Redesign of plant production systems for Australian landscapes

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Abstract

While rural production has played a major role in Australia's economic development, it has had a profoundly detrimental impact on the quality of land and water resources. Australia's geological history has created a unique, 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 landscape that is old, flat, salty and driven by a dry, highly variable climate. Unfortunately, most of our European style of agriculture, pastures and annual crops is ill suited to this landscape. The resulting land and water damage is well documented. Much of the degradation is the consequence of agro-ecosystems that leak carbon, water and nutrients. This poses a major challenge for agronomy and soil science: to find plant production systems that can capture this waste and turn it into wealth creating products and ecosystem services as part of the development of a new rural landscape. To achieve this goal, soil science and agronomy will need to lift its gaze beyond the crop plot, soil profile pit to the dynamics of soil and plant community processes at the scale of catchments and landscapes.

Background and matters of principle

Soil/plant 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/plant interactions determine the partitioning of rainfall, snowmelt or irrigation into overland flow, infiltration, storage, and 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/plant interaction in ecosystem and landscape function has rarely been the focus of soil science and agronomy. Much of both disciplines have been directed to serving a single production focus in agriculture. This is reflected in the fact that most soil science and agronomy departments at our universities have been historically married to agriculture, with only fleeting connections with ecology and the earth sciences. Few have been formally associated with ecology, ecosystem studies or earth science, although a trend towards association with natural resource management is increasing.

In the move towards ecologically sustainable development over the past decade there has been a clear recognition that this single, very narrow focus on agricultural 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 that studies agricultural production in the agro-ecosystem in which it is cast within the broader landscape. Soil/plant interaction and function are fundamental to ecosystem health and environmental quality. It is therefore imperative that the soil science and agronomy community moves its attention to increasing knowledge and understanding of these life-sustaining processes in the soil, the catchment and the landscape. The challenge before agricultural scientists is to direct their thinking and effort to the processes in the soil/plant system that 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 and agronomy 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 that lies at the heart of almost all land and water degradation issues. This leakage results in waterlogging, mobilisation 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 that 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. We will only make progress towards ecologically sustainable development as reflected in improved quality of the natural resource when our land use practices have ecosystem and landscape functionality that match those operating in the native ecosystems and landscapes.

To achieve this goal, the scientific effort must first recognise 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 that 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 between solving one problem and 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 soil science and agronomy refocus on their fundamental role in ecosystem and landscape function. In this paper I will seek to apply these principles to the issues soil science and agronomy will need to address in order to find solutions to dryland salinity. A focus on dryland salinity is important because of the profound impact that our current annual crops and pastures have on the increased volumes of water leaking into the landscape and thus driving the salinisation of our rivers and land.

The Australian landscape—a dry, salty and stable landmass

If Australia's geography and climate had been similar to those of North America and Europe, our current agricultural and pastoral systems would not have caused the major problems we now face. But the geography and climate of this continent are very different to those of the Northern Hemisphere landmasses.

Australia's geological history has created a unique, very ancient, very flat continent that has accumulated enormous amounts of salts in its soils, regolith, lakes and groundwater. The continent has been geologically stable, with little volcanic or seismic activity. With few mountains, it also lacks deep, rich soil formed via the weathering action of glaciers.

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 landscape. They are concentrated in the semi-arid and arid landscapes of Australia.

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 in the landscape

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 (15–150 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.

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

Australian Dryland Salinity Assessment 2000[1] 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 engineering interventions are used to intercept salt, 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.

The options for change

The urgent need, the market forces, and the 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 was addressed in a preliminary analysis by a CSIRO document[2]—*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 advocated the urgent need to pioneer the development of a new rural landscape. The case and general biophysical direction for a revolution in land use was set down.

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 capture multiple benefits such as maintaining 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 focused, comprehensive research, development and innovation; while others will need the building of whole new industries, where markets and infrastructure are all awaiting to be conceived and brought to birth.

