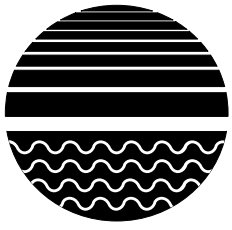
Opportunities to Breed/Select/Bioengineer Plant Species to Control Deep Drainage and Nutrient Leakage

Scoping Report July 2000

for the

Redesigning Agriculture for Australian Landscapes (RAAL) R&D Program



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The Redesigning Agriculture for Australian Landscapes Research and Development Program

The Redesigning Agriculture for Australian Landscapes (RAAL) Research and Development Program is a joint initiative of LWRRDC and CSIRO. Its mission is:

> *To design novel agricultural systems which ensure economic production and ecosystem and landscape function, by matching these systems to the unique biophysical characteristics of the Australian environment.*

Four objectives have been developed for the RAAL R&D Program:

1. To understand by comparison, the key biophysical processes affecting leakage of water and nutrients in cropping, grazing and natural systems.
2. To benchmark criteria for redesigning agricultural systems in Australian landscapes.
3. To develop a toolbox of redesign options to modify current, or develop new, agricultural systems for Australian landscapes.
4. To facilitate implementation of redesign options in priority Australian landscapes by exploring the socio-economic, institutional, policy, marketing and technological requirements and implications of each option.

The RAAL Program was initiated in 1996 as a first, but significant, step to design new agricultural systems for Australia. The RAAL R&D Program is researching how agricultural systems in Australia can be redesigned to address a range of sustainability issues. The initial focus of the RAAL R&D Program is on water and nutrient leakage, however, a range of sustainability criteria will be considered in developing redesign options, including protection of biodiversity.

The RAAL Program is being implemented in two phases. Phase 1 of the RAAL Program ran from 1997 - 2000 and has made substantial progress in understanding water and nutrient leakage in agricultural and native systems at three locations, and has identified broad principles necessary to redesign agricultural systems.

Phase 2 of the RAAL Program will run from 2000 - 2002. Phase 2 will use the outputs of Phase 1 to scope the design concepts, criteria and broad options to redesign agricultural systems against a range of sustainability criteria. Phase 2 will also provide the foundation to develop a toolbox of redesign options which are capable of being implemented in priority landscapes.

For more information about the RAAL Program contact;
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Executive Summary

Sustainable agriculture in Australia is currently facing a significant challenge as to what role annual crops and pastures can play in the control of dryland salinity and soil acidification. It is well recognised that the rotation of annual crops and pastures allows water and nutrients to move beyond the root zone, with adverse environmental consequences, including dryland salinity and acidification. In many landscapes, agricultural systems leak water and nutrients far in excess of natural systems, and far in excess of the capacity of the landscape to cope with that leakage. Work to date has suggested that annual crops and pastures are more likely to be a part of the problem than the solution, whilst perennial vegetation (agroforestry, plantations or native vegetation) is likely to be a major solution in many regions.

Crop and pasture breeding programs have successfully focused on grain yield and quality, disease and pest control and other limitations, providing an important contribution to agricultural productivity. However, few breeding efforts have focused on the role of crop and pasture species in controlling deep drainage and nitrogen leakage. It is only relatively recently that issues such as dryland salinity and acidification have become prominent. Best management practice development for crop and pasture systems has tended to first focus on improvements in yield and quality, and then any resultant improvement in water use. However the water use benefits achieved have often been incremental at best, and generally not capable of meeting specified recharge reduction targets.

The Redesigning Agriculture for Australian Landscapes (RAAL) Research and Development Program is working towards developing criteria and options to redesign agricultural systems which control deep drainage and nitrogen leakage (and address other sustainability issues) in key dryland agroecological zones across Australia.

In April 2000, the RAAL R&D Program commissioned a Scoping Study to identify and scope the possible contribution of breeding, selection and biotechnology to develop new varieties of crop and pasture plants to help reduce deep drainage of water and nitrogen. The Scoping Study aimed to use current understanding and experience in breeding, selection and biotechnology to explore how a range of functions and characteristics could be incorporated into crop and pasture species so as to control deep drainage and nutrient leakage. Scientists involved in plant improvement were invited to develop a brief paper scoping the various opportunities in terms of cereals, oilseeds, grain legumes, pasture and fodder plants, other new crops and pasture species.

The following papers were prepared as part of the Scoping Study.

- *Opportunities to breed / select / bioengineer species to control deep drainage and nitrogen leakage: temperate cereals*, Richards R.
- *Opportunities to breed / select / bioengineer species to control deep drainage and nitrogen leakage: grain legumes*, Cowling W, Lambers H, Lefroy T.
- *Perennial crops and fodders to complement annual crops and minimise deep drainage*, Downes R.
- *Developing sorghum plants with the capacity to control deep drainage and nitrogen leakage*, Jordan D.R., Borrell A.K., Henzell R.G., Hammer, G.L and Chapman, S.C
- *How can gene technology help re-design plants for an economic and sustainable agriculture in Australia?*, Chu P, Randall P, Jenkins C, Larkin P, Richardson A, Delhaize M, and Higgins TJ.
- *Opportunities for the development of oilseeds adapted to control deep drainage and nutrient leakage*, Salisbury P, Norton R.

This Scoping Study is one of a number of projects to be implemented in the second phase of the RAAL R&D Program which explore the principles, concepts, innovations and applications for redesigning agricultural systems. Research work in Phase 1 of the RAAL R&D Program has identified some of the functions and characteristics which may be required in crop and pasture species to control deep drainage and nutrient leakage, including:

- Deep roots; summer activity; perenniality; ability to grow over a broad temperature range; quick rooting growth; large leaf area and duration; ability to tolerate adverse soil conditions (eg high boron, aluminium or manganese levels); ability to tap shallow water tables; and ability to store and redistribute water and nutrients in the root system for later use.

Each Scoping Paper explores the opportunities to use breeding, selection and biotechnology to incorporate these functions and characteristics into a range of crop and pasture species. Some of the opportunities identified in the Scoping Study are:

- Breeding winter wheat varieties, capable of being sown in February and harvested in December, with potential for increased rooting depth and higher water use resulting from greater growth in the cold winter period when soil moisture is high in southern Australia.
- Breeding winter canola varieties.
- Breeding perennial cereals, which can grow year round, be grazed from March to September, with grain development during spring 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 for longer, with greater biomass production and water use.
- Increasing crop transpiration by increasing plant vigour and leaf area, increasing stomatal conductance, delaying senescence, altering root / leaf signalling.
- Improving tolerances of annual and perennial plants to disease and other constraints, eg. acid soils, so as to maximise biomass and water use.
- Extending the growing season of annual varieties by increasing the capacity to withstand high suction tensions at end of season (moisture stress), and by improving crop health through increased disease and pest resistance, increased nitrogen extraction capacity in roots, thereby increasing biomass and rooting depth.
- Increasing the range of grain legume crops and other perennial legumes so that there are varieties suitable for most farming areas and systems eg. selections from native glycine, soybean, prostrate lucerne.
- Exploring the “resurrection” capacity of some species to recommence growth after harvest and/or a period of drying and senescence.
- Developing spring crops eg. safflower or berseen clover, and summer (opportunistic) crops eg. sorghum that can be used to “mop up” soil moisture when sufficient is available in the profile as well as providing break crops and an economic return.
- Incorporating winter or summer activeness into perennial grasses—native, introduced and improved, so that in grazing systems there is some form of active leaf area and hence of water use at all times of the year.
- Mixtures of perennial crops and annual companions, or annual crops and perennial companions.
- Breeding sorghum varieties suitable for summer cropping in southern Australia.
- Incorporating characteristics in crops to allow management modification after planting to suit climate and other conditions eg genetic switches to control flowering and tillering dates to optimise water use and biomass production.

The Scoping Study has highlighted that the breeding, selection and bioengineering of crops and pastures has a high potential to contribute to ameliorating dryland salinity and soil acidification. This contribution is likely to be over and above current agronomic and other management improvements.

In addition, the Scoping Study has identified many opportunities that can be implemented in the short term. Whilst a number of the opportunities will require a long term (10–15 years or more) research and development program, the Scoping Study indicates that some short term investments in breeding, selection and / or biotechnology are likely to provide significant long-term benefits. In particular, current breeding programs for a range of annual crops and pastures (eg. cereals, oilseeds, grain legumes, other legumes) could, through relatively minor refocusing, achieve a range of beneficial outcomes for both productivity and sustainability.

1. Foreword

1.1 Richard Price, LWRRDC

The redesign of agricultural systems for Australian landscapes is more than an aspiration of a few environmentally conscious scientists. It is an imperative that will ultimately ensure Australia's unique landscapes share their productive and ecological bounty with Australians for many generations to come.

Acknowledgement of the need for fundamental change in our landscape interactions is reflected in the post Decade-of-Landcare debate, and across the wider research fraternity. Australians are maturing in the way we perceive and value our landscapes, and this shift is also emerging in our policy and managerial responses. The Commonwealth Government's discussion paper, *Managing Natural Resources in Rural Australia for a Sustainable Future*, and Murray-Darling Basin Commission's emerging response to the MDB salinity audit, both express concern about the adequacy of marginal changes to current resource use to achieve desired sustainability outcomes. Likewise, the research sector is also recognising that the challenge of sustainability within Australian contexts requires radically new modes of participatory and interdisciplinary research methods. To this end, we are witnessing a burgeoning interest among social scientists in matters that have long been dominated by the traditional agricultural sciences.

But in our haste to resolve our sustainability dilemmas, we can ill afford to overlook the technical dimensions of the problems we face. If we cannot put in place solutions that are technically feasible, all other effort is in vain. The papers in this volume were commissioned for this very reason. Each not only comments on the opportunities for the plant sciences to address the control of deep drainage and nutrient leakage specifically but, as a parcel, they contribute significantly to succinctly documenting the state of knowledge in these sciences. Perhaps more importantly, they throw down a gauntlet to the plant sciences to rethink the ultimate goals towards which they should direct themselves.

The authors are to be commended for this very useful and challenging document. It provides an excellent focal point for discussion with the many agricultural industries that now must share the challenges before us.

Richard Price
Land and Water Resources
Research & Development Corporation

1.2 John Passioura, CSIRO Plant Industry, GRDC

The need to get deep-rooted plants into the Australian agricultural landscape, plants whose roots can extract water to at least 3m depth in the soil, is beyond debate. That is the only way we can reduce to acceptable levels the leakage of water and nutrients below the roots of our annual crops and pastures, which rarely grow deeper than 1m. A few shelter belts or even trees along every fence line will not be enough. In terms of unacceptably high leakage every paddock has to be assumed guilty unless proven otherwise, and every suspect paddock in the main grain-growing areas (typically 350–600mm annual rainfall) will eventually have to have deep-rooted summer-active plants on every part of it for somewhere between 20% and 40% of the time. Furthermore, this has to be done profitably. Because perennials are generally less profitable than annual crops, the chances of incorporating perennials *and* remaining profitable are improved if the time requirement for the perennials is closer to 20% than 40%. In an important sense, this meeting was about devising ideotypes of crop and pasture plants that reduce (although they will never be able to eliminate) this time requirement. The less leakage there is under annual crops, the less is the requirement for deep-rooted perennials.

There is already a substantial effort into ideotype breeding for the Australian agricultural landscape, including the development of long-season vigorously growing crops that should both yield more and leak less, and the development of lucerne genotypes specifically adapted to "phase farming" – the use of alternating

phases of annual crops and the deep-rooted lucerne which gives promise, in some areas, of reducing by as much as two-thirds the leakage under continuous cropping.

The workshop was able to build on this existing effort. It especially highlighted the potential of incorporating into crop plants unusual physiological characters, such as the ability of "resurrection" plants to regain full function within a short time of being rewatered after extreme drought, and the development of perennial cultivars of the major annual crops. It thus stimulated the participants to think beyond the 10–15 year planning period of even the most adventurous existing breeding programs.

There is no single solution to the problem of reducing the leakage of water from our agricultural landscapes. If our farmers embrace the goal of reducing that leakage by, say, 70%, they will need to do so by grafting together many techniques and practices that might individually gain 5% to perhaps 50%. Every little helps, and the mix will vary from farm to farm, and from year to year, according to landscape, soil type, weather history, and economic requirements. As is typical of agricultural practices, these gains are likely to arise approximately equally from improvements in both agronomy and genotype. Active dialogue between breeders and agronomists will speed the rate of improvement.

John Passioura
CSIRO Plant Industry / Grains
Research & Development Corporation

1.3 Paul Trevethan, Primary Producer

Australian landscapes are in trouble. This is primarily a function of human activity and of our attempts to survive in a land that is somewhat frugally endowed with an agricultural resource base. The most obvious symptoms are soil erosion, tree decline and salinity. Less obvious are the specifics of vegetation decline, rising water tables, productivity decline and gradual move towards ecosystem dysfunction.

Many of the processes that we observe may have occurred anyway, but the intervention of humans has had a hastening effect. Whilst urbanisation and mining have had significant site-specific impacts, by far the most widespread effect on landscapes has been as a result of agricultural activities. For this reason it is important to evaluate the impact of our farming systems on the landscape.

Farmers are generally an innovative lot. Contrary to common perception, they are quite willing to change given adequate reason for doing so. The most compelling motivators for change relate primarily to economic and social well being. In this sense farmers are motivated by much the same drivers that exist for the rest of society.

It should come as no surprise that they are particularly averse to adopting technology that will head them towards financial difficulty to the point where the business will fail. It is for this reason that most farmers are wary of taking on projects that will earn them less money, involve significant additional capital investment, increase risk, delay timing of returns or require input of significantly more complicated levels of skilling.

It is unfortunate that many of the suggestions relating to the manner in which farmers should change are associated with the impediments mentioned above. One has to query whether the gradual demise of our resource base is a function of the fragility of the Australian landscape, the mismatch between capability and use or a function of a system where farmers have to compete in a corrupted global economy.

One thing is certain. Farmers will not move towards large-scale modifications in their farming practices unless their short-term goals are satisfied. Irrespective of the benefits for future generations, there is no point whatsoever in adopting a technique that will lead to bankruptcy at the end of the present financial year.

The pleasing aspect of the projects presented in this report is that they represent real possibilities for farmers to change production techniques at a pace that is acceptable from cultivation, technological and marketing perspectives. It is only through such mechanisms that meaningful and enduring change will occur.

Paul Trevethan
Primary producer

1.4 Brian Keating, CSIRO Tropical Agriculture

This scoping study sought to identify the opportunities for breeding, selection and biotechnology in the development of crop and pasture species that can better contribute to the control of deep drainage and nitrogen leakage. The papers in this volume have been very successful in identifying characteristics of current or potential future plants that may help address these challenges. However, it would be wrong to think that the identification of a potentially useful characteristic was sufficient. The possibilities raised by this study need to be further evaluated using a more formal design analysis. Where for instance and in what management system might a certain plant characteristic provide some benefit? What are the characteristics likely to provide the greatest benefits? What tradeoffs are likely between drainage reduction and production potential? It is important that

these questions be formally explored before major investment decisions are made to pursue some of the characteristics discussed in this volume in breeding, selection and biotechnology programs.

The notion that there is an important place for "design studies" in charting future directions for Australian agriculture has been an important theme in the LWRRDC / CSIRO RAAL Program. By "design studies" we mean quantitative analyses of system performance (productivity, yield, components of water and nutrient balances and acidity development) in relation to climate, soil, and management factors. The basic tools for these quantitative design studies are simulation models that can be used to explore how different plant characteristics and management practices perform under different soil and climate environments. The simple argument that underpins the deployment of models in design studies is that the interactions between plant–soil–climate and management are too complex to be fully resolved by experimental activity and human reflection alone. Simulation modelling has received some negative press over the years by those that see it as not science, but engineering at best, and cumbersome curve fitting at worst. While simulation used as a form of cumbersome curve fitting is unhelpful, its use as a form of engineering is legitimate and comes into its own with respect to the design issues addressed in this scoping study.

