DRYLAND SALINISATION: A CHALLENGE FOR LAND AND WATER MANAGEMENT IN THE AUSTRALIAN LANDSCAPE

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WHY DO WE NEED TO WORRY ABOUT DRYLAND SALINITY?

Dryland salinity is undoubtedly the greatest and most intractable threat to the health and utility of Australia's rivers, soil and vegetation. Saving the waters and land of the Murray-Darling Basin (MDB) from salinisation is one of the biggest environmental challenges facing Australians, both in the scale of the problem and in the time needed to turn it around. The 1998 report to the Prime Minister's Science Engineering and Innovation Council (PMSEIC) on dryland salinity noted that 'the time scales over which salinity establishes itself, spreads, and has its effects can be long, but once established it can be very difficult or impossible to contain or reverse. As a consequence salinity must inevitably continue to get worse in Australia as a result of land use decisions already made'.

In 1998, PMSEIC estimated that the costs of dryland salinity include $700 million in lost land and $130 million annually in lost production. The effects of dryland salinity include increasing stream salinity, and losses of remnant vegetation, riparian zones and wetland areas. Salinity is degrading rural towns and infrastructure, and crumbling building foundations, roads and sporting grounds.

The problem is not new (Wood, 1924; Martin, 1971; Talsma and Philip, 1971) and is certainly not under control, we can expect the effects of dryland salinity to increase dramatically (see Figure 1 for the estimated upper limit of the extent of the salinity hazard). For example, if we do not find and implement effective solutions, the area of land affected by dryland salinity is likely to rise to between 10 and 12 million ha over the next fifty years.

To place this in context, the area of dryland cropping is *c.* 45 million ha, of which *c.* 18 million ha are reliable cropping land. Thus, the area of land (15 million ha) that could be salinised in the next 50 years could be similar to the area of quality cropping land in Australia. Western Australia has the greatest area of dryland salinity at present (1.8 million ha) with the potential to rise to 6.1 million ha; all the rivers of south-western Western Australia are salinised or salinising. A similar picture is emerging for South Australia, where Jolly *et al.* (2000a) showed that all surface waters are either salinised or at risk of serious salinisation. New South Wales is of critical concern, with 7.5 million ha potentially at risk, much of which will endanger MDB rivers, groundwaters (Leaney and Herczeg, 1999) and the related ecological systems. While land lost to production poses a significant threat to agricultural production, its primary impact is in the salinisation of previously fresh rivers. If this is not controlled, there will be a marked decline in the viability of much of the MDB. Salinity will damage the supply of drinking water and water suitable for irrigation, with serious economic, social and environmental consequences for rural and urban communities.

Stream salinity is therefore a major concern. Projections for the town of Morgan, a key location used to monitor the effect of salinity in the lower part of the Basin and in particular, the water supply for Adelaide, illustrate the problem. Here, the salinity of the River Murray is expected to increase by a further 240 EC units (microSiemens cm^{-1}) over the next 50 years. This will bring salinity in this part of the river close to the World Health Organization's (WHO) limit of 800 EC units for desirable drinking water, and create concern for its long-term sustainability as a source of water for urban and agricultural use. In most northern tributaries of the Darling River in Queensland and New South Wales, it is expected that river salinity will rise to levels that seriously constrain the use of river water for irrigation. Not only is irrigated agriculture in jeopardy, but salinity rises will seriously threaten the biodiversity and ecosystem function of the floodplains, riverine habitat and wetlands. Many of these riverine environments have very high biodiversity values.

Salinisation occurs in both dryland and irrigation farming (MDBMC, 1987). Replacing native vegetation or applying irrigation causes more water to enter the landscape than can drain from it. This increased amount of water moving in the landscape mobilizes and relocates salt stored in the soil, regolith or groundwater. Once water moves near the soil surface or discharges there, the salinisation process is promoted by the evaporation of soil water containing small quantities of soluble salts. This concentrates the salts and deposits them on the soil surface, where they are readily washed to surface streams and rivers. In other geological and hydrological circumstances, the mobilized salt is carried in the groundwater to the stream and rivers along the discharge pathways in the landscape. It is possible, therefore, to have salinisation of streams and rivers with very little salinisation of land.