Continuing pragmatic research will bring the biophysical together with the economic and social to determine which land use mosaics of native vegetation, trees, crops and pasture can reduce leakage to acceptable levels and continue to generate attractive farm and community wealth.

issues

A revolution in land use considered emerging land use options and identified some of associated the redesign issues. These are surveyed below.

The authors discussed commercially driven tree and tree/crop options in terms of high-rainfall trees products (where annual rainfall exceeds 800 m), low rainfall tree products, and agroforestry.

High rainfall tree products such as sawlogs and pulpwood are both profitable and more effective in reducing leakage than any other land use. However, where high rainfall catchments are already flushed of salt, they are more valuable as contributors of fresh water in their cleared state. Therefore long-term research is needed to extend profitable forestry in a way that maintains water yield.

Low rainfall tree products are potentially the most effective land-use option for managing salinity by reducing leakage, but given the lack of markets to drive reforestation and/or re-vegetation at the necessary scale, this is not a commercially viable option. A major, well-focused research effort will be essential to develop new markets as well as the tree crops and forestry products listed above.

The careful location and arrangement of trees can increase their water access and growth rates and minimise the displacement of more valuable crops. Tree/crop mixtures are therefore highly relevant and more profitable than tree crops alone. Their effectiveness will depend on the area planted to trees, and on the skill of locating trees in the right parts of the landscape. Finding trees that are complementary to cropping or pastures remains a major obstacle. Further research is needed to determine which tree/crop/pasture mixtures can reduce leakage to acceptable levels and continue to give economic return. It will build on and benefit from work essential to the development of commercial tree crops and new agricultural plants.

Trees can also be tactically and profitably deployed in other ways. For example, identifying niches in the landscape particularly suited to trees or unsuited to cropping is a way of shifting the balance to woody perennials at least cost to the landholder. Thus convergent or concave hillslopes that contain waterlogged, salinised or eroded areas can be ideal locations for tree planting. Tree belts are particularly suited to the high rainfall pasture zone, where it is clear that pastures do not use all the rainfall. New techniques are being developed to identify areas where trees can be tactically deployed by siting them over areas with particularly large salt stores so that this salt is not mobilised. Along similar lines, yield mapping—the real-time measurement of grain yield during harvesting—can be used to help identify bad spots in single paddocks. These may be either season specific or due to shallow soil, sodicity or other toxicities that consistently reduce crop yield. Such areas may never be profitable under cropping. Revegetation with perennial vegetation that is suited to the particular impediment would reduce both recharge and the variable costs associated with cropping.

Annual cropping is the preferred economic option but it is not effective in attaining leakage targets and offers little opportunity for agronomic research to reduce leakage. Different cropping systems can reduce leakage beneath rotations with annual crops (eg opportunity cropping, which rotates winter and summer crops that are sensitive to the water conditions of soil), or make annual crops behave more like perennials (eg phase farming or companion farming, which combine and alternate perennials with annual crops).

Opportunity cropping is profitable, robust and moderately effective where summer-dominant rainfall coincides with soils that have high water holding capacity. An applied research effort on suitable crop/soil/rainfall combinations could yield improved systems in terms of salinity control and profitability.

The greatest obstacle to controlling leakage in annual cropping systems is season-to-season variability in rainfall. Any sustainable system must have the capacity to deal with the wetter-than-average years that contribute most to drainage. This can only be achieved using perennials. Phase farming is effective when the lucerne phase is long enough to dry the subsoil and the cropping phase is terminated before leakage recommences. Research over the next five years should overcome dependence on lucerne and fine-tune the application of phase farming to improve profitability and drainage outcomes. Companion farming is an emerging concept in which annual cereals are oversown into a perennial pasture system, which may be native grasslands or deep-rooted legumes such as lucerne or other novel species. Oversowing annuals into winter dormant perennial pastures may be a way of addressing year-to-year variability in leakage and the technical difficulty of changing phase. Research is needed on species and agronomic practice to provide viable systems.