Engineers are good at designing solutions to defined problems. How big a beam is needed to bear a certain load? How large a road is needed to achieve a certain traffic flow? How will a certain structure perform under wind force? There are equivalent design questions in agriculture. How deep a root system is needed to capture and utilise a certain rainfall pattern? What crop duration and flowering time optimises yield? What plant population is optimal for a defined water and nutrient resource?

In both built engineering and agriculture, tools are available to undertake the design analysis. These tools are based on a combination of physical "laws", biological principles and empirical / phenomenological relationships. We place our trust in good tools in the hands of experienced engineers every day, and yet we have been slow to accept a legitimate role for engineering in the design of our plant based systems. Some would argue that biological systems are "different", but the fundamental forces driving energy, water and nutrient balances in agriculture have much in common with those at work in systems in which engineering is an accepted approach. The farming systems modelling tools have advanced considerably in recent years. Can they help to sketch out new designs that reshape our basic concepts of what are sustainable farming systems?

While the design work supported by RAAL is intended to simulate thinking and enquiry on our future farming systems, it is not seen as a substitute for the practical design activity that farmers have always engaged in and that is central to innovation in farming practice. The aim is to create and support a stimulating environment in which fundamental issues of re-design can be raised, debated and trialed. Farming systems performance in terms of many of the sustainability dimensions is not easy for farmers to clearly observe (eg long term processes, off-site impacts) and hence the research has an important role in broadening out perspectives. However, we recognise it would be a mistake to think that research can be the only or even major source of innovative design. Hence the next scoping study the RAAL Program will support focuses on farmer innovations in design of more sustainable farming systems.

Brian Keating
CSIRO Tropical Agriculture

2. Introduction

2.1 Scoping Study–Opportunities to Breed/Select/Bioengineer Plant Species to Control Deep Drainage and Nitrogen Leakage

In April 2000, the Redesigning Agriculture for Australian Landscapes (RAAL) Research and Development Program commissioned a Scoping Study to identify and scope the possible contribution of breeding, selection and biotechnology to develop new varieties of crop and pasture plants to help reduce deep drainage of water and nitrogen. The Scoping Study aimed to use current understanding and experience in breeding, selection and biotechnology to explore how a range of functions and characteristics could be incorporated into crop and pasture species so as to control deep drainage and nutrient leakage. Scientists involved in plant improvement were invited to develop a brief paper scoping the various potential opportunities in terms of cereals, oilseeds, grain legumes, pasture and fodder plants, other new crops and pasture species.

The following papers were prepared as part of the Scoping Study.

- *Opportunities to breed / select / bioengineer species to control deep drainage and nitrogen leakage: temperate cereals*, Richards R (see Section 4)
- *Opportunities to breed / select / bioengineer species to control deep drainage and nitrogen leakage: grain legumes*, Cowling W, Lambers H, Lefroy T (see Section 5)
- *Perennial crops and fodders to complement annual crops and minimise deep drainage*, Downes R, (see Section 6)
- *Developing sorghum plants with the capacity to control deep drainage and nitrogen leakage*, Jordan D.R., Borrell A.K., Henzell R.G., Hammer, G.L and Chapman, S.C (see Section 7)
- *How can gene technology help re-design plants for an economic and sustainable agriculture in Australia?*, Chu P, Randall P, Jenkins C, Larkin P, Richardson A, Delhaize M, and Higgins TJ (see Section 8)
- *Opportunities for the development of oilseeds adapted to control deep drainage and nutrient leakage*, Salisbury P, Norton R (see Section 9).

This report presents each of the papers, along with the outcomes of a stakeholder workshop (participants at the workshop are listed in Appendix 1). At the workshop, authors presented their paper and participated in discussions with a group of key stakeholders regarding the identified opportunities and their implications.

2.2 About the RAAL R&D Program

Agricultural production in Australia relies on clean and productive land, water and vegetation resources, and also promotes these ingredients as a clear point of difference in the global market place. Yet some of our agricultural landscapes are degraded, and are continuing to degrade. It is well recognised that the rotation of annual crops and pastures allows water and nutrients to move beyond the root zone, with adverse environmental consequences, including dryland salinity and acidification. In many landscapes, agricultural systems leak water and nutrients far in excess of natural systems, and far in excess of the capacity of the landscape to cope with that leakage.

Whilst we have a good understanding of the cause, extent and severity of many of these problems, the challenge is to develop new solutions which not only address these degradation issues, but which also continue to support viable agricultural industries. We must utilise our knowledge and expertise to develop new agricultural systems which match the unique characteristics of the Australian environment.

The Redesigning Agriculture for Australian Landscapes (RAAL) Research and Development Program is a joint initiative of LWRRDC and CSIRO. Its mission is:

> *To design novel agricultural systems which ensure economic production and ecosystem and landscape function, by matching these systems to the unique biophysical characteristics of the Australian environment.*

LWRRDC and CSIRO support the Redesigning Agriculture for Australian Landscapes (RAAL) R&D Program as one initiative exploring opportunities to develop new agricultural systems. RAAL is taking an innovative approach to addressing problems such as dryland salinity and acidification by focusing on how agricultural systems can be designed to "mimic" favourable functions and characteristics of natural systems.

The RAAL R&D Program is working towards developing criteria and options to redesign agricultural systems which control deep drainage and nitrogen leakage (and address other sustainability issues) in key dryland agroecological zones across Australia. One of the aspects of the RAAL R&D Program is to identify the characteristics and functions required of plant crop and pasture species in order to design production systems which are more productive and ecologically sustainable in Australian agricultural environments.

This Scoping Study is one of a number of projects to be implemented in the second phase of the RAAL R&D Program which explore the principles, concepts, innovations and applications for redesigning agricultural systems. The Scoping Study has identified a number of opportunities for breeding, selection and biotechnology to play a significant role in the pursuit of sustainable agriculture in Australia, specifically by developing new crop and pasture species which can better contribute to the control of deep drainage and nitrogen leakage.

2.3 Design Principles

Research work in Phase 1 of the RAAL R&D Program has identified some of the functions and characteristics which may be required in crop and pasture species to control deep drainage and nutrient leakage, including:

- Deep roots; summer activity; perenniality; ability to grow over a broad temperature range; quick rooting growth; large leaf area and duration; ability to tolerate adverse soil conditions (eg high boron, aluminium or manganese levels); ability to tap shallow water tables; and ability to store and redistribute water and nutrients in the root system for later use.

Each Scoping Paper explores the opportunities to use breeding, selection and biotechnology to incorporate these functions and characteristics into a range of crop and pasture species.

3. Opportunities

Sustainable agriculture in Australia is currently facing a significant challenge as to what role annual crops and pastures can play in the control of dryland salinity and soil acidification. Work to date has suggested that annual crops and pastures are more likely to be a part of the problem than the solution, whilst perennial vegetation (agroforestry, plantations or native vegetation) is likely to be a major solution in many regions. Best management practice development for crop and pasture systems has tended to first focus on improvements in yield and quality, and then any resultant improvement in water use. However the water use benefits achieved have often been incremental at best, and generally not capable of meeting specified recharge reduction targets, thereby requiring a substantial replanting of perennial vegetation to bring affected landscapes back into balance. Much of the past breeding for production efficiency has in fact lead to reduced water use A notable exception in the dryland salinity toolkit is lucerne, which has been a major success story as a perennial pasture capable of significantly reducing recharge, and providing economic returns.

The genetic improvement of crop and pasture species includes a range of technologies, including selection; cross breeding and selection; selection using genetic markers; and, selection following genetic modification using recombinant DNA (biotechnology). The Scoping Study has identified a number of opportunities for breeding, selection and biotechnology to play a significant role in the pursuit of sustainable agriculture in Australia, by breeding new crop and pasture species capable of controlling deep drainage and nutrient leakage.

The opportunities discussed in the Scoping Study are based on existing knowledge, capacity and experience in breeding, selection and biotechnology. Whilst the latter is an emerging technology which has the potential to provide long term opportunities, the proven techniques of breeding and selection have demonstrated significant opportunities. In an apparent irony, several of the design principles now seen as desirable in crops and pastures have previously been selectively repressed in agricultural species. For example, the gene for perenniality is already present in some cereal species or their relatives!

Crop and pasture breeding programs have successfully focused on grain yield and quality, disease and pest control and other limitations, providing an important contribution to agricultural productivity. However, few breeding efforts have focused on the role of crop and pasture species in controlling deep drainage and nitrogen leakage. It is only relatively recently that issues such as dryland salinity and acidification have become prominent.

Some of the opportunities identified in the Scoping Study are:

- Breeding winter wheat varieties, capable of being sown in February and harvested in December, with potential for increased rooting depth and higher water use resulting from greater growth in the cold winter period when soil moisture is high in southern Australia.
- Breeding winter canola varieties.
- Breeding perennial cereals, which can grow year round, be grazed from March to September, with grain development during spring 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 for longer, with greater biomass production and water use.
- Increasing crop transpiration by increasing plant vigour and leaf area, increasing stomatal conductance, delaying senescence, altering root / leaf signalling.
- Improving tolerances of annual and perennial plants to disease and other constraints, eg. acid soils, so as to maximise biomass and water use.
- Extending the growing season of annual varieties by increasing the capacity to withstand high suction tensions at end of season (moisture stress), and by improving crop health through increased disease and pest resistance, increased nitrogen extraction capacity

in roots, thereby increasing biomass and rooting depth.
- Increasing the range of grain legume crops and other perennial legumes so that there are varieties suitable for most farming areas and systems eg. selections from native glycine, soybean, prostrate lucerne.
- Exploring the "resurrection" capacity of some species to recommence growth after harvest and/or a period of drying and senescence.
- Developing spring crops eg. safflower or berseen clover, and summer (opportunistic) crops eg. sorghum that can be used to "mop up" soil moisture when sufficient is available in the profile as well as providing break crops and an economic return.
- Incorporating winter or summer activeness into perennial grasses—native, introduced and improved, so that in grazing systems there is some form of active leaf area and hence of water use at all times of the year.
- Mixtures of perennial crops and annual companions, or annual crops and perennial companions.
- Breeding sorghum varieties suitable for summer cropping in southern Australia.
- Incorporating characteristics in crops to allow management modification after planting to suit climate and other conditions eg genetic switches to control flowering and tillering dates to optimise water use and biomass production.

The Scoping Study has highlighted that the breeding, selection and bioengineering of crops and pastures has a high potential to contribute to ameliorating dryland salinity and soil acidification. This contribution is likely to be over and above current agronomic and other management improvements. Whilst these improvements will not override the need for perennial vegetation to be a part of the solution, it has indicated an increased role for "improved" annual crops and pastures, including a number of opportunities for perennial or biannual crops and pastures.

In addition, the Scoping Study has identified many opportunities that could be implemented. Whilst a number of the opportunities will require a long term (10–15 years or more) research and development program, the Scoping Study indicates that some short term investments in breeding, selection and/or biotechnology are likely to provide significant long-term benefits. In particular, current breeding programs for a range of annual crops and pastures (eg. cereals, oilseeds, grain legumes, other legumes) could, through relatively minor refocusing, achieve a range of beneficial outcomes for both productivity and sustainability.

Three important points must be noted regarding the potential opportunities identified in the Scoping Study for breeding, selection and biotechnology to control deep drainage and nitrogen leakage:

- Firstly, any opportunities will only be a part of the solution for dryland salinity and acidification. Breeding, selection and / or biotechnology offers no "magic fix".
- Secondly, whilst a number of opportunities have been identified, each needs to undergo a rigorous analysis to determine what contribution they can provide to control dryland salinity and acidification. Priority should be given to those options which are capable of substantially controlling the cause of degradation problems. Some of the opportunities may be realisable within short timeframes, others may require extensive programs.
- Thirdly, all opportunities need to be evaluated against a range of economic and environmental benefits and costs. In particular, new temperate cereal cultivars must be associated with appropriate agronomic and management practices and premium grain quality. Where new species or varieties are introduced into Australia, their potential to become environmental weeds must be considered. Opportunities involving biotechnology must satisfy an extensive regulatory process, as well as address consumer concerns.

There is a need to continue exploring these opportunities. Now that they have been identified and scoped, it will be necessary to focus on priorities and take them to the next phase of development. This will require a combination of modelling and experimentation, and collaboration with a range of stakeholders and research and development organisations. Links should be established with other activities researching similar issues. An inventory of existing genetic stocks that can provide the plant characteristics sought should be undertaken, and these should be explored initially.

In addition, there is a need to present and discuss the opportunities with key investors (eg. Grains Research and Development Corporation, Rural Industries Research and Development Corporation, CSIRO Plant Industry, other breeding programs, agribusiness). The Scoping Study demonstrates that significant potential may exist for breeding, selection and biotechnology to play an important role in the control of deep drainage and nitrogen leakage. In particular, the focus on using these technologies to enhance the capacity of current crop and pasture species to contribute to solutions to natural resource degradation, is one which should be considered within all current and planned breeding programs. The Scoping Study has demonstrated the capacity within Australia's breeding, selection and biotechnology fields to play a key role in those solutions.

4. Opportunities to Breed/Select/Bioengineer Species to Control Deep Drainage and Nitrogen Leakage: Temperate Cereals

Richard Richards*

4.1 Introduction

Reducing the escape of water and nutrients beyond the rooting zone of our current cereals will not only require new cereal genotypes but also new, improved or more widespread adoption of appropriate management practices. New cereal genotypes must be developed to complement these management practices and should, where possible, have grain quality characteristics that attract a premium by the domestic and global markets to ensure widespread adoption by growers.

There are a number of opportunities to develop new cereal genotypes that will reduce the flow of water and nutrients out of the root zone of cereals. On the surface it seems relatively straightforward to achieve this. All we need to do is to select and then breed cultivars with deeper roots. Several selection methods have been tried. For example, by growing diverse genotypes in a drying soil that has a source of water at depth should favour genotypes with deep roots that are first to reach this water. Another method is to place a herbicide deep in the soil so that the first genotype whose roots reach the herbicide can be easily identified because of early leaf senescence induced by the herbicide. However, none of these methods have successfully been applied to select deep rooted plants and important cereal germplasm with a deep root system has not been identified.

We have very little understanding of the extent of genetic variation for rooting depth in cereals. Where comparisons have been made little variation has become evident. However, it is possible that empirical breeding for grain yield, may have indirectly selected for genotypes with a good root system. We do not know this and it is possible that our breeding programs are missing out on important variation. Fortunately, we know enough about the physiology of cereals and genetic variation in them to be able to develop indirect selection methods for developing cultivars with deeper and more extensive root systems.

* CSIRO Plant Industry

4.2 Opportunities

4.2.1 Extended crop duration

Clearing of perennial vegetation for annual crops and pastures has been identified as the principal cause of dryland salinity and acidity. The shorter life cycle of annuals allows water and nutrients to move beyond the root zone. Rooting depth is generally a function of vegetation duration. If water is available at depth then the only plants that will have access to it will be those long-lived ones that have time to grow deep roots. It is unlikely that the rooting depth of annuals will ever match that of perennials. Nevertheless, it is relatively easy to genetically extend the growth duration of cereals so as to increase water and nutrient use. Using our present understanding of the genetic control of flowering time in cereals, which involves differential responses to temperature and daylength, we can develop temperate cereals that have either a very short growth duration or a very long one. That is, temperate cereals that can be planted very late (e.g. September), or genotypes with delayed flowering that can be planted very early in February. Harvest of both types may be in December.

Breeding cereals that can be sown as early as possible is vital to capture water and nutrients. Early sowing provides an extended period for root growth in very favourable conditions as the soil temperature is warm, and until about September, the roots do not have large competing sinks, such as stems and ears, for assimilates. Hence, extending the duration of the vegetative period for as long as possible will enable roots to grow deep in the soil, providing there is moisture in the soil profile. If it is wet, long duration cultivars will have more roots to better capture mineralised nitrogen or applied nitrogen before it moves beyond the root zone. Phosphorus uptake is also greater by cultivars with a longer crop duration. A risk with longer duration cultivars is that if flowering time is delayed then grainfilling will occur with a more intense end of season drought and at higher temperatures; both of which will reduce yields.

