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Farming Without Harming – A Challenge for Soil Science

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Abstract
Land and Water damage resulting from farming the Australian landscape is well documented. Much of this degradation is the consequence of agro-ecosystems that are leaky with respect to carbon, water and nutrients. The challenge before soil science is to find plant production systems that can capture this waste and turn it into wealth creating products and ecosystem services. Soil science will need to lift its gaze beyond the profile to the dynamics of soil processes at the scale of catchments and landscapes. This presents a major challenge for soil science.

Background and matters of principle

Soil function is central to ecosystem function and ecological sustainability. Soil is a seething foundry in which matter and energy are in constant flux as it provides the support services for ecosystem primary production. A rich mix of mineral particles, biota, organic matter, gases, water and nutrients, soil constitutes a self-regulating biological factory essential for initiation and maintenance of life. Soil determines the partitioning of rainfall, snowmelt or irrigation into overland flow, infiltration, storage, deep drainage and, in turn, groundwater recharge. The way soil accepts, stores, and transmits water and associated solute, strongly influences the nature of rivers, springs, lakes and wetlands. Organisms in soil recycle residues converting them to nutrients and other compounds thereby providing the primary cleaning and recycling function for ecosystems.

This critical role of soil in ecosystem and landscape function has rarely been the focus of soil science. Much of soil science has been directed to serving a single production focus in agriculture. This is reflected in the fact that most Soil Science Departments at our Universities have been historically linked with agronomy and agriculture. Few have been formally associated with ecology, ecosystem studies or earth science, although a trend towards association with natural resource management is increasing.

Over the last decade there has been a clear recognition in the move towards ecologically sustainable development that this single focus on production has led to degradation of the natural resource and the environment. There is now increasing awareness that ecologically sustainable land and water management requires a shift to an ecological approach which studies agricultural production in the agro-ecosystem in which it is cast within the broader landscape. Soil function is fundamental to ecosystem health and environmental quality. It is therefore imperative that the soil science community moves its attention to increasing knowledge and understanding of these life sustaining processes in the soil. The challenge before soil scientists is to direct thinking and effort to the processes in the soil, which are critical to a better understanding of ecosystem function as a basis for more sustainable management of

Australia's land and water resources. In this way, soil science can play a key role in providing the scientific knowledge urgently required for more sustainable management of our ecosystems in the Australian landscape.

Rural production has played a key role in Australia's economic development, but it has had a profoundly detrimental impact on the quality of the land and water resources. Australian rural production systems have been built by drastically changing the nature and seasonal patterns in the hydrological and nutrient cycles of the native ecosystems. Tropical rainforest made way for sugarcane monoculture; semi-arid clay plains became irrigated croplands; and heathlands on sand plains were converted to wheat, canola and lupin fields.

Consequently, the exotic agricultural production systems of Australia's rural industries all face a common core of resource and environmental problems. These settle about the management of soil processes that determine the match between the sinks and the sources of water and nutrients in the ecosystem. Most of our farming operations leak water and nutrients. It is this very leaky nature of Australian agro-ecosystems, which lies at the heart of nearly all land and water degradation issues. This leakage results in waterlogging, mobilization of salt and other chemicals through the landscape, leaching of nutrients to generate soil acidification and leakage of nutrients to water bodies. We desperately need new biophysical solutions which can plug leaky systems and capture the water and nutrient for productive purposes. It is ironic that in Australian agriculture, where the shortage of both water and nutrients greatly restricts yield, it is the loss of both precious water and nutrient beneath crops and pastures that is the fundamental cause of both salinity and acidification. This immediately raises the prospect that if we can develop systems that make full use of available water and nutrients, they may be both more productive and more ecologically sustainable. At the moment, unfortunately, we have few, if any, such solutions.

Our best farming practices have not been designed, at the outset, to operate in harmony with the uniquely Australian ecosystems in which they are cast. Progress towards ecologically sustainable development as reflected in improved quality of the natural resource, will be made when our land use practices have ecosystem and landscape functionality which match those operating in the native ecosystems and landscapes.