Research progress in redesigning plant production systems

To be effective, recharge reduction must yield leakage rates for the catchment similar to native vegetation such that the recharge rates into the landscape are no greater than the capacity of the landscape to discharge this water to rivers and streams. This requires the revolution in land use noted above.

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 by the comprehensive work reported in NLWRA[1]. Before this, the CSIRO analysis of the effectiveness of current farming systems in controlling dryland salinity[3,4] 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 redesign of plant production systems for Australian landscapes becomes an imperative. Yet progress has been small and has focused on establishing a sound experimental and theoretical base for the increased leakage rates beneath agricultural systems compared to native systems preliminary. This understanding is fundamental to the design of future farming systems that do not drive salinisation or acidification processes.

Phase 1 of the Redesign of Agriculture for Australian Landscapes (RAAL) R&D Program was largely completed at the end of 2001[5]. The goal of this joint initiative of Land & Water Australia and the CSIRO is to design novel agricultural systems that ensure economic production and economic sustainability by matching these systems to the unique biophysical characteristics of the Australian environment. Phase 1 confirmed that either agricultural production systems will need to be substantially redesigned, or that land use will need substantial change, or that as a society we will need to be prepared to live with resource degradation.

The major outputs and findings of the projects include the following:

- In southern Australia, the amount of deep drainage beneath different plant communities varies significantly with climate (mean annual rainfall) and with soil characteristics (particularly sand/clay content). Measured figures for agricultural systems range from 0 (lucerne) to over 200 mm pa (wheat/lupin rotation on a sandplain soil), with most in the range 10–80 mm pa. The limited data available for native plant communities shows a similar range, from 0 to over 300 mm pa, with most figures in the range 1–50 mm pa. Where comparisons are possible between adjacent agricultural and native plant communities, deep drainage between the agricultural systems is approximately an order of magnitude more than that under the native system.
- The differences in deep drainage between agricultural and native plant systems are proportionately less in higher-rainfall zones, where drainage increases under both. The proportion of rainfall accounted for by deep drainage is also strongly influenced by its seasonal distribution. In parts of southern Australia where annual rainfall is mostly received in the colder winter months, deep drainage is likely to be higher under agricultural systems than in districts where rainfall is more evenly spread throughout the year.
- Overall, the data suggest that for dryland farming systems within a rainfall zone of 450 mm pa or above, deep drainage beneath agricultural systems will need to be reduced by at least 30-60 mm pa before these systems begin to match the water use performance of native plant communities. This is a huge challenge to current annual based systems.
- Data on annual nitrogen losses from agricultural systems range from 2 kg N/ha (a limed perennial pasture) to nearly 60 kg N/ha (wheat/lupin rotation on a deep sand). There is little information on nitrogen losses under native plant communities, but we could expect them to be low given the evidence of tight cycling of minerals between standing biomass, leaf litter and surface root systems.
- Important functional differences exist between annual crops and perennial plant communities. The essential difference between the two systems is therefore related to depth of rooting and water use, and potential for year-round growth versus a limited growth period each year

(reflecting the mix of winter-active and summer-active species in the native community). It should be noted that water use by annual crops from the upper soil levels is usually higher than that of native plant communities from this part of the profile.