We are just beginning to understand the molecular control of flowering and this may also open up new opportunities. One opportunity may be to regulate the time of flowering after a crop is planted. With current cereal varieties the flowering time is pre-programmed. That is, it is possible to accurately predict the time of flowering before the cultivar is even planted. An opportunity of the future is to sow varieties that are unable to flower until they are sprayed with a natural inductive chemical. These varieties could be planted as early as possible (February to May) and the inductive spray could be applied in late winter based on knowledge of the available soil moisture, expected seasonal rainfall and location, so as to have flowering timed to maximise yield. This could allow up to several months of extended root growth for cereals to use any additional water and nutrients that may otherwise not have been available to them. Grazing management of early planted cereals would need to be carefully monitored to maximise root growth.

A more extreme manipulation of crop duration would be to develop perennial cereals. A perennial wheat could be sown, say at the first break in March, grazed during winter when quality winter feed for animals is short, 'locked up' during late winter and summer for reproductive growth and then the grain harvested in summer. Many of the ancestors of wheat are perennials and there is little doubt that perennial wheat could be developed for parts of Australia. The most obvious regions where perennial wheats may grow are those where there is a high probability of summer/autumn rainfall. Along with the genetic manipulation of wheat to develop a perennial form will need to be a suite of additional traits. Perenniality may need to rely on some form of tiller bud dormancy, which will break after grain harvest if conditions are favourable for regrowth. Wheat already has some form of tiller bud inhibition associated with apical dominance, which under some conditions can be triggered just before flowering. Perennial wheats will also need to have a suite of disease resistance genes. Being perennial they will need to be resistant to all rust diseases so they won't constitute a threat to the main wheat zone. The major diseases of perennial wheat are likely to be root diseases, which are currently very difficult to genetically control (see later) and virus diseases such as barley yellow dwarf virus (BYDV). Projects to control BYDV, using conventional breeding methods, are well underway at CSIRO Plant Industry as well as an attempt to gain immunity to BYDV using transgenic methods. We may also need to use new methods in somatic hybridisation between wheat and related grasses to develop a suitable perennial wheat.

4.2.2 Cereals with higher water use

Increasing the vigour of crops provides additional opportunities to increase rooting depth. Substantial advances have been made to increase the above-ground growth of wheat crops by understanding the physiology of early seedling growth and then using conventional breeding methods to select for greater vigour. Increased vigour results in a faster closure of the leaf canopy which can result in more water use. The greater water and nutrient use by vigorous crops is not only from deep in the soil profile but also in the top 10cm as the top soil remains wet for longer periods enabling an extended period for nutrient acquisition in this nutrient rich zone. Greater vigour can also be an advantage when sowing rains arrive late and crop duration is shortened. More than two-fold variation has been observed among wheat genotypes for early vigour and it is evident that Australian wheats are less vigorous than wheats from some other countries. Little is known about the vigour of the root system in these new wheats. The indications are that the size of the root system is also greater in the top soil as well as at depth in spring wheats bred to have greater above-ground vigour.

Some of the poor vigour of Australian wheats can be attributed to the almost complete adoption of the *Rht1* and *Rht2* stem height reducing genes by Australian breeding programs. These genes reduce the height of the crop, which increases yield when conditions are favourable. However, these genes also reduce the vigour of seedling wheat and can often result in poor establishment, poor growth and reduced water use. Alternative dwarfing genes are now being incorporated into Australian wheats in the CSIRO breeding program. Lines with these new genes do not have the penalty of poor establishment and poor early vigour found in all current wheats grown in Australia.

It has been established that in addition to the increased vigour that can be achieved using new dwarfing genes, a number of other traits are important that control the vigour of wheat. The trait most likely to be important for increased above-ground vigour as well as root vigour is the size of the embryo. The embryo is only a very small part of the cereal kernel (as small as 1% in wheat), however it contains the root and shoot primordia responsible for initial growth. In temperate cereals the seminal roots, which are derived from the embryo in the seed, are the roots which grow deep into the soil whereas the nodal roots, mainly coming from the tillers, are quite shallow. This difference is probably due to the duration of growth discussed earlier. Increasing the size of the embryo of current wheats, which we are currently attempting, is likely to increase the number of seminal axes from say three, which is common, to five or more. Genotypes with an enhanced number of seminal axes may be very important to maximise the finding and colonisation of biopores where soil physical conditions restrict root growth and water uptake.

Whereas there has been a significant effort to identify wheats with vigorous above-ground growth there has not been a serious attempt to explore variation in rate of root growth. We may be missing out on important genetic variation in the elongation rate of roots that are able to quickly penetrate and proliferate through the soil matrix.

There is evidence that redistributing carbon to different plant parts by breeding may also be important to increase rooting depth. It is not yet known how to directly redistribute carbon to the roots but we have evidence that by restricting tiller growth may result in more assimilate being available for root growth. A tiller inhibitor gene has been identified in wheat (*tin*) and in barley (*uc*) and these may be important to increase rooting depth. A better understanding of carbon allocation patterns in cereals may allow us to directly increase root growth. It has been shown that the genes that control flowering time have a profound influence on root growth relative to shoot growth and may be a good starting point for increasing assimilate allocation to the roots. In addition, transporters of the photosynthetic products such as sucrose can be manipulated in cereals. Currently these transporters are being investigated to increase carbon supply to the growing seeds but with the appropriate promoter there is no reason why the direction of flow could not be reversed so that carbon is transported to the roots or even to storage organs if perennial cereals are desirable.

Substantial variation exists for the amount of water crops transpire per unit leaf area. Water loss occurs through stomata, small pores in the leaves, and variation among genotypes within species for stomatal conductance is quite large. Methods are now available for rapidly measuring the stomatal conductance of cereal leaves in a breeding program so as to identify profligate wheats. Stomatal response to environmental constraints is largely controlled by chemical signalling between the roots and leaves. This is thought to be via the hormone abscisic acid (ABA) or an ABA-like compound. Altering the plant's sensitivity to this chemical signal or reducing the level of the signal also offers ways to increase water-use by altering stomatal sensitivity to drying soil, hard pans, waterlogging etc.

An understanding of the control of leaf area development and senescence will also be important to increase water-use. We have made significant advances in understanding how to enhance leaf area development, but we have less understanding of the genetic control of senescence. Extending the duration of leaf area into grain-filling may help to mop-up any additional water in the soil from late rains. This, however, may come at some cost to grain protein as some nitrogen must then be retained in leaves rather than mobilised to the grain if the leaves are to remain green longer.

Other traits that could result in enhanced water-use and where genetic variation has been noted are: greater early nitrogen uptake (which results in a larger evaporating surface), osmotic adjustment (for more root growth and greater 'sucking power') and tolerance to waterlogging and fast recovery after waterlogging. Waterlogging typically results in a significant reduction in root growth and in root death. This subsequently drastically limits water and nutrient uptake and can be particularly devastating in crops that later experience a terminal drought. Improved tolerance and/or recovery after waterlogging may reduce these effects.

4.2.3 Tolerance/resistance to diseases and nutrient disorders

Some of the greatest impediments to increased water and nutrient use are soil physical and chemical conditions and soil-borne diseases. These factors can drastically limit the growth of roots in the soil and thereby result in substantial amounts of water and nutrients escaping beyond the root zone. They must be overcome through both breeding and management if rooting depth and crop growth are to be enhanced. Genetic opportunities to minimise soil physical constraints may be possible by increasing crop vigour, the ability to penetrate hard pans, the number of seminal axis, and altering the sensitivities of plants in chemical signalling between roots and leaves.

Crop rotations and herbicide management practices have been very important to minimise many of the soil-borne diseases of cereals such as nematodes, take-all and rhizoctonia. For example, yield of wheat growing after a break crop is about 20% higher than wheat growing after wheat, with commensurate increases in water-use. Healthy root systems are able to extract more soil water. These management practices will probably remain the most effective control of these diseases. However, extra genetic protection must also be provided. For the control of cereal cyst nematode (CCN), several resistance genes have been identified and these have been incorporated into some temperate cereals. There is also good genetic tolerance to root lesion nematode and crown rot. However, there is no known resistance to diseases such as take-all or rhizoctonia in wheat. The combination of simultaneous improvement of variety and management has been responsible for many yield improvements and it is likely that it will also lead to improved water-use. This will become particularly important as crop duration increases such as in the development of perennial cereals.

Other soil constraints are mineral deficiencies and toxicities. These typically reduce root growth, crop growth and subsequent water-use. For some of these constraints there are genetic means to reduce their impact. For example, there is important genetic variation for tolerance to boron, sodium (for salinity and alkalinity), aluminium (for acidity) among cereal

genotypes. However, we still do not know how important this variation is likely to be to increase water use. Similarly, genetic means to improve phosphorus utilisation are present in some plant species, particularly white lupin and canola. Some microorganisms can mobilise phytate P, and genes from these microrganisms when introduced into cereals may provide an important means to increase nutrient cycling and uptake and thereby crop growth and water and nutrient use.

4.3 Priorities and Timelines

Priorities must be formulated according to the features and practices of each agricultural region. For many regions, in particular the high rainfall zone, the single most important priority is to maintain a crop for as long as is possible, so that water and nutrients can be captured as they move down the soil profile. In drier regions, or where rainfall is strongly winter dominant, longer crop duration is not possible. Here, maintaining a healthy and vigorous root system that is able to tolerate transient waterlogging and/or resist soil-borne diseases and/or soil nutrient deficiencies and toxicities is vital. Clearly, these will need to go hand-in-glove with appropriate management strategies such as the use of rotations, stubble retention practices, liming etc. to maximise the chances of success.

The timescale to achieve these genetic changes will also vary with the nature of the genetic modification and the region. Many of the opportunities are already possible and could be developed now. For example, we can already genetically delay flowing time by several months to enhance root growth. Similarly, we are aware of important genetic variation controlling leaf area development, seminal root axis number, and resistance to CCN, and can transform wheat and barley to introduce immunity to BYDV. However, we are not yet able to develop a perennial cereal crop, or to greatly reduce soil constraints such as acidity, salinity and boron toxicity, or develop resistances to take-all and other root diseases. But, we are on the way to understanding and then identifying some of the genes which may be important to manipulate.

4.4 Future Directions

Future research directions must take into account the breeding opportunities that will result in the most effective ways to minimise deep drainage and nitrogen leakage out of the root zone, how feasible these breeding opportunities are and timescales, possible risks and trade-offs. These are summarised in Table 1. These breeding opportunities must be viewed in relation to current management practices as the simultaneous improvement of cropping systems through both breeding and management will be responsible for the greatest yield increases and the most effective control of deep drainage and nitrogen leakage.

4.5 Acknowledgements

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Table 1. Priorities and timelines to breed temperate cereals to minimise deep drainage and nitrogen leakage. A brief assessment of the feasibility of achieving these goals and any obvious risks or trade-offs are also given.

Breeding Opportunity	Priority	Current Feasibility	Timeline*	Risk/trade-offs
Crop duration				
Extended crop duration	High	Yes	Short	Vulnerable to drought
Perennial cereal	High	R & D required	Long	Vulnerable to disease build up
In-crop induction of flowering	Medium	R & D Required	Long	Reliant on accurate forecasting of soil-water availability
Profligate water and nutrient users				
Enhanced above-ground vigour	High	Yes	Short	Vulnerable to drought in some environments
Enhanced below-ground vigour	High	R & D Required	Medium to long	Low
Waterlogging tolerance/ recovery	High	R & D Required	Long	Low
Stomatal conductance	Medium	Yes	Short	Low water-use efficiency
Root-shoot signalling	Medium	R & D Required	Long	Unknown
Delayed senescence	Medium	R & D Required	Medium	Reduced grain protein
Tolerance/resistance to diseases/nutrient disorders				
Resistance/tolerance to soil-borne pathogens	High	Yes, some R & D Required	Short to long	Low
Tolerance to nutrient disorders	High	Yes, some R & D Required	Short to long	Low

*. Short–the capability, germplasm and understanding exists in Australia to initiate a breeding program immediately

Medium–some additional research required to identify appropriate germplasm but the capability exists in Australia to incorporate this into a breeding program

Long–additional research is required to understand the mechanism, to develop the technical capacity, or to identify appropriate germplasm, before initiating a breeding program.

5. Opportunities to Breed/Select/Bioengineer Species to Control Deep Drainage and Nitrogen Leakage: Grain Legumes

Wallace Cowling*, Hans Lambers* & Ted Lefroy*

5.1 Introduction

In seeking genetic solutions to water recharge and nitrogen leakage in Australian agricultural landscapes, it is important to understand the climate, soils and natural vegetation of Australia. (Flannery, 1994) points out that Australia is the only continent on which the variability of climate between years has had a greater influence on shaping the biota than within-year climatic variability. It is large and unpredictable episodic rainfall events that are driving deep drainage and water table rise in the agricultural landscape. Australian soils are typically nutrient deficient and highly phosphate fixing. The native vegetation has evolved to cope with these unusual conditions. Australian plants that belong to the Proteaceae and some Australian legumes have developed highly efficient cluster root systems whereas others have symbiotic associations with mycorrhizal fungi to increase their access to nutrients in sub-surface soil. In addition, the vegetation has developed deep roots to access the water table, and shoots that are able to tolerate very severe water stress.

Tolerance of the winter soil water surplus and its uptake over summer is an important feature of the maintenance of physiological functioning in natural ecosystems of the region (Dunin et al., 1999). In addition to deep roots and access to the water table in summer, Australian native perennial plants typically have high suction tensions – much higher than present annual crops (Lambers et al., 1998); H. Lambers, unpublished observations). However, in the agricultural landscape, unless this winter excess can be stored within the rooting depth of annual crops and transpired in spring when leaf area and available energy are high, it drains below the root zone and contributes to recharge of water tables. Deep drainage is estimated to have increased from between 0.1 and 1 mm yr^{-1} under native vegetation to between 15 and 100 mm yr^{-1} under agriculture (Walker et al., 1999).

The ley farming system practiced in southern Australia relies on the tactic of synchronising the life cycle of annual crops to the short winter rainy period. Over this period, from April to November, evapotranspiration by plant communities is energy limited. That is, with the exception of the arid margins of the cropping zone, more rain falls than there is energy available to return it to the atmosphere through evaporation and transpiration, resulting in a soil water surplus (Hatton & Nulsen, 1999). These limitations of southern Australian agricultural environments have lead us to propose a phase farming system that utilizes perennial, biennial and annual legumes. The annuals will continue to drive the economic profitability of the farm and will be bred to extend the effective growing season, together with perennials or biennials to reduce the water table when and where necessary. It is essential for farm profitability that breeding for economic traits continues in our annual legumes. It is also true that it will be very difficult to increase through breeding the total amount of water used by annual crops through evaporation and transpiration, and we will focus in this paper only on those attributes that may increase water use.

For annual crops, improvements in water use are most likely at the start or end of the season. We suggest ways to extend the growing season of annual crops - by planting on or before the “break” of the season, breeding for early germination and vigorous early growth, and selecting for deep root systems that access deeper ground water and allow the plants to remain green beyond the normal time for harvest.

We propose new genetic types of grain legumes that are equipped with “resurrection genes” through genetic engineering—to mimic the native “resurrection plants” of South Africa and Australia (Lambers et al., 1998). These engineered grain legumes will fully restore their physiological activity after harvest with the onset of summer rain. They could be used as biennials with a grazing phase over summer and a second winter cropping phase. Although “resurrection plants” are vastly different from any known crop plants, the genes that allow the resurrection habit are commonly expressed in drying seeds of all plants, which undergo the same processes as the vegetative structure of resurrection plants.

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We also propose genetic improvements in certain Australian perennial legumes such as *Acacia* species that may provide a food or feed of economic value and will pump ground water over summer. Such perennial legumes for food, feed or fibre would be planted in blocks on the soil types where water recharge is greatest.

Finally, we suggest breeding for grain legumes that tolerate transient water logging and moderate salinity, for those soils where these issues are a problem and current crops cannot cope. This combination of perennials and annuals/biennials in blocks, possibly in a phase farming rotational system, will help to restore stability to our agricultural landscapes and reduce the problem of deep drainage and nitrogen leakage.