For success in this goal, the scientific effort must first recognize that the soil/plant/animal agro-ecosystems must be studied in an integrated way and examined as part of the larger-scale ecological and hydrological processes that operate over the landscape. The solution must incorporate these functions at a range of scales including paddocks, hillslope, catchment, whole landscape and the regional basin. The landscape design will need to integrate sustainable production and maintenance of biodiversity for the catchment and region. Any revegetation program must have multiple objectives and, therefore, be designed to restore ecosystem function: hydrology, nutrient cycling, movement of biota and maintenance of habitat. Focus on short-term animal or plant productivity without consideration of the consequences on the other essential components of the agro-ecosystem and the larger-scale landscape processes, can be shown to be a primary cause for degradation of the natural resource. The way in which the production system interacts with the hydrological and nutrient balances, and the implications of these interactions for the longer-term stability and ecological functionality, has been neglected or studied in isolation from the production system. The first step in our search for an ecologically sustainable agriculture, requires that we address agricultural production as an agro-ecosystem which is part of the larger-scale ecosystem and landscape processes. Knowledge of how best to rebuild the Australian landscape and implement farming systems and land use that is ecologically sustainable and which can support viable rural communities, is critical to any regional development plan. At the moment, we run the risk of stumbling from solving one problem whilst creating another.

In the light of these driving forces, and the fact that knowledge of soil processes can make a key contribution to finding solutions to the causes of land and water degradation, it is timely that action be taken to refocus soil science on the fundamental role it has in ecosystem and landscape function. In this paper I will seek to apply these principles to the issues soil science will need to address in order to find solutions to dryland salinity.

The Australian landscape—a dry, salty and stable landmass

Australia's geological history makes it quite different from most other parts of the world. Australia, South America, Africa, India and Antarctica were once part of a large southern landmass called Gondwana. While these continents were joined, animal and vegetable life flourished in the favourable climatic conditions. The biomass deposited during this period accounts for our extensive coal deposits. Around 120 million years ago, Gondwana began to break up. Australia broke free from the other remnant, Antarctica, as late as 50 million years ago.

Compared to other continents, Australia has been geologically stable, with little volcanic or seismic activity. This stability meant there was very little extrusion of volcanic lava onto the surface and few high mountain peaks were formed. Without the surface lava, the rich soils common to volcanic regions did not develop. With few mountains, the continent also lacks deep, rich soil formed via the weathering action of glaciers.

As the Australian continent drifted northward its climate became drier. Hard leaf sclerophyll plants and eucalypts replaced most of the lush temperate and sub-tropical forests of conifers, cycads and ferns. The new plant varieties had to adapt, not only to the drier conditions, but also to the lack of deep fertile soils. Under these dry and infertile conditions, trees and plants with deep and thick root systems dominated.

Erosion through time has led to the accumulation of sediments, sodium chloride and other salts. The accumulated salts are derived principally from the surrounding oceans and carried inland in spray and rain; some are released from weathering rocks. In turn, over tens of millions of years, the salts are deposited, trapped and gradually accumulate in the soils, regolith (the partially weathered material between rock and surface soil), lakes and groundwater. Since the continent is flat, and dominated by a gentle fall towards its interior, most rivers and groundwater systems are very sluggish, with little capacity to drain the continent of its salt and water. As a consequence, enormous stores of salt characterise the Australian landscape.

These salt deposits are distributed widely and concentrated in the semi-arid and arid landscapes of Australia. They stretch as a huge arc from north Queensland, south, adjacent to the Great Dividing Range, then broaden and sweep south-west across the Murray-Darling Basin encompassing the Riverina and Mallee regions of New South Wales, Victoria and South Australia. In Western Australia they form a large arc from Geraldton, south and east across the semi-arid and arid landscapes of the state's south.

Across much of the continent, low rainfall compared to potentially high evaporation rates means one of the lowest rates of runoff to rivers and deep drainage to groundwater in the world—all conducive to the accumulation of salt that is not flushed out by water leaching. The saline lakes, streams and land are a natural part of the Australian landscape and native vegetation has adapted to these unusual conditions. Native plants take up most of the rain that falls, and since only very small amounts leak to the groundwater, the water table is prevented from rising because over time, the drainage capacity of the landscape is about equal to the small leakage to groundwater. The native plants have evolved a fragile balance to manage the low rainfall and large salt stores in subsoils, regolith and groundwater.