- Agronomic practice on their own can make a difference to the amount of rainfall lost by deep drainage, especially in areas where the excess of rainfall over crop water use is limited or in drier years in wetter climates. However, in terms of water leakage beneath the root-zone, the performance of agricultural production systems based on annual plants, or where perennial plants are regularly grazed to optimise production, remains a very long way from the performance of native plant communities.
- Field studies across different soil types and different regions in southern Australia have shown that the deep-rooted perennial legumes, lucerne and tagasaste, can withdraw water from depth during summer growth, and their inclusion in farming systems can bring the water use performance much closer to that of native plant communities. Highest water use can be achieved when these deep-rooted legumes are used strategically rather than for set blocks in a phase farming system, that is, they are planted to 'mop-up' deeper soil moisture unavailable to annual crops. In this situation, the water use performance of agricultural systems will approach that of native plant communities. However, in most situations the potential profit from these pasture legumes is well below the profit of annual crops, and this remains an important barrier to their widespread adoption.(see Figure 1)
- Methods were developed, and expanded on by other workers, to calculate the proportion of a particular landscape that would need to be replanted to deep-rooted species in order to bring local water use back to something approaching that of the native plant communities prior to clearing. This is a particularly valuable tool for use by communities in planning catchment-scale vegetation management to achieve particular goals in catchment hydrology.
- A notable feature of the Program has been the close linking of field data with simulation modelling. There is increasing acceptance of a reasonable degree of agreement between the data collected and the model simulations, leading to confidence that the model can be used to determine the likely performance of different agricultural systems in terms of water and nitrogen management. This has provided a new capacity to design and evaluate novel systems using simulations. Innovative agricultural systems developed by farmers can also be investigated as to their likely performance in water and nutrient management. There remains a requirement for validation of model outputs by comparison with field results wherever possible.
- Comparisons of agricultural and native plant communities identified critical characteristics for the sustainability performance of the latter to include, in addition to perenniality, a mix of deep-rooted and summer-active species with shallow-rooted and winter-active species.
- A number of desirable traits in crop and pasture plants that would serve to improve their performance and water and nutrient management under Australian conditions were identified. Opportunities to enhance these characteristics or to incorporate them into crop and pasture plants were identified, and provide a basis for determining priorities for further such work. Incorporating these 'sustainability characteristics' into existing and new crop and pasture plants should become a major priority for breeding, selection and bioengineering programs.

The Program has provided a sound, and to a significant extent quantitative, basis for the next steps in designing agricultural production systems that are better matched to the unique characteristics of the Australian environment.

Options and opportunities for new research

Our current crop and forage species have been bred and/or selected for yield and desirable agronomic characters. Little or no attention has been given to their ability to use water and nitrogen and restrict dryland salinisation. Breeding programs generally focus on grain yield and quality, pest control and other limitations. Few, if any, breeding efforts have focused on the role of crop and pasture species in controlling deep drainage and nitrogen leakage. In essence, crop and pasture species have not been designed with the control of natural resource degradation in mind.

However, there is some potential for selecting or breeding long season, perennial and/or deep rooted cultivars of current crop and fodder plants that may substantially reduce deep drainage and for fitting these plants into new farming systems.

A LWRRDC/CSIRO scoping study[6] examined the potential for breeding and selection to build new plants for more sustainable farming systems. It highlighted that the breeding, selection and bioengineering of annual crops and pastures can contribute significantly to ameliorating dryland salinity and acidification by reducing the leakage of nutrient and water beneath the root zone. This benefit of new cultivars is likely to be over and above current agronomic and other management improvements that are currently the focus of our agronomic effort. The study identified that while investments in breeding, selection and / or biotechnology are likely to reap short term benefits, most of the really significant opportunities will require long-term (10–20 years plus) research and development programs.

Some of the possibilities are as follows:

- Breeding winter wheat varieties, capable of being sown in February and harvested in December, with potential for increased rooting depth and water use.
- Breeding winter canola varieties.
- Breeding perennial cereals, which can grow year round, to be grazed from March to September, with grain development and harvest in December.
- Repressing the flowering gene in cereals to control the time of flowering, thereby allowing crops to be maintained in a vegetative state, and developing associated roots, all year round.
- Increasing crop transpiration by increasing plant vigour and leaf area, increasing stomatal conductance, delaying senescence, altering root / leaf signalling.
- Perennialising grain legume crops and other perennial legumes for example, native glycine, soybean, prostrate lucerne.
- Exploring the ‘resurrection’ capacity of some species to rehydrate after drying down.
- Developing spring crops, for example, safflower or berseen clover, and summer (opportunistic) crops, for example, sorghum.
- Incorporating winter or summer activeness into perennial grasses—native, introduced and improved.
- Mixtures of perennial crops and annual companions, or annual crops and perennial companions.
- Breeding sorghum (a perennial cereal) varieties suitable for southern Australia.