SALT IN THE AUSTRALIAN LANDSCAPE

Australia's geological history makes it different to most other parts of the world. The very ancient, flat, continental landmass has been stable through enormous lengths of geological time (see Figure 2 for the geological framework). Land surfaces and rocks have weathered, eroded, mobilized, accumulated and redistributed sediments and salts over this long stable history (Beckmann, 1983; Isbell *et al.,* 1983; White, 1997).

In addition, Australia has existed as a lone island floating in a vast expanse of ocean for many millions of years. While some of the salts in the landscape are released from weathering rocks, particularly marine sediments, most are carried from the surrounding oceans in rain to be deposited, trapped and accumulated in the soils, regolith, lakes and groundwater. This has been the pattern for millennia (Holmes, 1971; Isbell *et al.,* 1983; Simpson and Herczeg, 1994). The accumulated salts were blown and redistributed across the landscape during the extremely dry periods of geological time. Enormous amounts have remained in the landscape because there is little capacity to drain the continent of water and its salt burden. The continent is very flat, and dominated by a gentle fall towards the interior, so most of our rivers and groundwater systems are sluggish, with only a small capacity to move salt from the continent. Because these arteries and veins of the Australian landscape are not in good condition, they have limited capacity to drain the continent.

By its very nature, the continent must accumulate salt weathered from its ancient rocks and deposited from the surrounding oceans. Much of it amassed in the arid central regions as saline lakes, seeps and depressions, of which Lake Eyre is a good example. This stored salt is distributed widely across the semi-arid and arid landscapes of Australia, frequently occurring in patchy, complex patterns that reflect remnant features of ancient sequences of climate and geological events that characterize the evolution of the continent. These salt storages stretch in a huge arc from north Queensland, extending south and adjacent to the Great Dividing Range, then broadening and sweeping south-west across the Murray-Darling Basin to encompass the Riverina and Mallee regions of New South Wales, Victoria and South Australia. In the Western Australian landscape, massive amounts of salt are stored in a large arc that sweeps south and east across the semi-arid and arid landscapes of south Western Australia (see Figure 1 and Holmes, 1971).

A combination of natural factors has led to Australia's significant problems with dryland salinity. The continent is geologically old and stable. The climate is very dry and highly variable with a low rainfall compared to potential evaporation. This low, highly variable rainfall pattern means we have one of the lowest amounts of runoff (see Figure 3 for definition) to rivers and deep drainage to groundwater in the world (McMahon, 1992). As a result, most rainfall is used by native plants and only small amounts leak to the groundwater (Holmes and Colville, 1970; Holmes, 1971; Allison and Hughes, 1972; Allison *et al.,* 1985). This combination of ancient, flat, low-permeability landscapes results in conditions conducive to the accumulation of salt, which is not flushed from the landscape by leaching. The consequence is that saline lakes, streams and land are a natural part of the Australian landscape, and native vegetation has adapted to these unique conditions.

THE LANDSCAPE BEFORE CLEARING

In most cases, native vegetation in semi-arid Australia is dominated by trees or woody shrubs, with only limited areas of natural perennial grasslands (Cocks, 1992). This perennial vegetation, with its relatively deep roots, has become effective at taking full advantage of any available water (see Figure 3 for the terms in the hydrological cycle). As a result, native vegetation can use most of the rainfall in ways that have minimized the amount of water that leaks past the root zone (Holmes, 1971; Allison and Hughes, 1972; Allison *et al.,* 1985; Williams *et al.,* 1997; Williams *et al.,* 1998). The interception of rainfall on leaves, branches and stems and its subsequent evaporation before reaching the soil was an important strategy (Hillel, 1990) in the hydrological cycle in native vegetation. Further, some native vegetation, including native perennial grasslands, sheds rain as overland flow (Dunin *et al.,* 1999), while most use strategies of storage in soil and subsequent evapotranspiration (Nulsen *et al.,* 1986).