5.2 Opportunities

5.2.1 Opportunities to improve growth and water use of annual crops

Extending the "effective growing season"

In annual crops, where there is a well defined length of growing season, a substitution occurs between soil evaporation and transpiration as leaf area increases. As a consequence, the total amount of water returned to the atmosphere by a crop with high leaf area may be little different from the sum of evaporation plus transpiration in a crop with low leaf area. Within the existing limits of the crop growing season, it is erroneous to assume that the water use of a high biomass crop will be proportionately greater than that of a low biomass crop. (Smith et al., 2000) showed that doubling grain yield only resulted in a 5% decrease in deep drainage (Table 1).

However, breeders could make a minor but significant difference in water use of annual grain legumes by breeding for deeper root systems and increasing access to ground water, and as a result may also increase yield through greater biomass. This is the sense in which we consider extending the "effective growing season"—an extension resulting from increased access to ground water not normally accessible to annual plants.

Table 1: Evapotranspiration for wheat in a high yielding and low yielding agricultural system from (Smith et al., 2000).

Treatment	Biomass (t/ha)	Grain Yield (t/ha)	Evapo-transpiration (mm)
Low input wheat	10.8	3.4	404
High input wheat	15.8	6.4	439

Over the last 30–40 years of yield measurement in plant breeding, breeders have genetically improved the grain yield of annual crops, but have not changed their total above ground biomass (Cowling, 1996). Biomass is most likely linked to the length of growing season, which in southern Australia is limited by the inability of current annual crops to access deep moisture that has moved downwards over winter. To increase water use in annual crops it will be necessary to access water that would typically be recharged to the water table. Genetically, this will be achieved by selecting for rapid water absorption by seeds and rapid seed germination, vigorous early growth, deeper roots, better nutrient uptake, and pest and disease resistance that will help the plant to access deep ground water, and delay senescence and harvest. A note of caution is needed here—experience with lupins suggests that selection for rapid early growth is associated with weak stem strength and a propensity to lodge later in the season (W. A. Cowling, unpublished observations).

Genetic engineering may be required to increase the suction tensions withstood by our annual grain legumes at the end of the growing season when drought stress is high. In applied breeding programs, plant breeders will select grain legume breeding lines that stay green longer and continue to fill pods at the end of the growing season, in the hope that such breeding lines are gaining better access to recharge water. Such "stay-green" types have been observed in the narrow-leafed lupin breeding program in Australia (W.A. Cowling, unpublished observations).

Breeding must go hand-in-hand with improvements in the agronomy for early planting, such as, development of planting equipment for dry seeding, use of herbicides that remain effective on dry soils (to avoid the need to re-apply herbicides after crop germination), and avoidance or treatment of water-repellency in soils. Soil after lupins and other crops has greater water repellency, which reduces uniform water penetration and causes "staggered" germination. It should be possible to bioengineer crop species that will release organic products on breakdown into the soil that increase the wetting ability of soils in the following season. This will promote earlier planting, earlier germination, and greater vegetative growth due to better access to water early in season. However, a genetic solution may not be necessary if agronomic treatments are developed to improve wetting ability of soils.

Grain legumes are typically slow to produce a well-established canopy over winter. Genetic modification may be considered to improve winter growth in order to increase leaf area before spring. Rhizobial strains will be required that infect grain legumes rapidly after germination and form active nodules over the cool winter

months. Breeding for deeper roots and greater tolerance of water stress will enable plants to take up water when it is scarce in deeper soil layers and transpiration rates are high. As indicated above, one outcome of this may be crop types that "stay-green" at the end of the season, with larger leaf area, greater biomass, higher grain yields, and longer periods of transpiration than existing annual crops.

Genetically improving crop health

The relevance of crop health in the context of this paper is extension of the growing season of our "idealized" water-pumping annual grain legume. This includes reducing both biotic and abiotic stresses, such as salinity tolerance, nutrient deficiency and toxicity tolerance, and tolerance of transient water logging (Jayasundara et al., 1998). Annual grain legume crops that are bred for an extended growing season, with deeper root systems and rapid early growth, must also resist pests and diseases and tolerate abiotic stresses. It is also important to recognize that, independent of water use, grain legumes must be bred for increased profitability—annual grain legumes should be an important component of farm income that allow other forms of water use to occur (such as perennial plantations) in crop rotations on farms.

Proteoid roots are important in native species such as *Banksia* (Dinkelaker et al., 1995; Lamont, 1982) to allow access to the highly fixed nutrients such as phosphorus. *Lupinus angustifolius* does not produce proteoid roots, whereas the rough-seeded lupins and *L. albus* produce prolific cluster roots that improve the efficiency of phosphate uptake (Bolland M.D.A., 1997; Clements et al., 1993; Gardner et al., 1982; Keerthisinghe et al., 1998). It should be possible to bioengineer proteoid roots to increase phosphate extraction and better growth and water usage in *L. angustifolius*. Or, breeding could focus on the "natural" cluster root formers such as *L. albus* or the rough seeded lupins, to improve their ability to grow on a wider range of soil types and produce more economical yields. In the case of the rough-seeded lupins, breeding must first introduce domestication genes to produce a commercial crop plant (Buirchell, 1999). In either case, the goal is to extend the growing season through improved nutrient status of the crop.

Some grain legumes are very efficient at accessing fixed phosphate in acid soils. For example, chickpea, which does not form cluster roots, exudes large quantities of organic acids that dissolve phosphate in the root vicinity and render it available to the plant (Ohwaki & Hirata, 1992; Tang et al., 1998). A major gene for this trait could be isolated from chickpea and transferred to a non-acid exuding species.

There are trade-offs in breeding for improved nutrient-availability in grain legumes. Legumes reduce soil pH, and soil acidity is an increasing problem in cropping soils of southern Australia. Tolerance of acid soil and aluminium toxicity is apparent in some legume species, such as yellow lupin (*L. luteus*), on some naturally acidic soils. Yellow lupin is also known to exude organic acids, and is an efficient mobiliser of fixed phosphate in soil. However, lime treatment of soil may be inevitable to avoid major problems with acid soils on prime cropping land in future, and we do not believe that breeding for reduced soil acidification by grain legumes is a valid breeding goal, given the effectiveness and relatively low cost of lime.

Transient water logging occurs in most soils during winter in southern Australia, because the energy to drive evapotranspiration is insufficient to avoid this problem in most years. This occurs especially on duplex soils where a light-textured A horizon meets a heavy-textured, often toxic, B horizon layer. Narrow-leafed lupins (*L. angustifolius*) have a dominant tap root which is often killed or pruned by waterlogging at this impenetrable layer. Other crops such as wheat, which have stronger secondary root systems in the A horizon, are not as dramatically affected by transient water logging. Faba bean (*Vicia faba*) and yellow lupins (*L. luteus*) are significantly more tolerant of water-logging than *L. angustifolius*, peas, lentils and chickpeas (Jayasundara et al., 1998), and although infraspecific variation in waterlogging tolerance was measured in chickpea (Jayasundara et al., 1998) it is unlikely that breeding within chickpeas will be sufficient to overcome this problem. Genetic engineering would appear to be the major hope for transferring waterlogging tolerance to sensitive grain legumes such as chickpeas, lentils and peas.

Most cool-season grain legumes are sensitive or moderately sensitive to salinity, with faba bean relatively more tolerant than other species (Jayasundara et al., 1998). Breeding for salinity-tolerant grain legumes will be important for improving crop growth and profitability on mildly saline land (5–10 dSm^{-1} range) which will make up a large proportion of the projected 4–6Mha eventually affected by salinity in southern Australia. Breeding for salinity tolerance may be successful in peas if known tolerance in wild relatives *Pisum elatius* and *P. fulvum* (Jayasundara et al., 1998) can be transferred to *P. sativum*. Such an approach has been successful in cereals (Colmer et al., 1995; Omielan et al., 1991). However, there is little infraspecific variation in salinity tolerance known in any other grain legumes (Jayasundara et al., 1998), and nothing in the geographic origins of lupins to suggest tolerance should exist naturally in *Lupinus* (Cowling et al., 1998a). Any improvement in salinity tolerance and growth will inexorably lead to greater uptake, and less loss, of nitrogen and water, mostly through extending the growing season and growth capacity of the grain legume.

Considerable progress has been made in improvements in salt tolerance through genetic engineering, for example, with the transfer of enzymes involved in the synthesis of "compatible solutes" (e.g., sugar alcohols, glycinebetaine) used in osmotic adjustment to a number of species. Ion transport mechanisms involved in compartmentation of internal Na^+ concentrations have also been used (Blumwald et al., 2000). (Apse et al., 1999) demonstrated an improvement of salt tolerance in *Arabidopsis* via overexpression of a vacuolar Na^+/H^+ antiport.

Disease resistance is obviously important to help legume crops extend their growing season and use more water with deeper roots. Much literature exists on breeding for disease resistance, with different methods for breeding for horizontal or vertical resistance (Cowling, 1996), and there are potential solutions through genetic engineering. Root disease is traditionally the most difficult type of resistance to select, as demonstrated by Pleiochaeta root rot in lupins (Cowling et al., 1997). It is obviously important to maintain root health in order to access deep water tables. Disease resistance alleles could potentially be transferred across species. For example, in lupins strong resistance to anthracnose (*Colletotrichum gloeosporioides*) occurs in *L. angustifolius* but not in *L. albus* (Cowling et al., 1999). The major alleles for resistance in *L. angustifolius* could be isolated, cloned, and transferred to *L. albus* with a high probability of success, given the similar genetic response to this disease in both species. Molecular mapping populations are being developed in both species that will aid the identification and isolation of anthracnose resistance alleles (GRDC project CLM30, supervisor W. A. Cowling).

5.2.2 Opportunities for perennialisation of legume crops

The "resurrection lupin"—one step towards perenniality

Tolerance of extreme dessication is observed in resurrection or "poikilohydric" plants that dehydrate in times of drought until the water potential of protoplasm is in equilibrium with dry air, and then almost fully restore their physiological activity after a shower of rain (Lambers et al., 1998). There are similarities between the genes expressed upon dehydration of resurrection plants and those expressed in ripening of the embryo in developing seeds. The proteins involved in the survival of dehydrated embryos are similar to those expressed during dehydration of resurrection plants and other plants undergoing water stress (Lambers et al., 1998).

We propose to genetically engineer lupins with these genes for poikilohydric behaviour. Lupins have a suitable plant structure (Dracup & Kirby, 1996) to be engineered with resurrection genes and to maintain their cropping potential over two years: an upright growth habit with inflorescences on the tips of branches; main stem and branch leaf nodes that carry axillary meristems that are often suppressed and remain dormant or die during the growing season; and a relatively high harvest height that could leave many potential axillary meristems in the standing straw. After drying before normal seed harvest, the standing straw of our "resurrection lupin" would rehydrate in the first summer rain, sprouting meristems at nodes on the main stem and branches. The genetic engineering of a resurrection lupin would require that normal senescence of roots and shoots would not occur, and that axillary meristems in the root and stem tissue would not die but survive dehydration and rehydration under the extreme temperatures and low humidity of summer in southern Australia. The protoplasts of the conducting tissues and meristems of the roots and stems of our resurrection lupin must be able to withstand water potential in equilibration with dry air.

Summer rainfall will be "soaked up" by the resurrection lupin, thereby activating the dormant root system and setting in motion the soil moisture pump that is necessary to lower water tables in agriculture. The resurrection lupin will provide an economic yield of grain in the first year, and the onset of growth with summer rain will most likely be grazed lightly. This would be an extremely valuable source of fodder in the "lean" months prior to the break of the season. Lupins prefer cool weather for fruit set, and we suggest that growth in the second year will produce deep root systems and large plants that will achieve much greater water use than in the first year and produce another valuable seed harvest at the end of year two.

Perennial legumes

Obvious choices for perennial legumes are the tagasaste or tree lucerne (*Chamaecytisus proliferus* Link.), from the Canary Islands, and forage lucerne (*Medicago sativa*). Tagasaste is being planted on a wide scale in Western Australia in the medium rainfall zone on sandy soils for use as a high value fodder. Tagasaste and lucerne are being studied in various arrangements to quantify the trade-off between water use and grain yield that occurs when perennials are introduced into cropping systems for water management (Lefroy & Stirzaker, 1999; Lefroy et al., 2000). The options being examined are segregated (block planting), integrated (alley cropping and intercropping) and rotated (phase farming) use of perennials (Lefroy & Stirzaker, 2000). The goal of this research is to produce design criteria for the optimal use of perennial plants in a cropping landscape by measuring the deep drainage reduction:yield displacement ratio for the various combinations of species, site and arrangement. This drainage:yield ratio is an aggregated measure of the degree of competition or complementarity

existing between the annual and the perennial in terms of the dual objectives of water management and grain production. These studies will guide the development of perennial grain legumes for cropping systems.

Perennial lupins exist in Mediterranean climates. The perennial lupin *L. arboreus* survives over summer in New Zealand, southern Chile and on the coast of California where it originates. The summers are not hot, summer rainfall is common, and drought is rare. This perennial plant stays green over summer and does not dry down as with "resurrection" plants. The extreme drought and high temperatures of summer in southern Australia would prevent the survival of this lupin in the grain belt, unless it was bred with special drought tolerance mechanisms and exceptionally deep root systems. A perennial lupin could grow under a cereal crop in the first year, establish a deep root system, and may tolerate light grazing over summer. Such a plant would vigorously respond to rain over summer and at the beginning of the next growing season. Seed production would occur in the second year.

However, there are problems in breeding the existing perennial wild lupins as grain legumes—they are extremely bitter, no sweet forms are known, no non-shattering forms are known, and they are highly cross-pollinating. We believe that it would be better to introduce perenniality into an existing domesticated annual lupin (that is self-pollinating) rather than to domesticate wild, bitter, shattering perennial relatives.

Development of perennial crops has been underway in the United States for two decades (Jackson, 1980). Most attention to date has been focused on perennial relatives of wheat, notably *Thinopyrum intermedium* (Becker et al., 1991; Wagoner, 1990; Wagoner, 1995; Wagoner et al., 1989). Two perennial legumes that are the subject of current research are *Cassia marilandica* and *Desmanthus illinoensis* (Jackson & Jackson, 1999). The latter has produced yields of 2000 $kg.ha^{-1}$ in monoculture while a harvest index of 0.31 has been measured in *C. marilandica*. Interestingly the grain yield in *D. illinoensis* was found to be higher when grown in a biculture with a C3 grass, as the grass covered the soil and reduced the incidence of splash-borne bacterial disease in the legume, opening up the prospect of polycultures (Jackson & Jackson, 1999). At the heart of the question of developing biennial and perennial crops however is the trade-off between longevity and reproductive effort. (Jackson & Jackson, 1999) present some encouraging evidence that such a trade-off may not be inevitable in grasses.

5.2.3 Opportunities for use of Australian native legumes as crops

We extend the concept of grain legume crops to the Australian native legumes. Considerable work has been done on analytical quality of Australian native legumes (Murray, 1984). Leguminous shrubs such as *Hovea elliptica*, *Hardenbergia violacea*, *Crotalaria cunninghamii* and *Kennedia nigricans* have seed compositions of possible value for human food (Hocking, 1980; Rivett et al., 1983). As fast growing, short lived early colonisers after fire, species such as *H. violacea* and *K. nigricans* are candidates for development as biennial or short lived perennial crops.

There are exciting possibilities for using some of the arid zone native bush food plants in land amelioration programs. Perennial legumes that have received some attention in Australia for their potential economic returns from seed production include the Acacias (Turnbull, 1987). Most research was done on Acacia spp. from central and northern Australia which are unsuited to the traditional cropping zones. Recent work is focussing on Acacia spp. from southern Australia (Maslin et al., 1998). There are also opportunities to use wild Solanum species and wild citrus species to name a few.

5.3 Examples

We know of no current research in transferring "resurrection genes" by genetic engineering to crop plants.