In summary, the immediate opportunities lie in longer season cultivars and species. Good prospects exist to develop winter wheat and canola varieties that can be sown as early as February if rainfall conditions allow, and grazed in May. They then regrow to produce a grain yield over the normal spring–early summer period. Longer term opportunities lie in the use of both improvements in conventional plants and developments in biotechnology to develop new plants with more extensive root systems, greater perenniality, and different degrees of winter and summer activity. Other traits such as enhanced early vigour, waterlogging tolerance and disease resistance would also improve their use of water. It may also be possible to add ‘resurrection genes’ to annual crops, giving them the ability to re-sprout after harvest in the event of summer rain.

While the scooping studies give every ground for optimism about what could be achieved, it important to recognise that the development of ecologically sustainable farming systems that are profitable is a very difficult problem, both scientifically and socially.

The first step is to think of farming systems as ecosystems that need to be integrated with the processes occurring in the landscape and catchment. The flow of water and nutrient to and from the agro-ecosystem need to be well matched to the flows that can be accommodated by the landscape. In most instances these flow of energy and matter will need to be well matched to that which took place in the native ecosystems.

The search for profitable farming systems that have leakage rates similar to native vegetation is in its infancy. Brian Keating introduced a simple diagram that is helpful in understanding that moving from our relatively profitable but leaky annual crops to other farming option usually require a trade-off. Most systems that have reduced leakage are also less profitable. This is demonstrated in Figure 1. To date there are few options that sit in the win-win quarter of Figure 1. The challenge before us is to build more systems that fall in this win-win quarter.