Whatever the dominant combination of these mechanisms in our diverse native vegetation, the 'leakage' of excess water (the 'drainage' term in Figure 3) into the deeper soil below the roots is usually small, if it happens at all. Various studies have shown that over most of Australia's current dryland grazing and cropping areas, this leakage was commonly between 1 and 5 mm per year (Allison and Hughes, 1972; Allison *et al.,* 1985; Williamson, 1998). Over thousands of years, the minimal leakage has allowed the salts introduced through rainfall or rock weathering to build up in the soil below the depth of plant roots. The native vegetation evolved over a long time so that the deep drainage or leakage beneath the plant roots into the landscape's internal drainage systems was approximately the same as the drainage rates or discharge rates from the landscape. It is well documented that healthy native ecosystems within catchments are in hydraulic and salt balance (Peck and Hurle, 1973; Peck, 1976). The input of salt to the catchment is balanced by the salt discharged from the catchment. Once clearing occurs and agriculture is introduced, the salt discharged from the catchment begins to greatly exceed the salt entering the catchment (Peck and Hurle, 1973; Peck, 1976; Simpson and Herczeg, 1994; Jolly *et al.,* 2000b).

WHAT HAPPENS AFTER CLEARING

European settlers have unintentionally changed the hydrology of the Australian landscape to a remarkable degree in a relatively short time. Large-scale clearing of native vegetation and its replacement with annual crops and pastures have substantially increased the amount of water leaking beneath the root zone and entering the internal drainage and groundwater systems of the landscape (Williamson, 1998). These increased amounts of water now entering the groundwater under land used for agriculture greatly exceed the capacity of the groundwater systems to discharge the additional water to rivers and streams. Since the input exceeds the output to the groundwater, the watertable must rise (see Figures 4 and 5).

As the watertable rises, more water is discharged to the land surface as seepage comes to the surface (usually at lower positions in the landscape). Wherever this groundwater contains or intercepts salt stored in the soils or regolith of the landscape, salt is mobilized to these seepage faces, and hence to the land surface, streams, rivers and wetlands. This simple salinisation process operates at a number of scales in the landscape (see Figure 6).

The process can occur in local, shallow groundwater on a hillslope stretching over less than a kilometre, where seepage faces develop as the slope flattens near the stream. Alternatively, it can occur in large, regional groundwater basins stretching over hundreds of kilometres, where the salinisation is expressed on the lower parts of the basin and on the floodplains. The amount of water leaking into the groundwater system depends on various factors, including the climate (particularly the distribution and amount of rainfall) the depth, water storage-capacity and permeability of soils and subsoil and vegetation characteristics. For example, any water leaking beyond the root zone does not always end up in groundwater; in certain situations it can move laterally through the soils and end up in surface streams. In other situations, leakage can occur from the base of the streams into groundwater systems. Once the leakage beneath the root zone is increased and this water begins to move along pathways that connect salt stored in the landscape to land surfaces, and intersects with rivers and streams, the dryland salinisation march has begun.

EFFECTS OF SALINITY ON LAND AND WATER

In 1998, the Prime Minister's Science, Engineering and Innovation Council (PMSEIC, 1998) outlined the effects of dryland salinity. These can be summarised as follows:

Stream salinity

Increasing salt concentrations can be observed in many streams and rivers, particularly in the southern half of the MDB (see Figures 7 and 8). Rising groundwater in the Basin leads to saline discharges to streams and at the soil surface, where it affects runoff quality. Salinity levels in the Murrumbidgee River are increasing at between 0.8% and 15% per annum, depending on where measurements are made. Stream salinity in the Murray currently exceeds WHO levels for about 10% of the year. These changes have significant effects on aquatic ecosystems and all extractive uses, including drinking water, mining and irrigation.

