil water content, structural stabilisation and subsequent management. They have noted that soils that are sodic at depth should receive substantial additions of gypsum *before* deep tillage so that the soil response will be more friable and less plastic and that the structure created will be more stable; application at the time of tillage may well be too late. Once created, this soil structure at depth should be rapidly colonized by plant roots.

Smith *et al.* (1983) have suggested that more attention should be paid to overcoming transient water-logging problems in fine-textured soils using deep tillage and drainage works in large-scale irrigated enterprises.

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[10] In colder climates freezing and thawing is also important.

A further approach to soil disturbance at depth may be provided by drying the soil profile. Jayawardane and Chan (1994) have reviewed the management of irrigated sodic soils, including subsoil and suggest the use of roots to dry soils with high shrink-swell potential. More recently Currie (2006) has observed ten-fold increases in the saturated hydraulic conductivity of clay subsoil cores that had been dried to the permanent wilting point to induce cracking.

In the long term, however. There seems little doubt that plant roots present the best opportunity to the continuous creation and maintenance of soil structure at depth so that they should form an integral part of any strategy to reclaim and improve structurally damaged soil.

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