Programs on perennialising the major grain crops are underway at Kansas and Washington State Universities, the Rodale Institute in Pennsylvania and The land Institute, Kansas (W. Jackson, pers. comm.) and could all serve as models for Australian programs (see above).

Research is underway in Plant Sciences at UWA to explore the variation in cluster roots in *Banksia*, *Hakea* and other members of the Proteaceae, that all have cluster roots, but differ in the range of exudates these clusters release. Different exudates are probably suitable for different soil types. Likewise, it is important to explore variation in the genus *Lupinus*, some with and others without cluster roots, to discover how to engineer lupins to make cluster roots.

Likewise, a collaborative research programme in Western Australia at UWA, Kings Park and Botanic Gardens and AGWEST provides a good example the capacity to develop a native Australian plant species for agriculture. The research involved documentation of the genetic resources of Geraldton Wax (*Chamelaucium uncinatum*) (Egerton-Warburton et al., 1995), assessment of its water use characteristics (Akilan et al., 1994), understanding its breeding behaviour and commercial attributes (Manning et al., 1996), and the work has resulted in commercial release of selected varieties (Considine, 1997).

5.4 Priorities

The top priority is to extend the growing season and enhance the water use of annual crops, and to develop phase farming systems that combine annuals, biennials and perennials in rotation. Annual crop legumes must be bred to cope with stress at the beginning (low temperature, waterlogging) and end (high temperature, dehydration) of the growing season. We suggest selection of annual plants for vigorous early growth and longer leaf area duration, and with greater ability to acquire nutrients, and deeper root systems to access ground water longer at the end of the growing season.

We propose a priority for research into genes controlling the "resurrection" status of some wild plants, and investigation of ways of introducing similar genes or expressing existing genes at the end of the growing season in a "resurrection lupin."

"New" crops (from existing species) are at least as attractive as genetically engineered "old" crops. For example, 'new' lupins are being explored in a project at AGWEST and UWA (Buirchell & Cowling, 1992). Native legumes could be explored for grain producton (for example, *Kennedia*, *Hardenbergia*, *Acacia*, others?). New species with salt-tolerant should be explored.

5.5 Capacity, Timelines, Confidence, Risks

While we recognize that annuals will never be the final solution to the water and nitrogen recharge problem in southern Australia, much can be done to improve their profitability and to extend the growing season of annuals to use more water. Profitable farms will have cash to spend on controlling water recharge by other means.

The growing season of annual legumes may be extended by traditional breeding using rapid recurrent selection for the "stay-green" character at the end of the year. Strong legume breeding programs exist in southern Australia for lupin, chickpea, field pea, faba bean, and lentil. New genes may be sought from genetic engineering to promote a longer growing season. This will require a 10–15 year breeding effort.

The capacity to develop a "resurrection lupin" exists in Australia. AGWEST is the home of the national lupin breeding program with the genetic resource collection; CLIMA at UWA is the home of the transgenic pulse program of which lupins are a prime interest; the Plant Sciences and Botany groups at UWA are studying lupin seed development and seed gene regulation. Similar work occurs in CSIRO Plant Industries, Canberra. The genes of interest may be present in lupins—such genes are activated during embryo ripening. It may be a simple matter of transforming lupins with its own genes that are normally down-regulated. The intellectual capacity is available to achieve the goal of isolating and cloning such genes, but the 'hands' are lacking. We suggest that this project is a 10–15 year project. We are moderately confident of success, but if the use of annual lupins is not productive, the perennial lupins may have to be tackled, and this will extend the project further.

Woody *Acacia* species are currently being examined by Maslin and others at CALM Herbarium, Perth. Toxic components exist in seed of some Acacia spp. and other legumes. Toxic components can be eliminated by breeding, as was done with some annual lupins (Cowling et al., 1998b), although for a perennial *Acacia* this will be a longer process. We suggest a thorough examination of the genetic resources of the most promising *Acacia* species for use as a perennial legume crop, to determine if toxin-free lines exist.

The biggest risk is to ignore one group of plants for the other—annuals and perennials are both needed in the agricultural system, and new phase farming approaches are needed to combine the best of both groups. The biggest challenge is to find productive perennial or biennial legumes that are economical crop plants and survive the summer drought.

5.6 Future Directions

What future directions are required to further explore these opportunities?

1. Explore endemic new species, including promising WA species. This may have limited potential as herbaceous perennial grasses and legumes are under represented in the flora of south western WA compared to most other parts of the world (Gardner, 1944) due to the adaptations necessary to survive summer drought.
2. Explore wild relatives of existing crop species to search for interesting traits such as "stay green" (extended growing season), salinity tolerance, or transient waterlogging tolerance.
3. Research dehydration genes in "resurrection" plants and similar genes expressed in developing seed embryos.
4. Explore the potential of exotic herbaceous perennials that have become naturalised in the region. Many of these are from southern Africa and display high levels of drought tolerance but have yet to be selected for seed yield or quality.

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6. Perennial Crops and Fodders to Complement Annual Crops and Minimise Deep Drainage

Dr Ross Downes*

6.1 Introduction

For the last fifty years, much of southern Australian agriculture has been based upon annual cereal crops grown in rotation with annual pasture legumes, mostly sub clover or medic. This system has caused the ecological and environmental problems which are outlined below.

Although the pasture legume phase is expected to contribute nitrogen for subsequent crops, it is invaded by annual grasses which use much of the nitrogen and host the fungi responsible for 'take-all' which reduces yield of cereal crops in rotation. The annual grasses also become weeds of subsequent crops and many are now difficult to control because of herbicide resistance. Some of the nitrogen produced by the annual legumes contributes to soil acidification through the leaching of cations from the upper horizons. An extremely important issue is the movement of nutrients and water beyond the root zone of annual crops and pastures, causing water tables to rise and leading to salinity.

Evidence is mounting that land use based on annual crops and pastures is not sustainable, but it is not practical to plant the continent to trees to lower water-tables. The challenge is to develop modified land use practices to prevent the situation from getting worse, and to help reclaim degraded land while allowing continuing production of foods, feeds and fibres. We have, or can readily develop, biological resources to rapidly meet this challenge.

6.2 Opportunities

6.2.1 Annual Plants

In southern Australia most of the varieties of annual crops are spring types which were bred to be sown in May or June, to flower after the risk of frosts, and to mature while soil moisture reserves remain. Annual spring crops may leave considerable quantities of water in the soil profile, and summer fallowing allows summer rains to add to the soil water with the chance of some water and nutrients moving past the root zone and adding to the water table.

There are options to develop and use more winter crops which can be sown early if conditions permit, in March or April, to use surplus soil water. Winter crops have the ability to develop a deep rooting system while they remain vegetative and this allows them to tap deep water and nutrient reserves late in the growing season. In this way winter crops can use more of the soil water in both the autumn and spring than spring crops can. Australian winter wheat varieties are available and winter varieties of canola and linseed can be readily adapted.

Another option is to develop varieties of annual crops which can continue to use water and produce feed or a second crop after the main crop is harvested. Late tillers are sometimes produced by cereals and sorghum, and regrowth can be produced by canola. There is likely to be no difficulty in breeding appropriate varieties to enhance the ability of these crops to produce aftermaths using residual water or summer rains.

Annual pasture legumes are being replaced to some extent by annual fodder legumes which lend themselves somewhat better for cutting for hay or silage. They have potential in a system of continuous cropping in which animals can be excluded from cropping land. Fodder legumes can compete with weeds and cutting in spring can markedly reduce weed seed set.

Although annual legumes are an important source of low-cost nitrogen for crops in rotation, they do not appear to have the potential to substantially increase the amount of water used and help reduce leakage beyond the root zone, unless they are capable of regrowth in summer. Berseem clover varieties warrant evaluation in this context. Annual fodder legumes also have potential to use some soil water and fix nitrogen as short-season green manure crops in rotation with irrigated rice and cotton crops.

* Innovative Plant Breeders P/L

A range of weeds grow well in summer, using some of the stored soil moisture. Wire weed and saffron thistle are two of these. Instead of weeds, summer-growing annual crops have potential. Safflower is grown as a spring-sown summer crop in the Wimmera, and is under evaluation elsewhere for use when conditions prevent the sowing of main season crops. Safflower has deep roots and is effective in drying the soil, but the preceding winter fallow may have implications for increasing the risk of deep drainage.

If substantial rains are experienced in spring, a full profile may remain when annual crops are harvested. Opportunistic summer crop strategies could be developed to reduce soil water levels, and will become increasingly important as summer rainfall increases in total amount but becomes more episodic in areas affected by the greenhouse effect. Short season varieties of millet or sorghum among the cereals, the oilseeds sunflower or safflower, and pulses such as soybean or cowpea could be evaluated.

6.2.2 Perennial Plants

Many annual cereals have perennial wild relatives which could potentially be used to breed perennial crops with the quality features of annual crops. These can be expected to produce a grain crop, dewater the soil profile in summer and produce a crop in the following year. Additional characteristics required in a perennial cereal include: much greater virus and root rot resistance; summer dormancy to aid survival when water is depleted; deeper roots; and underground stems or rhizomes to help compensate for the loss of individuals in the stand. Perennial grain legumes include pigeon pea (*Cajanus*), the fifth most important pulse crop in the world. Improved germplasm is available from an ACIAR program in Queensland. Winged bean (*Psophocarpus*) also has potential. Sunflower has perennial relatives which might be used to develop perennial oilseed crops. Others will discuss the prospects for perennial cereals, grain crops, pulses and oilseeds in more detail.

Native perennial grasses and associated plants evolved under the variable rainfall and temperature conditions, and frequently low fertility, that characterise unimproved Australian farm land. In grassland, or in dry sclerophyll forest in association with shrubs and trees, perennial grasses survive conditions in which the water and nutrients rarely escape the root zone. If low input management of grazing land is required, perennial native grasses are available, but may often be too unproductive to utilise soil water effectively.

Under conditions of improved fertility, introduced grasses replace native species. With adequate inputs, exotic grasses tend to be more productive. In the winter rainfall zone of southern Australia, introduced grasses such as ryegrass, cocksfoot, fescue and phalaris grow well in winter and spring, tending towards summer dormancy to aid summer survival. Thus they may allow some leakage to occur following intense summer storms. Summer water use could be increased if grass pastures contain a summer-growing component such as love grass or paspalum. Well adapted perennial grass varieties are available for use in improved pastures.

Native perennial legumes are a largely undeveloped group in Australia though some relatives are used in other countries. Species in many genera including *Atylosia, Glycine, Psoralea and Rhyncosia* are well adapted to various parts of the country from high rainfall to desert conditions. They have deep roots and underground storage organs to help survive drought and fire. Some have rhizomes or underground stems. They comprise a virtually untapped and unselected resource of legumes which could be used to minimise deep drainage.

Perennial pasture legumes such as white and strawberry clovers are common in improved pasture, particularly in high rainfall districts. However, ecotypes of white clover occur in intermittently dry situations suggesting their roots tap deep reserves of water, but in some areas they behave as annuals. In areas subject to prolonged hot and dry conditions the outstanding perennial legume is lucerne.

Lucerne has a long history of use in Australia as a hay crop in high rainfall areas and under irrigation. In some districts, lucerne taps shallow water tables which provide a form of subterranean irrigation. Lucerne also has a place in providing feed during droughts as its roots access water deep in the soil profile.

In recent times lucerne is increasing in popularity in a new role. It is being grown in rotation with crops to help dry soil water reserves and thus minimise deep drainage. Several studies throughout the country to explore the potential of lucerne as a dewatering crop are being supported by GRDC. Two features of lucerne are particularly important, deep roots and moderate tolerance of saline conditions. For two or three years, or more, a lucerne crop dries the soil profile to a considerable depth while providing grazing for farm animals. When the lucerne is removed, nitrogen is available for the annual crops in rotation. It normally takes some years for the soil profile to be replenished to the point where deep drainage reemerges as a problem.

Although lucerne in rotation with crops is among the best options for reducing deep drainage at present, it is not a perfect solution. Lucerne stands can be expensive to establish (about $100/ha) if is not sown under a nurse crop to provide returns, and it can be difficult to kill when it is time to revert to a cropping phase in the rotation. Residual lucerne plants can provide physical difficulties

in harvesting and contamination in the grain of subsequent crops. If dry conditions are experienced in the first crop after lucerne has dried the soil, the crop may suffer a yield penalty through inadequate soil water reserves. On the other hand, the lucerne cycle may dry the soil well but if there is a very wet episode after the lucerne is removed, the root zone of the annual crops may be partially replenished with water, negating the positive effect of the lucerne phase.

In limited areas particularly in high rainfall areas with deep sandy soils in Western Australia, tree lucerne (tagasaste), *Chamaecytisus palmensis*, is used to remove surplus soil moisture and produce fodder. This small tree is used in agroforestry and alley cropping rather than in rotation with crops. It requires careful management because of its vulnerability to damage by stock. Of the fodder trees evaluated, tagasaste is considered to have the greatest potential for fodder, shelter, soil conservation and groundwater control.

There are large numbers of other perennial legumes which warrant consideration in rotation with crops. Species in the genera *Astragalus, Coronilla, Glycyrrhiza, Hedysarum, Lespedeza, Lotus, Melilotus, Onobrychis, Vicia* and *Vigna* are used for fodder in other countries and many are being evaluated in Victoria, ACT and Western Australia. It is important that palatable perennials be planted in diverse environments to identify potential species to help address the problems of deep drainage, especially in situations in which lucerne and tagasaste are poorly adapted, such as on acid soils. GRDC-funded work to evaluate perennial grass and legume accessions is in progress in Western Australia.

6.2.3 Mixtures

If perennial crops are developed they will benefit from having an understory of annual legumes to provide nitrogen for the crops and to occupy a niche which might otherwise be occupied by weeds. The situation would be somewhat analogous to the grass and legume associations in perennial pasture. Mixed cropping, with both species growing at the same time tends to provide up to a 15% yield penalty for the crop and a 50% yield penalty for the understory. This amounts to a yield increase over the crops alone and reflects additional or more efficient water use. There is an adequate range of varieties of legumes for this role. Traditional low growing annuals such as sub clover and medic will serve in dry areas and white clover can provide an understory in high rainfall districts.

Although there may be opportunities in future to use perennial crops to ensure water and nutrients rarely pass the root zone, we are currently dependent on annual crops. Consequently it is important to consider strategies for use now, to complement current annual crop varieties and reduce deep drainage.

An option is to grow mixtures of the currently commercially valuable annual crops with complementary species so that together they ensure that water and nutrients do not pass through the root zone. A possible complementary plant in a mixture with annual crops could be one which meets the following criteria:

- It is perennial
- It is winter dormant so that it does not compete with annual winter crop for water
- It should be low growing so that in spring it does not interfere with crop harvesting
- It should be summer active with deep roots so that the deep drainage risks are minimised
- It should transfer cations from depth to high in the soil profile
- It should be drought resistant to survive dry conditions
- It should produce palatable and readily digestible feed for stock, or a seed or grain crop
- It should be a legume so that it fixes nitrogen for use by subsequent crops.

Such a plant, together with an annual crop direct drilled each year, would readily meet virtually all of the RAAL design principles: deep roots, summer activity, perenniality, ability to grow over a wide temperature range, quick root growth, large leaf area and duration, ability to tap shallow water tables and ability to store and redistribute water and nutrients in the root system for later use. Additional effort would be required to adapt the system to particularly difficult soil conditions.

Although several native legumes possess many of these characteristics they have been eliminated from improved crop land and pastures through poor adaptation to high fertility and through cultivation, competition and herbicides. Species of Glycine, Kennedya and Hardenbergia in southern Australia, and Rhynchosia, Atylosia and Vigna in northern Australia are some of these. Varieties could be developed from species in these genera for use in mixtures with crop plants to minimise deep drainage.

Other varieties for this role can be developed from exotic germplasm. In this context, species of the genera, *Astragalus, Coronilla, Glycyrrhiza, Hedysarum, Lespedeza, Melilotus, Onobrychis, Vicia* and *Vigna* warrant continued introduction, evaluation and breeding for adaptation to Australian conditions. However accessions of lucerne, *Medicago sativa* and *M. varia* are already available and are undergoing evaluation as summer-growing, winter-dormant, perennial companion crops for winter annual crops.