Biodiversity and environment

Rising watertables and increasing salinity have serious effects on native vegetation. Remnant native vegetation is threatened, and as this is the only remaining habitat for a variety of important animal species, these are also under threat. Riparian vegetation, critical to the stability of stream banks, and wetland areas, are already damaged and under increasing threat. For example, the 1996 situation statement for salinity in south-western Western Australia identified the extensive impact of salinity on natural values. It found that 80% of the length of rivers and streams was degraded by salinity, and half the water bird species had disappeared from the many wetlands that were once fresh or brackish. Under threat are 80% of remnant vegetation on private land, up to 50% of conservation reserves, at least one population of each of ten declared rare fauna and the entire population of a declared rare orchid. These consequences of salinity for biodiversity and nature conservation also affect tourism.

Public infrastructure

Road and bridge damage caused by shallow, saline groundwater is a major cost to local governments. It is believed that high watertables affect about 34% of state roads and 21% of national highways in south-western New South Wales, with damage costing $9 million per year. Preliminary work by the MDB Commission has reliably estimated the annual cost of salinity in eight of the most salt affected of the 22 tributary catchments at $247 million per year for all forms of damage to public infrastructure (personal communication, Kevin Goss). A 1997 investigation of salinity and waterlogging on main roads in Western Australia showed that 230 km were already affected, a figure likely to double in 10 to 20 years and to cost an additional $50–$100 million in maintenance and reconstruction over the same period. Structures associated with communication and gas pipelines are subject to a similar fate. The town of Wagga Wagga in New South Wales is one of the worst affected by dryland salinity; it sustains costs of *c.* $500,000 per year from salinity-induced damage to roads, footpaths, parks, sewage pipes, housing and industry. Across Australia, many other towns and rural infrastructure are at risk of, and currently experience, rising watertables and consequent salinity problems (GHD, 1999).

Urban households

Saline water and high watertables affect households in various ways, from structural damage to houses and motor vehicles, through damage to hot water systems and household appliances, to increased use of soaps, detergents and water conditioners. Loss of property value is a major concern to householders and can lead them to deny the existence of problems until they are very obvious. Increased salinity in the Murray-Darling system is estimated to cost Adelaide $55–$65 million per year, largely in dealing with harder, more saline water.

Agriculture

Salinity leads to loss of productive land area and agricultural production. As noted earlier, PMSEIC estimated that the capital value of land lost is *c.* $700 million, with production losses of around $130 million annually, and increasing. In addition, the costs to farmers of protecting land and surface waters from salinisation and/or of moving to alternative, more sustainable uses have not been determined, but are likely to be high (VCG and GNRM, 2000). The effects are being felt mainly in the grains, wool and grazing industries of the intensive land-use zone of Australia.

In summary, the high level of intervention needed to deal with dryland salinity, combined with the landscape's slow response to any changes, mean that now is the time to devise new ways to manage the problem.

THE CHALLENGE OF SALINITY: OPTIONS AND SOLUTIONS

The recent synthesis of the nature and impact of salinity on Australia's water, soil and vegetation in the PMSEIC (1998) report, the MDBC Salinity Audit (MDBMC, 1999) and the Natural Resource Management Policy Discussion paper (AFFA, 1999), has focused community attention on the economic, social and environmental costs of salinity. In a new development, governments, community leaders and scientific leaders have recognised the seriousness of the problem and the need for radical changes in land use if we are to bring salinity under control. Radical changes are necessary because farming systems that can control salinity while generating sufficient income for social and community well being do not yet exist (Walker *et al.,* 1999; Stirzaker *et al.,* 2000) for most of the agricultural zones in Australia.

It can take a long time for salinity to establish itself, spread and have its effects, but once established, it can be difficult to contain or reverse (Fitzpatrick *et al*., 2000). The result is that inevitably, salinity must continue to get worse in Australia as a result of land-use decisions that have already been made. The repercussions of those decisions need not be local. In some places, the cause of the problem and the resultant salt scalds at the bottom of hill slopes are on the one property; in other cases, the cause of the problem may be hundreds of kilometres from where the symptoms become obvious.