Native vegetation evolved to balance salt and water

Trees, woody shrubs and perennial grasses comprise much of Australia's native vegetation. This perennial vegetation, with its relatively deep, dense, root systems, takes full advantage of any available water, thereby minimising the amount of water that leaks past the root zone to groundwater.

Unlike deciduous trees and shrubs, which have no leaves for a significant part of the year, rain is caught on the leaves, stems and branches of the evergreen Australian natives. This, combined with the high rates of evaporation over most of Australia, reduces the amount of water reaching the ground. Any water making it to the ground tends to run off or be slowly absorbed into the surface soil where the dense root networks of native trees, shrubs and grasses, trap and store it, allowing little to seep through into the groundwater. Thus the leakage to groundwater is kept small and aligned to the drainage capacity of the landscape by means of water moving as run-off, interception, and for the most part, evaporation. By contrast, the shallow root systems of cultivated grasses or crops allow considerable leakage of rain into the deeper soil. Various studies have shown that over most of Australia's dryland regions, the leakage rate in areas of native vegetation was commonly between 1 and 5 mm/year.

The evolutionary traits of our native vegetation have meant that the rate of leakage past the plant roots into the landscape's internal drainage systems is approximately equal to the drainage or discharge rates (0.5 to 5 mm/year) of water from the deeper soils of the landscape. Healthy native ecosystems within catchments are in hydraulic and salt balance. The salt discharged slowly from the catchment balances the input of salt to the catchment.

Changing native vegetation set water and salt moving—the start of salinisation

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 has substantially increased the amount of water leaking beneath the root zone (15 to 150 mm/year for cultivated grasses and crops) and entering the internal drainage and groundwater systems of the landscape. This has caused the water table to rise—bringing the salt with it into the topsoil.

The amount of water leaking into the groundwater system depends on the climate (particularly the distribution and amount of rainfall); the depth, water storage-capacity, and permeability of soils and subsoil; and vegetation characteristics. Not all the water leaking beyond the root zone necessarily ends up in groundwater. It also moves laterally through the soils to drain into surface streams. In other situations, leakage can occur from the base of streams into groundwater systems. Once the leakage beneath the root zone is increased, and this water begins to move through salt stored in the landscape, either to land surfaces and/or to rivers and streams, the dryland salinisation march has begun.

Dryland salinity and what it does to our water and land

The increased amounts of water entering the groundwater as a result of agricultural land use today greatly exceed the rate of drainage from the groundwater systems to rivers and subsequently, the oceans. In seeking a new hydraulic balance, the water table rises and in places, reaches the surface of the land, rivers and wetlands to appear as seepage at these lower points in the landscape. If this groundwater contains salt or passes through salt stored in the soil or regolith, it carries this salt up to the seepage faces; hence the land surface, streams, rivers and wetlands become saline. This can be seen in small, local, shallow groundwater seepage faces on a hill slope as the slope flattens near a stream, and in large regional groundwater basins stretching over hundreds of kilometres, where the salinisation shows on the lower parts of the basin and on the flood plains. Salinisation occurs in both dryland and irrigation farming. Replacing native vegetation with crops requiring traditional irrigation will always cause more water to enter the landscape than can drain from it.

It is possible to have salinisation of streams and rivers with very little salinisation of land if the salt is leached from the land into the groundwater, which then discharges into streams or rivers without seeping to land surfaces. This is particularly true where streams or rivers cut down into the landscape.

The warning signs of a landscape affected by dryland salinity include sick or dying trees, declining vegetation, the appearance of salt-tolerant volunteer (weed-like) species such as Sea Barley Grass and Spiny Rush, bare salty patches and saline pools in creek beds. Any of these affect the remaining native vegetation and its associated fauna, thus escalating loss of biodiversity and loss of water in rivers and streams for drinking or irrigated agriculture, while reducing crop productivity and the sustainability of agriculture on the land itself. In built-up areas, salt rising to the surface can cause building and road foundations to crumble.