Perennial *Medicago* species and ecotypes have evolved over an extremely diverse range of environmental conditions in Europe and Asia, from Siberia to the desert

conditions of the Middle-East. In contrast to the typical lucerne plants grown in Australia many of which now trace to varieties from California, adaptation to this range of conditions has led to races with winter dormancy, creeping roots and rhizomes, prostrate habit, probably tolerance of acid soils, and hardiness through tolerance of cold, drought and disease. A particularly interesting ecotype is a wild type 'mielga' from north central Spain which evolved under exposure to cold winters, hot summers and constant grazing. It is prostrate, winter dormant and spreads by underground stems. Similar types have evolved in Turkey. Some of the diversity within wild lucerne populations was described by Piano et al (1996).

The Spanish wild type of lucerne is being evaluated to test the hypothesis that crops could be direct-drilled into existing lucerne stands in autumn (i.e. intercropped) as part of an existing GRDC-funded project (CSP243). The winter-dormant lucerne should not compete with the crop for water or light, and as it is prostrate it should not interfere with crop harvest. When the crop is harvested, the lucerne can grow during the summer to remove surplus water and nutrients from the root zone, fix nitrogen and provide forage for livestock. When the soil moisture is depleted, the lucerne becomes dormant to survive until rains arrive. Underground stem development, which is most pronounced during the short days of autumn, allows plants to spread and compensate for stand loss through direct drilling or disease. The availability of the prostrate Spanish lucerne types now allows the concept of mixed cropping to be evaluated. If this proves to be successful there will be grounds for developing varieties of species of the genera mentioned above. Both native and exotic germplasm should be considered to develop a range of winter-dormant perennial legume varieties for various environmental conditions, into which annual crops can be direct-drilled each autumn.

One particularly interesting prospect would be the development of a winter-dormant, summer-active perennial soybean. Some of the earliest efforts to cross soybean with wild Australian perennial relatives were made in Canberra. (Broue et al 1982). This research has been continued in the US where fertile hybrid plants have been developed. Modification and extension of this work could lead to a perennial soybean crop in summer mixed with winter/spring cereal or canola crops. As with the prostrate lucerne mentioned above, such a combination would reduce the chance of water and nutrients passing through the root zone of crops.

Similarly it would be possible to develop perennial varieties of winter-dormant, summer-active grasses to remove surplus water and nutrients in summer. They could be particularly useful for summer pasture or grain crops into which pulse crops like lupins or chickpeas could be direct drilled in autumn. The sorghum genus has particular potential in this regard possibly through hybridisation between perennial Johnson grass and grain sorghum or sudan grass.

6.3 Examples

6.3.1 Annual Plants

French (1978) in South Australia, demonstrated a yield increase in wheat achieved by long fallowing to save soil moisture, with no consideration of loss of water through deep percolation. Similarly, French and Schultz (1984) did not consider deep drainage when attempting to account for poor water use efficiency in wheat crops in South Australia. Black and Siddoway (1976) in Montana, found that production efficiency per unit of water used was three times higher for annual cropping systems of winter wheat and safflower than for spring wheat and fallow. They concluded there is an excellent opportunity to reduce potential precipitation losses to deep percolation by using intensive cropping systems.

Halvorson (1988) proposed the use of safflower or sunflower crops in rotations because they are normally deeper rooted than grain crops and deplete soil water to greater depths and increase the capacity of the soil to store precipitation. He cited work by Black et al (1981) who found that safflower extracted water to a depth if 2.2 m, about the same depth reached by lucerne and Elymus junceus in their establishment year.

Farahani et al (1998) reviewed the crop and fallow systems used on the Great Plains in the US with an emphasis on water use efficiency rather than water movement through the root zone. They showed that a change from spring wheat-fallow to more intensive management including winter wheat and summer crops made more efficient use of precipitation and almost doubled grain yield per year. They drew attention to the hypothesis of Peterson and Westfall (1997) that "zero tilling, coupled with intensified crop rotations, is a movement toward an agroecosystem that mimics the Great Plains prairie ecosystem before cultivation began".

In experiments in Canada, reported by Biederbeck and Bouman (1994), annual legumes were established as green manure crops into wheat stubble. Although they extracted water from only 0.6m of soil during 2 months of growth, this was considered preferable to fallow with the attendant risk of deep drainage.

6.3.2 Perennial Plants

The value of lucerne to extract soil water from 3 to 4m depth was reported by Brun and Worcester (1975) who regarded lucerne as a valuable crop to reduce soil wetness

to alleviate saline-seep problems. Halvorson and Reule (1980) noted the potential for percolation of soil water below the root zone of grain crops during fallow periods. They found that lucerne prevents or reduces deep percolation by evapotranspiration of as much soil water as is usually received from precipitation during the growing season on the Great Plains.

Halvorson (1988) reported Brown (1983) as demonstrating that it took 7 to 8 years to recharge a soil when a fallow-winter wheat-barley rotation followed 3 years of lucerne. He also noted that Black et al (1981) found that established legume swards removed water from considerable depths: lucerne depleted soil water from 5.5m, *Onobrychis* from 4m, and *Melilotus officinalis* from 2.7m. Shamsutdinov and Kostyakova (2000) reported the use of the perennial legume licorice (*Glycyrrhiza glabra*) which is tolerant of saline conditions in Central Asia.

Although perennial pastures may minimise deep drainage, Francis (1995) addressed the problem of nitrate leaching after a pasture was ploughed in. He concluded that to minimise losses, ploughing should be delayed as long as possible in autumn or winter. Campbell et al (1994) cautioned that though lucerne could remove nitrate and water to 2.4m, nitrate leaching could occur if land is fallowed after legumes are ploughed in. However, this need not be the case as nitrogen is not released from lucerne as fast as from annual legumes.

6.3.3 Mixtures

Forms of mixed cropping, relay cropping and multiple cropping are widely used in tropical countries and in southern Asia to spread risks and to provide diverse crops on limited areas. In many of these cases the crops are harvested by hand. Opportunities for mixed cropping are limited when mechanised harvesting is practised, although farmer experience suggests that a combination of engineering solutions and changed management practices (e.g.windrowing prior to harvest) may overcome some of the problems.

Furthermore, grain crops are frequently used as nurse crops for establishing pastures. Clover and lucerne, for example, establish well when sown with cereals and canola or direct drilled into stubble, so the concept is feasible. Sometimes pasture is weakened by herbicide to allow a crop to be sod-seeded and this could be a viable approach to suppress competition in other alternative intercropping systems. Apart from some recent GRDC-funded trials with lucerne, the concept proposed here of crops being direct-drilled into a perennial legume stand does not appear to be under study elsewhere.

6.4 Priorities

- Evaluation of the concept that annual crops can be direct-drilled into a perennial winter-dormant, summer-active prostrate legume stand using lucerne ecotypes as a model. If positive results are achieved with a Spanish ecotype, breed more suitable varieties of lucerne for use in Australian agriculture.
- Evaluate germplasm and assess opportunities to breed a perennial, winter-dormant, summer-active soybean.
- Evaluate safflower and other summer crops for opportunistic sowing into stubble when soil moisture levels are elevated.
- Introduce and evaluate diverse native and exotic perennial legumes to provide more flexibility in the use of winter-dormant, summer-active legume swards as a sustainable base in which annual cropping can be practised. Breed adapted varieties as required.
- Evaluate winter cereals, canola, linseed and other winter crops, especially varieties capable of continued vegetative or reproductive growth after the main crop is harvested.
- Evaluate available perennial crops of wheat and rye relatives and perennial legume crops to monitor water use, summer survival and practicality of use of perennial grain crops. Identify problems of disease and summer survival limiting second and subsequent year performance.

6.5 Capacity

There is the intellectual capacity in Australian institutions to evaluate the above concepts and to breed appropriate required varieties. However, funding for original research is currently limited.

6.6 Timelines

Evaluation and some selection and breeding can be achieved in a 5 to 10 year timeframe if adequate resources are available.

6.7 Confidence

The above concepts can be evaluated and many, but not all, of the required varieties can be bred using traditional means though for some aspects biotechnology may provide requirements rapidly.

6.8 Risks

- Weed control may be a problem in perennial legume swards. Biotechnology can readily provide herbicide-resistant varieties if required.
- Perennial cereal crops may suffer from virus and root rot attack. Resistances may be located in wild relatives or provided by biotechnology. If summer survival is a problem for perennial crops, some

summer dormancy may be transferred from wild relatives, but diversion of resources to provide perennial roots, dormant buds and stem-base reserves would reduce grain yield.
- In some species it may be difficult to find resistance to adverse soil conditions. Soil chemical features may be modified by changing the soil pH, or by biotechnological support for breeders.
- Removing legumes early under wet conditions can lead to nitrogen and water percolating through the root zone

6.9 Future Directions

A research workshop should be held to define research objectives emerging from this meeting. Imaginative agronomists, biotechnologists, breeders, geneticists, and physiologists should be invited to make contributions on opportunities to develop varieties and strategies to minimise the risk of water and nutrients passing beyond the root zone in crops and pastures.

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7. Developing Sorghum Plants with the Capacity to Control Deep Drainage and Nitrogen Leakage

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7.1 Introduction

Grain sorghum, Sorghum bicolor (L) Moench is a drought resistant tropical C4 cereal. It is a member of the tribe Andropogoneae that also includes maize and sugarcane. Large variability exists within cultivated sorghum germplasm for characteristics influencing plant architecture, grain characteristics, phenology and adaptation. Sorghum is grown as a commercial grain crop from the tropics to approximately 42° of latitude and as a traditional crop at elevations up to 2500m and between the equator and up to 50° of latitude.

Sorghum is cultivated as three distinct crop types: grain sorghum, forage sorghum and sweet sorghum. Grain sorghum cultivars are usually F1 hybrids between two inbred lines. The hybrids grow to between 0.8–1.3m tall and are harvested with conventional headers. Dryland grain yields in Australia can be as high as 12t/ha but average around 2t/ha with plant available water being the main determinant of yield. Forage sorghums are hybrids between a sudangrass (grassy sorghum) inbred and a conventional grain sorghum inbred. Sudangrasses are tall thin stemmed and profusely tillering types with good regrowth potential. Forage sorghum is suited to direct grazing, hay and green-chop. The sweet sorghums resemble sugarcane in growth habit and also accumulate sucrose in their thick stems. However, unlike sugarcane they also produce significant quantities of grain. In developed countries the cultivars are generally hybrids between a normal grain sorghum female and a sweet sorghum male. In Australia, sweet sorghum is grown as an annual crop that is either used for direct grazing or for green chop and silage. Sweet sorghum is being used as an alternative source of sucrose in China and has been investigated for sugar production in a number of countries. Renewed interest has been shown in sweet sorghum as a biomass crop to produce carbon neutral energy products such as ethanol combined with paper products from the fibre.

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Sorghum is a well-established crop in northern Australia and significant research capacity exists in the fields of breeding, molecular biology, plant physiology, crop modelling and agronomy. This review will concentrate on the current situation and potential for improvement of sorghum relative to the functions and characteristics identified by the Redesigning Agriculture for Australian Landscapes (RAAL) Research Program.

7.2 Sorghum characteristics and functions relative to RAAL design principles

Deep roots

- Sorghum is a deep rooting crop, with roots reaching a maximum depth of up to 1.9m shortly after anthesis (Robertson et al., 1993). This compares with rooting depths of approximately 1m for winter cereals such as wheat and barley.
- In general, later maturing sorghum genotypes have the potential to develop deeper roots. The potential rooting depth of perennial and ratoon sorghum has not been documented but may be even greater than those recorded for annual sorghum crops.
- Genotypic variation in root distribution has been observed (Damodar et al. 1978), with drought-resistance genotypes exhibiting heavier roots, greater root volume, and higher root:shoot ratios compared with drought-susceptible genotypes (Nour and Weibel, 1978). In Queensland, significant genotypic variation in transpiration (248 to 373mm) has been observed among sorghum hybrids grown under post-anthesis drought on deep soils. Genotypes derived from Nigerian Kaura extracted more water from the profile than other genotypes (Borrell et al. 2001).

Development of germplasm

- It is technically difficult to measure root characteristics directly in a large-scale breeding programs (Blum, 1988) and genotype by environment

interaction may further complicate the identification of superior genotypes (Gulmon and Turner, 1978).
- Indirect measurements of root activity, such as the determination of water extraction by water depletion methods are very prone to errors associated with the separation of extraction and drainage (Stone et al., 1973), unless deep soils that have a lower layer with low hydraulic conductivity are used (Ludlow and Muchow, 1990).
- It may be possible to directly measure root growth in a limited number of accessions, such as parents and individuals from mapping populations. If QTLs with large effects exist, it should be possible to identify linked molecular markers which could then be used for marker assisted selection.
- If genetic variation for root characteristics proves to be controlled by many genes with small effects then traditional selection combined with some sort of indirect screening technique would be the best approach. This might involve the use of managed environments.

Sorghum roots can extract water from the soil to a depth of at least 1.9m. Genetic variation in rooting depth and nutrient uptake has been observed. Selection for deep rooting in breeding programs would be difficult, but could be achieved with adequate resources. Variation in rooting depth associated with perenniality needs further investigation.

Ability to grow over a broad temperature range

- Sorghum is a C4 grass of tropical origin and is generally favoured by relatively higher temperatures. Sorghum leaves are killed by frosts and significant genetic variation for frost tolerance has not been identified. However the basal nodes and/or rhizomes of mature plants are quite frost tolerant and have the capacity to regrow in spring from basal nodes after being exposed to winter temperatures as low as minus 10°C.
- Both germination and growth are affected by temperature and genetic variation exists for both characteristics.
- Wade et al (1993) identified considerable genetic variation among commercial sorghum hybrids. Base temperatures ranged from 5.9° to 9.8°C and actual germination rates varied up to two-fold. In a study of sorghum germplasm lines Thomas and Miller (1979) concluded that minimum germination temperature may vary within the species from 4.6° to 16.5°C.
- In Australia it is commonly recommended that daily minimum soil temperatures of 15°C and above at planting depth are required for successful germination and establishment.
- The minimum temperature for C4 photosynthesis is between 5° and 10°C. Under favourable conditions of moisture and nutrition, canopy leaf area development is strongly associated with temperature (Hammer et al., 1987, 1993). They found accumulation of total plant leaf area was represented well by a logistic function of thermal time from emergence (TT) for a wide range of environments and genotypes. TT was calculated using a base, optimum and maximum temperature of 11°, 30°, and 42°C respectively. These cardinal temperatures were derived by examining the effect of temperature on rate of appearance of fully expanded leaves. There was genotypic variation among the hybrids examined, but they were elite cultivars.
  - Biomass accumulation rate is also affected by temperature in sorghum (Peacock, 1982). In summarising effects of temperature on growth rate in their sorghum crop model, Hammer and Muchow (1994) used a function that reduced growth proportionately as average daily temperature fell from 20° to 8°C. Ontogeny of sorghum is known to respond to temperature in a similar way, with base temperatures ranging from 9° to 13°C depending on genotype and stage of development (Hammer et al, 1989).
  - Seed set in sorghum is reduced by exposure to low temperatures around flowering, which causes male sterility (Downes and Marshall, 1971). Temperatures below 13°C during pollen mother cell meiosis can give rise to this effect. Brooking (1976) confirmed the mechanism associated with the sterility and reported significant genetic variation in low temperature tolerance in sorghum (Brooking, 1979).

Development of germplasm

- There is an opportunity to reduce this minimum temperature constraint for germination and establishment. Minimum germination temperature may vary within the species from 4.6° to 16.5°C (Thomas and Miller 1979). Sources of cold tolerant germplasm such as the Kaoliangs from China have been identified.
- Genetic variability for growth at low temperatures exists within sorghum and could be exploited by conventional breeding.
- Conventional breeding for frost tolerance is unlikely to be successful, however biotechnological approaches may hold some promise.