Decisions taken now cannot prevent salinity and its consequences from becoming worse in the short term. While we should seek to slow the degradation and to learn to adapt to it, salinity has indirect, delayed and intractable affects. Australia's potential response to the salinity challenge entails serious trade-offs between short and long-term benefits, between existing primary industries and alternative land uses, between economic gain and the environment, and between rural and urban values. The management or response options are set out in Figure 9 and discussed in the following paragraphs.

The complex combination of a heterogeneous landscape and socio-economic trade-offs makes a uniform national response inappropriate. The nature of the groundwater systems could be used as a basis for choosing salinity management options (Coram, 1998; Figure 2). Some of the local options are to: (i) do nothing that will add to the problem, (ii) maintain current land use, (iii) adapt to a salinising environment, (iv) adopt engineering approaches to mitigate salinisation and (v) reduce recharge.

Do nothing that will add to the problem

It would be inaccurate to wholly ascribe the causes of salinisation to past resource policy. Widespread land clearance for agriculture still occurs in places such as northern New South Wales and Queensland, posing a significant salinity hazard (Bui *et al.,* 1996; Williams *et al.,* 1997). While southern Australia has been the focus of salinity analysis, there is sound scientific evidence (Bui *et al.,* 1996; Williams *et al.,* 1997; Bui, 2000; Gordon *et al.,* 2000) that all the factors that contribute to salinity hazard exist over large areas of the semi-arid zones of tropical Australia. The degree to which salinity will develop following land clearing, and the time delay for it to occur, will vary from catchment to catchment, but all the factors that contribute to salinity hazard exist throughout tropical Australia. While there will be landscapes where salinity will not be a serious issue, the regions at greatest risk of salinisation resulting from land clearing need to be established. There is an urgent need that robust analysis for salinity hazard to be made for northern Australia as a foundation for implementing policy and good practice in vegetation management. Broad-scale land clearing with little or no regard for the salinity hazard is the recipe to repeat, over large areas of northern Australia, the huge problems that we now face in the southern and central parts of the MDB. A hazard analysis is essential to establish those areas of northern Australia at greatest risk to salinity from land clearing and vegetation. The technology and science to underpin such an analysis has been developed. An investment in this approach to avoid salinisation in the first place is a lot more cost-effective than expensive action to combat active expression of salinisation.

Clearly, a society committed to protecting land and water resources from salinisation would take a more cautious approach to development. This precautionary approach extends to the development of new industries that, by virtue of their demand for water, will increase river salinity downstream. A more subtle precaution relates to initiatives, driven by commercial forestry, to extensively afforest the headwaters of major river systems. In these higher rainfall areas, historical clearing and associated decreases in evapotranspiration yielded greater runoff and little or no salt. Afforestation of these areas is attractive from a silvicultural point of view, but will be associated with decreased flows of fresh water downstream (Vertessy and Bessard, 1999; Zhang *et al.,* 1999). These flows are vital in diluting saline rivers.

Maintain current land use

In a number of situations, the amount of salt stored in the regolith is relatively small, the gradients are reasonable, and the rainfall is relatively high. While these areas are currently contributing salt loads downstream, there is a foreseeable horizon (perhaps only a few decades) at which discharge will begin to freshen. Eventually, farming systems yielding high groundwater recharge may contribute positively to regional water resources and dilution flows to salinity-affected river systems downstream.

Adapt to a salinising environment

There is no question that whatever Australia's response, regional river and land salinity will continue to increase. Any national response must facilitate our adaptation to, and exploitation of, salinised resources. This may take the form of new saltland farming (Stirzaker *et al.,* 2000; Walker, 2000), inland mariculture, or other new extractive industries. Another form of adaptation is to find alternative sources of fresh water for towns and industries that currently rely on salinising sources. In this context, aquifer storage and recovery of urban runoff and desalination are both being tried, but it is too early to be certain of their effectiveness.