Extent and impact of salinity

The National Land and Water Resources Audit's (the Audit) dryland salinity assessment—*Australian Dryland Salinity Assessment 2000*—has, for the first time, objectively defined the distribution and impacts of dryland salinity across Australia.

- Salt is intercepted by rising groundwater and transported by water to streams, rivers, and wetlands—by 2050, up to 20 000 km of streams might be significantly affected by salt. Unless the cause of salinisation is controlled, salt will continue to move to our water resources causing loss of water for drinking and irrigated agriculture and loss of biodiversity associated with our rivers and wetlands.

- Currently, 630 000 ha of remnant native vegetation and associated ecosystems are at risk—with projected potential increases of to up to 2 000 000 ha over the next 50 years. The impact on biodiversity and loss of landscape functions will be great.
- Australia rural towns are not immune—over 200 towns might suffer damage to infrastructure and other community assets from dryland salinity by 2050.
- Some 20 000 km of major roads and 1600 km of railways are at risk—with estimates suggesting this has the potential to increase to 52 000 km and 3600 km respectively by 2050.
- Approximately 5.7 million hectares (equivalent in area to about 25% of Victoria) are at risk or already affected by dryland salinity. It has been estimated, based on the best available information, that in 50 years this area could potentially increase to 17 million hectares (equivalent in area to 75% of Victoria).

How we can respond and what we can do to control salinity

Australian Dryland Salinity Assessment 2000 provides an understanding of the functioning of the major groundwater systems across Australia and the critical role this plays in interpreting and analysing the likely impacts of different management options on the control of dryland salinity.

Managing the salinisation process will involve treating the cause, ameliorating the symptoms, or a combination of both. It is essential to specify the objectives when evaluating the appropriateness of the proposed management options:

Treating the cause:

- Managing recharge to reduce (a) the rate of rise of groundwater, (b) the area of land affected by salinity, (c) the delivery of salt to water resources; and/or
- Intercepting fresh water to reduce the rate of rise of groundwater and salt delivery to land and water resources.

Treating the symptoms:

- Intercepting and storing salt and reducing the groundwater level to reduce the current and future impacts of salt on assets such as water resources, infrastructure and biodiversity; or
- Managing the current and future saline discharge using new systems and adapting to the more saline land and water conditions.

If recharge control is not implemented, all other management activity allows salt to move towards the streams and the low points in the landscape or groundwater system. In catchments where we judge it is not possible to control recharge effectively, unless salt is intercepted through engineering interventions these catchments will continue to salt their water resources until the salt store is exhausted. This biophysical reality must be central to our strategic planning for salinity management. While it is popular to promote use of salinised land for agriculture, it must be understood that unless the cause of the salinisation is brought under control, the land and its associated water resources will continue to salt. Salt will continue to be delivered to the water and accumulate in the land. In most circumstances this is not understood.

In managing the dryland salinity process we are managing salt delivery to the land surface and to streams, wetlands and groundwater. Our management options depend on successful recharge control unless we are able to engineer effective salt interception. If salty water is intercepted, the resulting salt must be stored safely. It is unacceptable in most circumstances to discharge salty water to fresh water streams. It may be justifiable to discharge to streams that are already salinised, as is the practice in Western Australia in order to protect valuable natural or build assets; however where streams are not already salinised, this is not an effective way to control salinity. Our response to salinisation will fail if all we do is pass the salt to another part of the landscape or to a downstream community.

If the results from *Australian Dryland Salinity Assessment 2000* are extrapolated across Australia, the implications are sobering. Both the extent of land use change required to effect a useful level of recharge control and the likely lag times involved in achieving a response to the treatment of the cause of salinity are far greater than policy strategy, implementation agencies and community currently recognised.

Reducing recharge requires a revolution in land use

To be effective, recharge reduction must yield leakage rates similar to native vegetation and occupy approximately 40% of a catchment or landscape. This requires a revolution in land use. The recharge under current agriculture using the best practice of the day is from 2 to 20 times greater than that required to make a significant impact. Although not widely appreciated, this is well established in *Australian Dryland Salinity Assessment 2000*. It follows the CSIRO analysis of the effectiveness of current farming systems in controlling dryland salinity that was released with the Audit. This analysis clearly indicated that few of our current farming systems can significantly reduce recharge to levels compatible with the discharge capacity of the landscape and approach groundwater recharge rates similar to those that existed under natural vegetation.