The susceptibility of sorghum leaves to frost is the major limitation to its ability to maintain functioning leaf area during the cooler parts of the year. Traditional breeding is unlikely to produce sorghum genotypes with significant frost tolerance. Biotechnology may provide a means by which frost tolerant sorghum could be developed. Genetic variation for germination, emergence and growth under cool temperature exists within current germplasm. Traditional breeding techniques combined with

appropriate screening environments should produce sorghum with improved cold tolerance. Given the physiological limitations of C4 photosynthesis it is unlikely that sorghum will be highly productive during winter. However, the ability of leaves to survive periods of cool temperatures or frost at the beginning or end of the growing season would be an advantageous.

Perenniality

- Sorghum is an opportunistically perennial species and significant genotypic differences in the degree of perenniality exist within the genus and species, varying from strongly perennial types such as the rhizomatous weedy species *Sorghum halepense* (Johnsongrass) to types with strongly annual habit. All commercial sorghum hybrids grown in Australia exhibit some degree of perenniality.
- Grain sorghum becomes more annual if water deficits are experienced during grain filling. Typically post-anthesis water stress results in leaf senescence, and under severe drought, plant death. Considerable genetic variation for non-senescence during post-anthesis drought exists within germplasm used by breeders (Borrell et al 2000a, Borrell et al 2000b, Van Oosterom et al 1996, Rosenow et al 1996). The genetic control of non-senescence is relatively well understood. QTLs controlling stay-green have been mapped in a number of studies (Tao et al 2000, Crasta et al 1999, Tuinstra et al 1997). Genotypes with high levels of non-senescence are more strongly perennial.
- Sorghum plants have the ability to regrow from basal nodes/or rhizomes. Genetic variation exists for both rhizome production (in wild relatives) and ratooning ability. In fact QTL controlling regrowth, tillering and rhizome formation in sorghum have been mapped (Paterson et al 1995).
- Susceptibility to diseases, particularly Johnsongrass mosaic virus (JGMV) can significantly affect perenniality by reducing plant vigour and causing plant death. Genetic variation for tolerance to JGMV exists in sorghum germplasm (Franzmann et al 1996).

Development of germplasm

- Selection for regrowth potential has been carried out in forage sorghum breeding programs. However, the trait is of little interest in most grain sorghum breeding programs. Development of germplasm with improved ratooning ability should be quite achievable by conventional plant breeding. Development of grain sorghum genotypes that produce rhizomes should also be relatively easily achieved through conventional breeding.
- Green leaf area at physiological maturity has proved to be an excellent indicator of stay-green, and has successfully been used to select drought-resistant sorghums in the USA (Rosenow et al., 1983) and Australia (Henzell et al., 1992). Genetic variation exists in sorghum for resistance and tolerance to a range of leaf diseases including JGMV. Successful selection for tolerance and resistance has been achieved in current breeding programs through conventional breeding.
- Biotechnology may provide a means to produce germplasm with durable resistance to JGMV through viral coat protein-mediated resistance. This type of resistance has been demonstrated with a closely related virus in sugarcane (Joyce et al 1998).
- Ratooning of sorghum has been successfully carried out with current varieties by a small number of sorghum growers (Calderwood et al 1996), however the agronomy and economics of ratoon based farming systems have not been well investigated.

Current sorghum varieties show quite high levels of perenniality. If required the degree of perenniality in sorghum could be rapidly improved through selection for non-senescence, ratooning ability and disease resistance. Rhizome production could also improve perenniality, however the value of this trait would need to be assessed relative to the danger of weediness. Biotechnology could further enhance perenniality through frost tolerance and durable virus resistance.

Quick rooting growth

- Few studies have been undertaken to examine genetic variation in rate of root growth in sorghum. The water extraction pattern of two genotypes grown under continuous soil drying was analysed by Robertson et al. (1993). They found that the extraction front velocity averaged 3.43cm per day. They reported no significant difference in extraction front velocity between the two genotypes E57 (highly drought-resistant) and Pride (moderately drought-resistant).
- However due to the rapid growth rate of sorghum shoots under suitable conditions it is likely root growth is also quite rapid compared with other species.

Evidence of variation in rooting growth is required before this trait can be considered for selection in a plant-breeding program. Given the variability within sorghum for most traits it is likely that variation exists. However, even if genetic variation is found, measurements of rooting growth will not be easy to determine en masse. If suitable screening methods were developed it may be possible to measure this trait in a limited number of accessions, such as parents of crosses or progeny in mapping populations. It may then be possible to develop molecular markers linked to the QTLs controlling the trait.

Large leaf area and duration

- Sorghum has a large leaf area per plant compared with most other cereals. Under ideal growing conditions leaf area accumulates rapidly. It also has the capacity to maintain leaf area throughout grain filling through the non-senescence trait and via ratooning, to maintain leaf area all year round if moisture and temperature conditions are favourable.
- Total leaf area for a sorghum plant is the product of culm number per plant, total leaf number per plant, and area per leaf. Considerable genetic variation has been found in each of these components (Hammer et al., 1987; Van Oosterom, 1996; Borrell et al., 2000a).
- The stay-green trait will increase leaf area duration in sorghum by reducing the loss of green leaf that normally occurs during grain fill under water limiting conditions. Hybrids possessing the stay-green trait maintain more photosynthetically active leaves compared with hybrids not possessing this trait (Rosenow, 1977; McBee, 1984; Borrell et al., 2000a, Borrell et al., 1999).
- These studies suggest that there is considerable scope to develop sorghum plants with large leaf area duration under a range of water regimes. The perenniality of sorghum can also result in extended leaf area production via ratooning.

Development of germplasm

- Variation in stay-green can effect leaf area duration and has been observed and exploited in sorghum.
- Leaf area and leaf area duration of sorghum can be relatively easily manipulated by varying maturity and additional genotypic variation for leaf area also exists within a maturity group.
- The perenniality of sorghum can result in year-round leaf area production via ratooning. However, sorghum's susceptibility to frost and its low growth rate under cool conditions limit winter growth particularly in southern regions.

Sorghum has a large leaf area and it's perenniality can result in year-round leaf area production and large leaf area duration. However this potential leaf area will be modified by environment. Under conditions of water stress, the degree of drought tolerance will constrain leaf area duration. In regions where frosts occur, frost tolerance and the ability to grow at low temperatures will impose a limit on leaf area duration. Cold tolerance, drought resistance and matching leaf area to environment is more likely to maximise leaf area duration compared with selection for increased leaf area per se.

Ability to tolerate adverse soil conditions

- Sorghum has been classified as being moderately tolerant to salinity (Maas 1985) and substantial genotypic variation for tolerance to salinity has been reported within cultivated sorghum (Taylor et al 1975, Azhar and McNeilly 1987, Maiti et al 1994) and its wild relatives (Yang et al 1990a; Yang et al 1990b).
- Genetic variation for aluminium tolerance exists in sorghum (Boye-goni and Marcarian 1985, Maciel-GA et al 1995) and estimates of its heritability are high enough to suggest that breeding for improved tolerance is feasible (Gourley et al 1990 Maciel et al 1994: Borgonovi et al 1987).
- Genetic variation for tolerance to toxic concentrations of manganese has been identified in sorghum (Mgema and Clark 1995). Mechanisms of tolerance are known to be different from those that are involved in aluminium tolerance.

Development of germplasm

- Despite the known genetic variability, no studies have been published showing the outcome of selection studies for increased salinity tolerance of sorghum (Igartua et al 1995). Breeding for salinity tolerance is complicated by spatial and temporal variability in salinity and variation in the susceptibility of different plant growth stages to the deleterious effects of salinity.
- The relatively simple genetic control of aluminium tolerance in other cereals suggest that genetic advance for aluminium tolerance in Australian sorghum germplasm should be rapid using either traditional or marker assisted selection. In most countries sorghum is grown on soils of neutral or slightly alkaline pH, however sorghums tolerant of the nutritional problems associated with acid soils are grown in countries such as Brazil and Argentina and selection has been successful in producing sorghum genotypes with improved aluminium tolerance (Duncan et al 1992).
- Little research has been carried out into the potential for improving Mn tolerance in grain sorghum.

Genetic variation exists within cultivated sorghum for tolerance to adverse soil conditions associated with soil salinity and acidity. The prospects for improving resistance of Australian sorghum hybrids to soils with high levels of toxic aluminium are promising, particularly given the success of other breeding programs. However, while genotypic variation in tolerance to salinity and manganese toxicity exists, exploitation of this variation by conventional breeding will require the development of suitable screening methodologies.

Ability to store and redistribute water and nutrients in the root system for later use

- There is some evidence that deep roots may have additional benefits for water extraction and root function because water uptake continues at night, leading to an increase in the soil water content of upper soil layers and presumably of roots in these

layers (Richards and Caldwell, 1987). Extraction of water from these upper layers occurs the following day. Such 'hydraulic lift' would keep roots alive in the upper layers where most of the nutrients occur and would therefore promote nutrient uptake.
- There is no evidence to suggest that sorghum plants have the ability to store water for later use. It is likely that sorghum rhizomes have some water storage potential and while this may enhance survival, it will probably not contribute to productive growth.

The prospects for improving the ability of sorghum to store and redistribute water and nutrients in the root system for later use is largely unknown but likely to be poor.

7.3 Capacity

Sorghum is a well-established crop in northern Australia and significant research capacity exists in the fields of agronomy, breeding, biotechnology, plant physiology, crop modelling and agronomy.

Agronomy

- Sorghum is a major component of farming systems in the northern grain belt.
- The technology needed to establish grain or forage sorghum is available to most grain growers, including planting harvesting and weed control.
- Sorghum can be used to produce a range of products including grain, forage, sucrose and fibre.

Breeding and germplasm

- The Australian sorghum industry supports one public and five private sector breeding programs.
- Using winter and or glasshouses it is possible to grow three generations per year so genetic progress can be rapid.
- Access to diverse sorghum germplasm is available through the world sorghum collection, the Tropical Genetic Resource Centre based at Biloela and germplasm exchange with other public sorghum breeding programs around the world.
- Because sorghum is a hybrid crop it can often be relatively easy to develop new hybrids with adaptation to specific environments by manipulating parental combinations. For example a female parent line developed to have improved tolerance to toxic aluminium could be used both as the parent of a grain sorghum hybrid and as the parent of a forage sorghum hybrid developed for grazing.

Biotechnology

- Sorghum is a diploid with a compact genome that is amenable to genetic manipulation by both conventional and biotechnological approaches.
- The sorghum genome is relatively small compared with other cereals and less than twice the size of rice and about 1/20 the size of wheat.
- Polymorphism levels in breeding populations are high relative to many other cereals.
- The QDPI, CSIRO and various international research programs have active molecular marker research programs in sorghum.
- Sorghum can be transformed by the particle inflow gun technology and the University of Queensland is carrying out sorghum transformation research.
- The capacity to carry out genomics/micro-array research in sorghum and sugarcane is being developed by CSIRO Tropical Agriculture.

Physiology and modelling

- The physiology of sorghum is relatively well understood.
- An excellent sorghum crop model has been developed by the agricultural production systems research unit (APSRU).
- Research into sorghum physiology currently being carried out by both the QDPI and CSIRO Tropical Agriculture.

7.4 Opportunities

We believe that the tremendous genetic diversity of sorghum combined with its inherent characteristics present a number of opportunities to develop sorghum genotypes that will help to control deep drainage and nitrogen leakage from agricultural systems. These opportunities include: 1) Perennial cereal crop; 2) Perennial forage crop and 3) deep rooted carbohydrate/ biomass crop. Table 1 below identifies traits that we think are important in each case and provides some estimate of the degree of difficulty in developing genotypes with those characteristics.

Perennial cereal crop

Current grain sorghum hybrids all exhibit some degree of perenniality. If temperature and soil moisture conditions are suitable sorghum will continue to grow and produce new tillers after the initial grain crop matures. Harvesting and ratooning after grain maturity further encourages growth from basal nodes and, if conditions permit, further grain production can occur. During the cooler months, low temperatures and frosts slow or prevent active leaf growth. However, the basal nodes of mature plants are quite frost tolerant and have the capacity to regrow after being exposed to winter temperatures as low as minus 10°C. Some investigation has been carried out into the potential for growing perennial/ratoon sorghum in Central Queensland (Calderwood et al 1996).

Much of the soil in the northern grain belt (Liverpool Plains and Darling Downs) consists of deep clay with

high water holding capacity. Rainfall is highly variable and bimodal with a peak in summer. Major rainfall events that cause waterlogging, runoff, and deep drainage occur during summer. To reduce deep drainage and nutrient loss, active crop cover through spring–summer–autumn is needed, especially during SOI positive phase conditions, where high rainfall likelihood is enhanced. Perennial sorghum might be one way to maintain crop transpiration over this period. However in drier years where water conservation is required for successful cropping, a perennial sorghum would be disadvantageous. It is likely that a combination of genotype, management and climate forecasting might provide the balance needed to minimise solute leaching risks, while not jeopardising financial risks (Hammer et al., 2000). For example, short season and/or wide row configuration annual crops would be preferred in drier years that are often associated with SOI negative phase conditions, whereas long season, ratoon and high density perennial cropping would be preferred with SOI positive phase conditions. Some capacity to have a system allowing adjustment mid-season, depending on circumstances, would be valuable. This might be facilitated via herbicide resistance genes in half the population allowing simple spray out. Biotechnological or management approaches to control dormancy, canopy development, tillering, timing and synchrony of flowering would also be valuable to manage water use. Breeding to increase the temperature range at which sorghum will grow and improving frost tolerance may also be of value. Given that current sorghum genotypes are already partially adapted to this type of farming system, the probability of developing suitable genotypes is high.

A highly drought resistant summer cereal like sorghum could have a role in the traditionally winter cropping regions to control deep drainage and nutrient loss during the summer period. Sorghum is grown commercially in the USA at latitudes of up to 42°. This would include all of mainland Australia. Temperatures in summer in southern Australia are more than adequate for sorghum production and the major factor limiting grain sorghum production in southern regions is the availability of moisture during the growing season. Sorghum crops best suited to this environment would have enhanced rooting depth and the capacity to tap shallow water tables as well as make opportunistic use of summer rainfall events. Initial establishment of the crop may impose a limitation unless supplementary irrigation is available. Improved germination and establishment under cool temperatures may play a role in expanding the potential planting window for the crop. Additional characteristics might include enhanced drought resistance and tolerance of various soil toxicities (salinity and aluminium). The role of using sorghum's perenniality to enable stands of sorghum to survive the winter and produce adequate yields in summer would also need to be investigated.

Perennial forage crop

Like the grain sorghums, current forage sorghum hybrids also exhibit some degree of perenniality and will continue to grow while temperature and soil moisture conditions are suitable. Again, low temperatures and frosts limit or prevent active leaf growth during the cooler months and plants will regrow from basal nodes when temperature and water conditions are suitable. Improved perenniality, cold and frost tolerance, increased rooting depth and, may result in improved adaptation to this type of system. Rhizome production would result in increased perenniality and persistence but the weediness potential of these cultivars would need to be assessed. The success of perennial sorghum varieties as pioneer pasture species in newly cleared brigalow areas suggests that, at least in northern Australia, the use of sorghum in the role of a perennial pasture species is feasible.

Forage sorghum genotypes with improved adaptation to southern regions could be developed through improved perenniality characteristics, increased rooting depth and improved drought, cold and frost tolerances. Forage sorghum crops best suited to this environment would have enhanced rooting depth and the capacity to tap shallow water tables as well as make opportunistic use of summer rainfall events. Initial establishment of the crop may impose a limitation unless supplementary irrigation is available. Improved germination and establishment under cool temperatures may play a role in expanding the potential planting window for the crop. Additional characteristics might include enhanced drought resitance and tolerance of various soil toxicities (salinity and aluminium). The potential for perennial sorghum to survive winter and produce adequate yields in the following summer would also need to be investigated. Currently forage sorghum is grown in some areas of southern Australia either when opportunity arises through summer rainfall or under irrigation. Little breeding effort has been placed into the development of forage sorghum with improved drought resistance, and given the progress that has already been made in grain sorghum, the prospects are bright. Forage sorghum is generally grown in monoculture, however it may prove fruitful to investigate the value of incorporation of sorghum into perennial pastures.