Adopt engineering approaches to mitigate against salinisation

Enhancing drainage to control high-saline watertables, or intercepting saline groundwater by pumping to evaporation basins, can be effective strategies for controlling salinity, especially in cases of extreme necessity and urgency (see Figure 10 for brief description of a salt interception arrangement). Given the immediacy of salinity risk and the impact of salinity on important built environments (e.g. 80 townsites) and natural assets (e.g. key Ramsar wetlands), no solution involving recharge control will afford timely protection, and Australia will have to look to engineering approaches to protect these assets. Similarly, large areas that are already affected, such as the regional valley systems in Western Australia, are in such an advanced state of salinisation that no form of recharge control is likely to maintain current farming enterprises. Local and regional drainage schemes are in operation, under development, or planned as part of the mix of activities aimed at keeping farmers in business.

With any engineering solution, the crucial issue is the disposal of the saline drainage water. The management of the salt that must accumulate in all such schemes poses a significant environmental hazard. Careful feasibility studies, due diligence and understanding the environmental impact are essential. The degradation of rivers through disposal of salt can not only destroy fresh water ecosystems but equally, it can damage natural saline river ecosystems. While many rivers in Western Australia and South Australia are already salinised, and further salinisation may be acceptable, this is not the case in the MDB, where much care and attention will be required in the case of these engineering solutions. This inherently involves the trade-off between on-site benefits and off-site effects. In many out-salinising catchments, however, the systems are either so thoroughly degraded already, or on such a steep trajectory towards degradation, that the consequences of drainage to further salinisation of the rivers may be acceptable to protect high value assets.

Reduce recharge

The most widely promoted response to salinity control is to restore the original water balance (or best approximation) to ensure catchments are not leaking water in ways that mobilize salt. Leakage (see Figure 11 for the influence of tree clearing) can be much greater under current agricultural systems than under natural vegetation (Holmes, 1971; Williams *et al.,* 1997; Williamson, 1998; Walker *et al.,* 1999). It occurs when the plant/soil system cannot cope with the amount of water that has fallen over a period of time. The magnitude and the periodic nature of deep drainage or leakage is caused by a complex interaction between soil, climate, amount and distribution of rainfall and vegetation characteristics such as canopy and root development.

Controlling salinity by reducing recharge requires a major shift in the water balance towards that existing in the vegetation of native ecosystems (Hatton and Nulsen, 1999). This is generally due to the extraordinarily low transmission (discharge) capacity of most of the aquifers at risk. It is so low they rarely accommodate more recharge than that originally generated by the native ecosystems, without raising watertables (Salama and Hatton, 1999). Therefore, the approach must encompass and foster genuine commitment to change and improvement, so that our land uses and land management practices better match the capacity and capabilities of the land and meet performance standards for water balance.

The onerous recharge target implied above has two aspects. The first is the long-term average recharge rate under a particular land use; the second is the scale at which the land use must be adopted to effectively control groundwater discharge. The first aspect becomes a key issue when radical change in land use is advocated to address the cause of salinisation. It is often assumed that there are land uses available that will control salinisation and generate sufficient wealth to support a viable rural community. For most of the cereal cropping regions of Australia, this is not so. We have very few farming systems that can control salinisation and support economically viable communities (Stirzaker *et al*., 2000; Walker *et al*., 1999). It seems that policy developers and most scientists remain reluctant to face this critical issue. The cause of salinity can only be brought under control by the development of new industries and land uses based on deep-rooted perennial plants that are commercial, able to generate attractive farm incomes and control the leakage beneath the root zone at levels similar to native vegetation. This is a most demanding task and will require a long-term, well-focused and funded strategy of research and development and on-farm innovation.