The need, market forces and opportunity for a change in land use in rural Australia are upon us. 'Business as usual' is not an option, but what are the options for change? This question has been partly addressed by a second CSIRO document—*A revolution in land use: emerging land use systems for managing dryland salinity*—released with the MDBC's *Draft Basin Salinity Management Strategy* in September 2000. Among other things, the CSIRO report concluded that we need to pioneer the development of a new landscape. This landscape would comprise a mosaic of tree crops driven by large-scale industrial markets such as biomass fuels and high value annual crops, mixed perennial-annual cropping systems, and significant areas devoted to maintaining those elements of native biota that depend on native vegetation. Such innovative solutions, which may lead to revolutionary new ways to use our 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 and community well-being.

No single land-use option will halt the growth of salinity and the loss of native biodiversity in our land and rivers. We need to develop and deploy a suite of novel land uses that are matched to the diverse climate, soils, and hydrological conditions of the areas in which they are deployed. These land uses, in combination, need to deliver leakage rates past the root zone that approach those of natural vegetation. This will require radical change to land use, incorporating:

- The development of commercially driven tree production systems and/or novel tree species for large areas of current crop and pasture zones. These would include trees to produce fruits, nuts, oils, pharmaceuticals, bush foods and forestry products such as specialty timbers, charcoal, and biomass energy.
- New farming systems comprising novel mixes of all the best current annual and perennial plants, the best agronomy, companion plantings, rotations and combinations.
- New forms of cereals, pulses, oilseeds and forages selected or bred for characteristics that substantially reduce deep drainage and nitrogen leakage.
- Refined land assessment tools that best locate native vegetation, tree crops, other perennial plants, and high-value annuals to meet water quantity and quality targets, and biodiversity goals.

Devising the optimal placement of these land uses in terms of salinity control, productivity and maintenance of native biodiversity will require a robust understanding of landscape process and function, and good maps of landscape properties, particularly salt storage and groundwater flow.

Some of these options are more beneficial than others in controlling leakage. Some are available now; others require well focused, comprehensive research, development and innovation. Further research is also needed to determine which tree-crop-pasture mixtures can reduce leakage to acceptable levels and continue to generate attractive farm and community wealth. While a vision for the new industries and prospective land uses is emerging, many of the components described above do not yet exist. A substantial new R&D effort is needed that tackles the redesign of farming and forestry systems and their integration into the landscape as a whole. This needs to combine biophysical and economic studies that deliver novel designs well matched to soil, climate and catchment circumstances including biodiversity; on-farm measurement and improved land assessment techniques; modern genetic improvement techniques; and a participatory process that engages community and land managers.

Sluggish groundwater systems mean very slow responses to land use changes
Even with a mosaic of land use that significantly reduces groundwater recharge, the response in the landscape depends on how full the groundwater system is and how sluggish the groundwater flow is in low permeability aquifers. In local and intermediate groundwater flow systems in deeply weathered rocks, even with a revolution in land use, the low permeability and low hydraulic gradients of many aquifers means it is likely to take at least 20 to 50 years before a substantial reduction in groundwater levels becomes apparent. It will take even longer before groundwater discharge is reduced sufficiently to have a marked effect on stream salinity.

Adopting land uses that partially reduce recharge levels merely delays the onset of salinisation for several decades. In the long term, only extensive or complete re-vegetation with native or other plants that have similar recharge rates would reduce groundwater to pre-clearing levels. In most situations this is unlikely to be the management goal. Partial changes in land use may well be the realistic option while the prospects for new solutions from research, development and innovation are explored and implemented.

By overlaying our understanding of the geophysical characteristics of each salinity province with the knowledge acquired from recent modelling of groundwater and land use options, we can develop a set of principles about the effectiveness of existing or radical new land use options to control salinity.