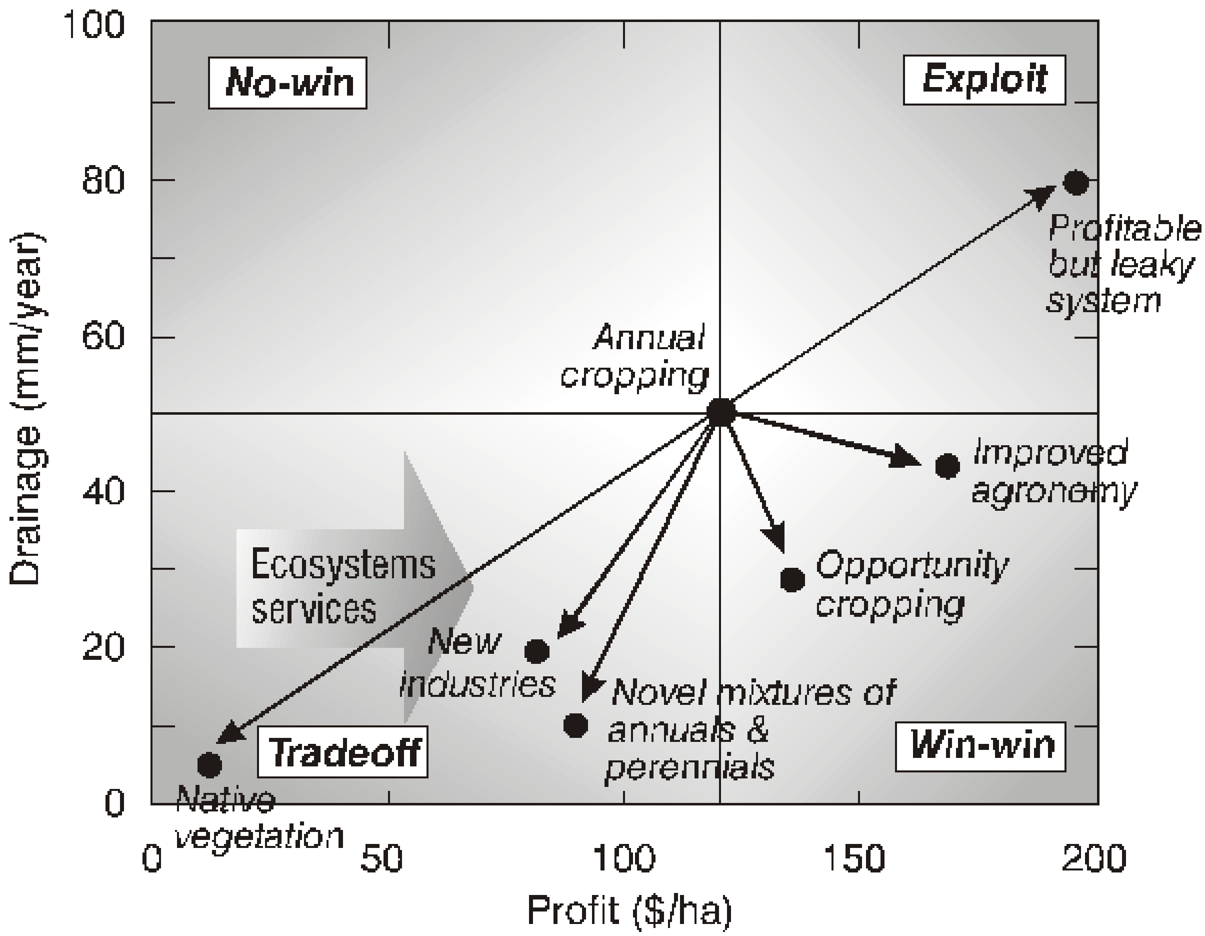

Figure 1: The profit–drainage matrix. Most of our farming system options that reduce deep drainage leakage also reduce profitability and are in the trade-off quarter. Very few farming system options reduce leakage and also increase profitability. The importance of economic benefit from sale of ecosystem services is illustrated. (This figure was developed by Brian Keating, CSIRO Sustainable Ecosystems, and is used with his generous permission.)

While a vision for the new industries and prospective land uses is emerging, many of the components described in Figure 1 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.

The challenges ahead

Even with a revolution in land use and a mosaic of land use that significantly reduces groundwater recharge, the response in the landscape will depend\ on how full the groundwater system is and the sluggishness of the groundwater flow in low permeability aquifers. In local and intermediate groundwater flow systems in deeply weathered rocks, 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.

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 on 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 synergy of more than one industry to manage salinity effectively.

Australia's farming systems must be able to work in a land that is old, flat and salty and which is driven by a dry, highly variable climate. Unfortunately, our current farming systems based around annual crops and pastures do not work well in such a landscape because they leak far too much water past the roots so that much more water enters the landscape than leaves the landscape. Groundwater rises 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 are ecologically sustainable, coupled with native ecosystems that provide a suite of ecosystem services which stakeholders and beneficiaries value and pay for. We also need to develop innovative and inclusive approaches that permit fair comparison of market and non-market values. Developing the concept of valuing ecosystem services as part of this process is increasingly important.

In this context of dryland salinity, where is soil science and agronomy? It appears to be caught functioning at scales that cannot be moved readily from the soil pit to the catchment or landscape on one hand or to the root rhizosphere on the other. For example, the use of soil properties and processes measured at traditional scales to predict or interpret the behaviour 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 so, soil science and agronomy is faced with much more serious soul-searching than I initially 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, neglected when buried in a production focus, are the drivers and determinants of the fundamental land and water degradation processes. Soil science and agronomy will need to find ways to take this detailed process knowledge and apply it at the scales of the catchment. As it does, I think we are about to witness a new dawn for our much-loved science. Certainly, the young scientists who are tackling this give me ground for hope

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