Recent reports about the effectiveness of current farming systems in the control of dryland salinity (Stirzaker *et al*., 2000; Walker *et al.,* 1999) evaluated the role we can expect our current farming systems to play in controlling salinity in the future. The reports establish the prospects for new farming systems if they are to be part of strategies to control salinisation by treating its cause. It is ironic that Australia is a continent that lacks both water and nutrients, yet land and water degradation, such as dryland salinity, results from an excess of water and nutrients leaking into parts of the environment where they can cause destruction (Williams, 1991; 1995; 1999). This immediately raises the prospect that if we can develop farming systems that make full use of available water and nutrients, they may be both more productive and ecologically sustainable. Unfortunately, in large areas of regional Australia we do not have farming systems that will do that at the moment (Stirzaker *et al*., 2000; Walker *et al.,* 1999). This is demonstrated in Figure 12 and in Petheram *et al.* (2000) for a range of crops and pasture systems across the MDB.

Discovering and building new land-use practices that meet these essential criteria will require solutions to scientific and technical problems that are many, complex and difficult. At present, there are few such biophysical solutions on the horizon (Figure 12) and the extensive review of field estimated recharge rates under annual, perennial and trees by Petheram *et al.* (2000). Most, if not all of our current agricultural systems, have leakage rates to groundwater systems that greatly exceed the drainage capacity of the landscape. Little work has been done on the use of native plants, their genes and the processes these plants use to capture water and nutrients. There are serious gaps in our ecological and biogeochemical understanding of the rehabilitation process in Australian landscapes (Fitzpatrick *et al*., 2000). There is good evidence that there is very strong hysteresis in most biophysical processes associated with landscape rehabilitation and renewal. For instance, once the watertables rise following clearing, the redox status of soils changes and subsequent reversal on rehabilitation releases a spectrum of chemical effects, ranging from acid sulphate conditions to mobility of Fe, Al and silicon. The implications for water quality are significant. Re-afforestation to reduce ground-water recharge will usually result in reduction in water yield. These are just two illustrations of the strongly interacting biophysical processes that must be addressed in landscape rehabilitation and renewal.

With our present knowledge and capacity in system synthesis we may solve one problem only to generate others. There are encouraging prospects for new solutions arising from research, development and innovation (Stirzaker *et al*., 2000). However, these innovative solutions, which may lead to revolutionary new ways to use the land, will need to be incorporated into the landscape not only to help deal with the growing problem of salinity, but also to maintain native biodiversity, water resources, and community well being.

One robust biophysical solution is to plant trees and expand remnant native vegetation. There is no question that establishing trees in most of the drier country at risk (<750 mm of annual rainfall) will essentially eliminate groundwater recharge (Hatton and Nulsen, 1999; George *et al.,* 1999). However, the control that trees are likely to exert on water tables is only local to the plantings (George, 1990). Further, we lack tree crops that can compete economically with current farming systems in this dry end of the system (Hajkowicz and Young, 2000; Stauffacher *et al.,* 2000; Stirzaker *et al.*, 2000).

Even with attractive, alternative land uses that do not leak substantial amounts of water to saline aquifers, the issue of scale remains. The most widespread and pernicious impacts of salinity are, and will be, associated with more regional groundwater systems. In such systems, most of the landscape will require recharge control (Bari, 1998; Hatton and Salama, 1999). Changed land use on this scale is a heroic challenge, economically and socially. A significant aspect of this challenge is the timescale of response. While it is possible for local catchments to respond to best management practices within several years (e.g. George, 1990; Bari and Schofield, 1991), the larger regional and intermediate systems may take upwards of 50–100 years to show any response at all. If we fail to achieve the required scale and intensity of intervention by changing land use, we will gain some time, but achieve little else.