The flow systems where radical land use change might be expected to deliver whole-catchment or end-of-catchment salinity benefits within an acceptable timeframe comprise highly permeable aquifers in either local, or perhaps some intermediate flow systems. These are not extensive in the Australian landscape and are found mainly in some fractured rock aquifers in eastern Australia.

The sobering reality for most groundwater flow systems is that while reducing recharge may restrict the expansion of saline land and in some cases, even reduce its area, it is unlikely to reduce the delivery of salt to the streams, rivers and wetlands. The salinisation of the water resources in these systems is assured unless engineering interventions to intercept and store the salt are implemented.

Summary of responses to dryland salinisation

Protection and prevention that avoids initiating the dryland salinity process is a primary option because the sobering evidence gathered by the National Land and Water Resources Audit shows that once the process commences, it is extremely difficult to control or manage, if not impossible in some instances. Preventing dryland salinisation to avoid its impacts on land and water resources is by far the best investment option available. Hazard assessment has confirmed that large areas of the tropics and subtropics have a potential salinity problem if clearing for agriculture occurs. Therefore in these extensive areas of the Australian continent, particularly in northern Australia, protection and prevention management options are still available. This implies that much of northern Australia can avoid degradation from dryland salinity. Robust assessment of areas identified as having a hazard, particularly areas of extensive clearing in central and southern Queensland, is required to underpin the development and implementation of vegetation management policies and guidelines designed to avoid salinisation. There is an opportunity for a major, national, well-focused investment in preventative action in northern Australia to avoid and thus contain the spread of salinisation across Australia.

Current farming system options for combating dryland salinity are very limited in their ability to achieve sufficient reductions in recharge both at the scale at which they would need to be applied, and in the delays in influencing regional, intermediate and many local groundwater flow systems. Farming, agro-forestry and forestry systems will also have to demonstrate economic benefits in their own right if they are to be adopted at the required scale. There is urgent need for new industries based around perennial woody plants that are commercial and that control recharge to levels approaching the drainage capacity of the landscape. Researching, developing and building these new industries must be core business in finding long-term solutions to the salinisation of the Australian landscape. No single option is likely to work in isolation and most situations will require a suite of ‘tools’ to be implemented to manage salinity effectively. A new mosaic of land uses is urgently required.

The challenge to Soils Science

Australia's geological history has created a unique, very ancient, very flat continent that has accumulated enormous amounts of salts in the soils, regolith, lakes and groundwater. Most of our rivers and groundwater systems are sluggish, with only a small capacity to move salt from the continent. Thus our farming systems must be able to work in a land that is old, flat and salty. Unfortunately our current farming based around annual crops and pastures does not work well in such a landscape because they leaks far too much water past the roots so that much more water enters the landscape than leaves the landscape. Groundwater rise as the landscape fills causing the abundant salt stores to be moved to valley floors, rivers, wetlands.The challenge is to build a mosaic of commercial land uses that yield food and fibre and which are ecologically sustainable coupled with native ecosystems that provides a suite of Ecosystem Services which are valued and paid for by stakeholders and beneficiaries. We also need to develop innovative and inclusive approaches that permit fair comparison of market and non-market values. Developing the concept of valuing of ecosystem services as part of this process is increasingly important.

In this context of dryland salinity where is soil science? It appears to be caught functioning at scales that cannot be readily moved from the soil pit to the catchment or landscape on one hand or to the root rhizosphere on the other. For instance the use of soil properties and processes measured at traditional scales to predict or interpret the behavior of hillslopes, catchments and water bodies remains beyond reach, and to some represents folly. Maybe it is an example of "trans-science" as described by John Philip many years ago. If it does then soil science is faced with much more serious soul-searching than originally anticipated.

New solutions to salinity will require soil science to be able to work with the small slowly changing residual terms of the water, nutrient and carbon balances and cycles. These small terms we neglected when buried in a production focus but are the drivers and determinants of the fundamental land and water degradation processes. Soils science will need to find ways to take this detailed process knowledge and apply it at the scales of the catchment. As it does this I think we are about to witness a new dawn for our much-loved science. Certainly the young scientists who are tackling this gives me ground for hope

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