CONCLUSION

Changes to the Australian landscape over the past two hundred years or so have resulted in the widespread and rapidly growing problem of dryland salinity. Farmers were among the first to be affected, through salinisation of rivers and agricultural land. It is becoming clear that regional and urban infrastructure, such as water supply, roads and buildings, as well as biodiversity, are also at risk. It is perhaps our most serious natural resource management issue. While landholders will have a crucial role to play in reshaping the nature of agriculture and land use in Australia, landholders and rural communities cannot and should not bear the economic burden alone: scientists, politicians, and society as a whole must work together to find solutions. The enormous level of intervention needed to deal with dryland salinity, and the landscape's slow response to any changes, mean that now is the time to devise new ways of managing the problem or of implementing the variety of existing responses.

Options must recognise the geographic scale of the problem and ensure that investigations and actions take place at the appropriate scale, typically regional or catchment-wide. They must address the diverse nature of the issue, and deal simultaneously with the biological, physical, social, economic and institutional factors involved. Where possible, they must ensure that proposed solutions address causes rather than merely ameliorate symptoms or transfer the salt damage to another segment of the landscape. For example, many of the engineering options essentially intercept the saline water and store it as safely as possible, while the water that was lost to productive purpose in the first place is evaporated. However, where local built and natural assets are at immediate risk, engineering interventions may be required and justified. In any event, we will be faced with the need to devise productive uses of salinised resources. This includes effective engineering solutions as well as new industries based on saline land and water.

Much of the activity currently associated with salinity control will not ultimately protect the built or natural environment. Rather, it gives us time to employ management strategies that make sufficient changes to slow down the onset and expansion of dryland salinity, but eventually allow it to reach a new, more saline equilibrium. A combination of ‘buying time’, devising appropriate agriculture and land-use patterns to control leakage, and developing strategies and production systems for adapting to a salinising environment, seems the best overall approach, combined with a commitment to limit those activities that have contributed toward salinisation in the past. The magnitude of the required response is huge, but Australia faces little choice.

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Figure 5. Schematic diagram of groundwater flow with geologically constrained discharge that is common in the Australian landscape. This makes it easy for leakage to groundwater from agricultural crops and plants to exceed the discharge capacity and drive the rise in watertables and the salinisation process. The native vegetation had leakage rates to groundwater that were similar, over time, to the discharge capacity.

Figure 6. Schematic diagram of the dryland salinisation process following clearing of native deep-rooted perennial vegetation and its replacement with annual crops and pastures.

Figure 7. The salt loading from the landscape to the Murray River, from the eastern highlands in New South Wales and Victoria to the estuary in South Australia (redrawn from Jolly *et al*., 2000a).

Figure 8. The salinity trends over time in the Murray River at Morgan, South Australia (redrawn from Stirzaker *et al*., 2000).

Figure 9. Management options for salinity control. Option A is to do nothing; option B is to change land use and slow down the rate of salinisation but adjust to living with the same extent and severity; option C is extensive and radical change in land use to slow the rate of salinisation and reduce its extent and severity; option D seeks to reverse the extent and severity (redrawn from Walker *et al.,* 1999).

Figure 10. Schematic diagram of salt interception scheme. To reduce salt loading to the Murray River, salt is intercepted by pumping saline groundwater as it moves towards the river and holding it in large evaporation basins where the water is evaporated and the salt concentrated. The opportunity to use the concentrated salts for industrial purposes is being explored and developed. Note that the water is essentially wasted as it originally leaked past the root zone of the agriculture, only to be evaporated without ever having passed through a plant.

Figure 11. One hundred years of simulated deep drainage (leakage) beneath trees and perennial native grass compared to perennial native grass pastures for a deep permeable soil in the semi-arid tropics of North Australia near Charters Towers, Queensland. Note the greatly increased leakage beneath the grass and the strong periodicity of the leakage driven by the highly variable monsoon rainfall pattern (redrawn from Williams *et al.,* 1997).

Figure 12. Simulated average deep drainage (leakage) along a rainfall gradient across the Murray-Darling Basin for a series of cropping and pasture production systems compared to estimates of the landscape's drainage capacity. Most agricultural systems have leakage rates many times greater than the drainage capacity of the landscape (redrawn from Stirzaker *et al.,* 2000).