Deep rooted carbohydrate/biomass crop for the northern region

Sweet sorghum is a deep rooting and water efficient crop that has the potential to produce large quantities of biomass (up to 45tDM/ha) in the form of grain, sucrose and fibre (Dalianis 1997). This type of sorghum could be used as an energy biomass crop to produce a variety of products including sucrose, fibre for paper making, and bio-ethanol. In addition sorghum biomass crops could potentially be used to produce specialised products or

feedstocks via genetic modification. Bio-production of products such as feedstocks for plastic production has been demonstrated in canola. Suitable commercially viable products for cereals are yet to be developed. Currently the use of biomass producing crops for energy production is not commercially viable. However, government intervention to tax carbon producers or reward carbon users could dramatically influence the profitability of biomass crops. Recently, the Commonwealth Government has agreed to not place any excise on the production of ethanol from crop biomass, increasing the attractiveness of this industry. Pilot programs are currently under way in the USA and Europe to evaluate the feasibility of producing fuel ethanol from sorghum. Three experimental ethanol production plants are currently being run in Kansas using ethanol derived from grain sorghum. This ethanol is blended with 15% petroleum to produce a fuel suitable for modified motor vehicles. The Ford motor company has produced a range of motor vehicles designed to run on this fuel.

Using existing variation within sorghum germplasm it would be possible to develop sorghum as a perennial or annual carbohydrate/biomass crop in much of the northern grain belt. Breeding work could further develop sweet sorghum hybrids with adaptation to the northern region. Traits such as those previously listed for the perennial cereal would also be of value for the biomass crop. Sweet sorghum could also complement sugarcane in the northern coastal zone by making increased use of sugarcane infrastructure during periods when sugarcane is not being crushed. While sorghum would need to be harvested more frequently than sugarcane, there are many features of the crop that make it easier to manage than sugarcane. It is much quicker to establish than cane, and can therefore maintain a higher leaf area/year than cane. This increases the ability of the crop to remove excess water and nitrogen. Commercial sugar production from sorghum is carried out in China and India. Biomass production from sorghum is possible in southern regions, however it is unlikely that this production could be sustained without significant supplementary irrigation.

The economics of bio-ethanol production is a major impediment to the development of this type of crop. Factors such as the development of suitable infrastructure are also critical. The development of suitable alternative bio-engineered products is also uncertain.

7.5 Conclusion

The agricultural crops grown in a region are a complex function of genotype (crop adaptation), environment, management practice and economics. In order to successfully redesign agricultural systems it is important to consider all of these components together.

A key feature of agricultural systems designed to significantly reduce leakage of water and nutrients will be the matching of crop water use to water availability. This is inherently difficult in our production environments due to the variable nature of rainfall events, particularly in the northern cropping region. Because of this variability, high water use systems designed to prevent deep drainage will be intrinsically unstable. One possible solution to this problem is to develop cropping systems that can be altered during the growing season either via management or a combination of management and genotypes. Biotechnology may provide us with some useful tools for this type of management. A simple example of a management system which allows for adjustment of crop water use mid-season is the deployment of herbicide resistance genes in half the population (eg alternate rows) allowing simple spray out. Combined with improved climate forecasting these “management genes” could greatly improve the potential to develop stable systems that are able to match climatic variability.

Genetic manipulation of crops to alter specific characteristics or functions either via conventional breeding or biotechnology becomes increasingly more difficult and time consuming as the number of traits which need to be changed increases. Selection response in traditional plant breeding programs is a function of the genetic variation available and selection intensity. For a given set of resources the selection intensity and therefore the rate of genetic progress declines as the number of traits which are being simultaneously selected increases. Selection is further complicated due to genotype by environment interaction and interactions among traits.

Given these impediments, we believe that the most fruitful path to develop crop and pasture species with many of the characteristics and functions identified by the RAAL is to attempt to modify crop and pasture species which already have many of the required characters. Current commercial sorghum germplasm has many of these functions and characteristics or substantial genetic variation exists within the species for them. In addition the germplasm, expertise and capacity in key technologies already exists in Australia to further develop sorghum genotypes with these traits. Crop models that include plant, soil and climatic factors are a very valuable tool for evaluating particular modifications to crops or cropping systems. The agricultural production systems simulator (APSIM) simulates crop production, soil water balance, soil fertility, and soil erosion from dryland production regions (Hammer et al 1996, Hammer and Muchow, 1994; McCown et al., 1996; Hammer et al., 1999). In combination with climatic databases the sorghum component of this model has been used to investigate the value and effects of particular traits.

We believe that the best approach to developing new sorghum genotypes to control deep drainage and nutrient leakage would be to:

- Identify best bet strategies and traits via simulation studies using existing sorghum and cropping system models (Hammer and Muchow, 1994; McCown et al., 1996; Hammer et al., 1999).
- Concurrently carry out field trials involving current varieties that have potential to function in these new cropping systems. These trials would help to provide accurate specification for such simulation analyses for traits such as ratooning.
- After the most appropriate combinations of traits were identified for a particular system, work could commence to identify sources of germplasm and develop sorghum genotypes with these characteristics via the most appropriate combination of conventional breeding and biotechnology.

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Table 1. Characteristics important sorghum crops with the capacity to control deep drainage and nitrogen leakage

Trait	Role	Importance			Natural genetic variation	Methodology	Prospects of success
		Perennial cereal crop	Perennial forage crop	Biomass crop			
Acceptable forage yields	Economic productivity		High		Current germplasm	breeding	Achieved
Acceptable grain yields	Economic productivity	High		High	Current germplasm	breeding	Achieved
Biomass	Economic productivity			High	Current germplasm	breeding	Partially achieved
Alternative bio engineered products	Economic productivity	?	?	?	None	biotechnology	Unknown
Ergot resistance	Economic productivity	High	Low	High	Current germplasm	breeding	High
Low HCN levels	Economic productivity	Low	High	Low	Current germplasm	Breeding + biotechnology	Partially achieved
Sorghum midge resistance	Economic productivity	High		High	Current germplasm	breeding	Achieved
Sucrose accumulation	Economic productivity		?	High	Current germplasm	breeding	Partially achieved
Control of flowering (delayed)	Management tool	Mod	High	Mod	Current germplasm	breeding + biotechnology	Partially achieved
Control of flowering (timing + synchrony)	Management tool	High		High	Current germplasm	breeding + biotechnology	Moderate
Control of tillering	Management tool	Mod		Mod	Current germplasm	breeding + biotechnology	Moderate
Herbicide tolerance	Management tool	Mod	Mod	Mod	Current germplasm	Biotechnology	High
Cold tolerance	Water and N use	High	High	High	Current germplasm	breeding	High
Frost tolerance	Water and N use	High	High	Mod	None	Biotechnology	Low
Deeper rooting	Water and N use	High	High	High	Current + wild germplasm	breeding	Moderate
Salinity Tolerance	Water and N use	Variable	Variable	Variable	Current + wild germplasm	breeding	Moderate
Aluminium Tolerance	Water and N use	Variable	Variable	Variable	Current germplasm	breeding	High
Frost Tolerance	Water and N use	mod - high	mod - high	mod - high	Current germplasm	Biotechnology	Moderate
JGMV virus resistance	Water and N use	High	High	High	Current germplasm	breeding	Partially achieved
Leaf disease resistance	Water and N use	High	High	High	Current germplasm	breeding + biotechnology	Partially achieved
Non-senescence (Stay-green)	Water and N use	High	?	High	Current germplasm	breeding	Partially achieved
Strong perenniality and regrowth	Water and N use	High	High	High	Current germplasm	breeding	Partially achieved
Rhizomes	Water and N use	?	?	?	Wild germplasm	breeding	High

8. How Can Gene Technology Help Re-Design Plants for an Economic and Sustainable Agriculture in Australia?

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8.1 Introduction

Over the past 200 years the development of food and fibre production industries has led to significant changes in the Australian landscape. Eucalypt woodland has given way to pastures and crops, sandplain vegetation to wheat and lupins, riverine plain to irrigated fields. This has resulted in marked increases in productivity of the land with substantial benefits to the economy. These changes have also had other consequences, including acceleration of the natural processes of soil acidification, proportionate increases in nutrient removal, and imbalances between water added in rainfall and irrigation and water use by crops and pastures. In the longer term, while acidity (at least in surface soils) can be neutralised by lime and nutrients can be replaced by fertilizer, the changes in water use have resulted in alterations to the hydrology of landscapes with consequent rising water tables and dryland salinity that is more difficult to counteract. The annual imbalance in water use in dryland farming systems may be as little as 20mm more drainage than under native vegetation (Dunin et al., 1999), but the cumulative effects of this water escaping to the ground water are indeed serious.

Several solutions are being contemplated including re-afforestation, the planting of trees in agroforestry and modifying existing agricultural systems to increase water use and bring it into balance with water inputs. These are based on the notion that the soil water imbalance has resulted from replacing deep-rooted, perennial species with shallower rooted annual crops and pastures that grow through the winter and spring (Dunin et al., 1999). In attempting to overcome some of these problems, modelling of nutrient responses in crops and fertilizer application (Angus et al., 1993; Xu et al., 1993) aim to provide information useful to farmers in making decisions about managing fertilizer application and the breeding of crops for tolerance to adverse environmental conditions. One promising modification to agricultural practice is the use of lucerne, a perennial with deep roots and a strong summer growth habit producing a valuable herbage. Lucerne uses substantial amounts of water over the summer months and dries out the soil profile so that when grown in rotation with cereal and oilseed crops and managed appropriately, the water use of the system is more nearly in balance with rainfall (McCallum et al., 2001). As well as choosing appropriate cropping options and managing rotations effectively, there may also be scope for altering characteristics of existing crops, such as seasonal crop growth patterns and root distribution in the soil to achieve the desired water use. This paper examines the potential offered by biotechnology in improving plants for better water use in agriculture.

Biotechnology is a recent addition to the techniques of plant improvement by genetic approaches. We define biotechnology as consisting of two distinct technologies. The first is marker technology in which genetic markers (DNA fragments) are used in marker assisted selection (MAS) to expedite the combining of existing desirable characters within a new plant line. The second is gene technology in which desirable genes are reconstructed by recombinant DNA methods and transferred into plants to provide new genetic variability. Plants derived using gene technology are termed genetically engineered or modified, organisms (GMOs), whereas plants derived using marker assisted selection are not considered to be GMOs.

In this paper we will focus attention on the opportunities presented by gene technology for improving dryland agriculture. The use of MAS is beyond the scope of this brief paper and will be considered separately under selection and breeding.

The first experimental plants produced using gene technology appeared in 1983. Since then a number of crops have been commercialised. The majority of these plants contain new characters that either provide enhanced competition with weeds or protect against insect pests or viral disease, all of which can be classified as biotic stresses. These new characters were all supplied

* CSIRO Plant Industry

through the introduction of single genes, most of which were derived from microbial sources.

8.2 What are the opportunities to use gene technology to develop plants with improved water and nutrient use?

Currently, in order to successfully use gene technology for plant improvement there are a few criteria that must be met. First, it is necessary to go through a tissue culture phase in which cells containing the new gene are selected on a specific growth medium and regenerated into whole plants. This is labour intensive, slow and it requires the use of selectable marker genes capable of permitting growth on selective agents such as antibiotics, herbicides or nutrients that require uptake and/or metabolism. New methods of gene transfer that do not involve a tissue culture step are under experimental evaluation eg in barrell medic. These new procedures will require good methods to screen for the introduced character.

Tissue culture-based methods for gene transfer have been developed for many crop and pasture plants. A small selection is shown in Table 1. Only a fraction have reached the stage of commercialisation. In Australia, cotton and carnation are the only plants in commercial production. Overseas, canola, soybean and maize are the dominant commercial crops. Many crops are in field trials and under regulatory evaluation prior to commercial release over the next five to ten years.

Table 1 Selected plants already in field trials or commercial production and to which gene technology has been applied in field trials

Cereals	Wheat, Barley, Rice, Oats, Maize*
Oilseeds	Canola*, Rapeseed*, Soybean*, Sunflower
Grain Legumes	Lupins, Peas, Chickpeas, Lentils
Pastures	Lucerne, Subterranean Clover, White Clover, Barrell Medic, Perennial Ryegrass, Fescues
Horticultural Crops	Potato, Tomato*, Papaya, Pineapple, Melon, Squash*, Carnation**, Grape
Fibre Plants	Cotton**, Eucalyptus, Poplar, Flax

*. Already in commercial production globally
**.Already in commercial production in Australia

The second criterion to be met is the availability of genes for defined functions. Until recently, there were relatively few genes available. Large scale genomic sequencing projects have almost reached completion for one dicotyledonous plant, Arabidopsis thaliana and for one monocot, rice. This means that we will have all of the genes present in plants. In addition, the genomes of yeast, a number of bacteria, the fruit fly and a nematode have also been completed. A knowledge of the DNA sequence of all these genes will be useful for the construction of new genes for plant improvement.

The third criterion for the successful use of gene technology in plants is a good understanding of how the genes work. This is currently being approached on a small scale using the techniques of biochemistry, cell biology, gene transfer, physiology and agronomy using a handful of available genes. Progress is still slow and because the genomes of plants contain more than 50,000 genes there is a pressing need to speed up our progress in understanding gene function. The new developments in genome research called functional genomics will begin to provide such an understanding when this is integrated with an analysis of the proteins and the products of metabolism. Functional genomics aims to knock out all of the genes one at a time in one or a few model plants. Such “gene knock-out” plants have already been generated in Arabidopsis and are under development for rice. Analysis of the effects of each of these gene disruptions will provide an understanding of the role of the gene and could enable a rational deployment of that gene for future plant improvement (Cushman and Bohnert, 2000).

8.3 Examples where gene technology may contribute solutions to control water and nutrient leakage

Desirable plant morphology

Table 2 lists the potential opportunities available from gene technology to produce plants with the identified characteristics. Gene technology has, so far, been limited in its scope to introduce gross changes in plant morphology. Besides the introduction of single genes to improve plant performance under stress, plant breeding and selection remain the best option, currently, for introducing gross morphological and physiological changes, such as large leaf area, deep roots, perenniality, broad optimal temperature range and summer activity.

Table 2: Potential for gene technology-based approaches for producing plants with better water and nutrient use

Desirable Traits for Dryland Agriculture	Gene Technology and Selection
Deep Roots	-
Summer Activity	
- Drought Tolerance	+
- Heat Stress	+
Perenniality	-
Broad Temperature Range	
- Cold stress	+
Quick Root Growth	+/-
Large Leaf Area and Duration	+/-
Tolerate Adverse Soils	
- Salt tolerance	+
- Flooding tolerance	+
- Heavy metal tolerance	+
- Acid soils	+
Tapping Shallow Water Tables	-
Storage and Re-distribution Capacity in Roots for Water and Nutrients	+/-

Some attention has been paid to breeding and selection of root characteristics for improved uptake of nutrients. For example, selection for increased root hair length in white clover was successful in improving P uptake (Caradus, 1981) and new techniques are available for identifying root characteristics that are important in nutrient uptake (Nielsen et al., 1998). However, plant breeding to alter root growth rates, root morphology or depth of rooting has been difficult not only because of the intrinsic difficulty of measuring these characters and selecting on a large scale but because root growth is markedly responsive to environmental influences and the genetics of root growth is complex (Lynch, 1997). Molecular genetic approaches have shown some promising progress with the recent isolation of a gene governing how plant cells proliferate and organise to form root systems (Benfey, 2000). Understanding such genes and the promoters that control them will provide insights into root growth and identify opportunities for manipulation. Other genes have also been identified that regulate root proliferation in the vicinity of localised concentrations of nitrate (Zhang and Forde, 1997; Zhang and Forde, 2000). This work holds some promise for manipulating root systems for rapid response to nitrate, with the prospect of more complete scavenging to reduce leaching losses.

Root growth, is often limited by factors such as Al toxicity in acid subsoils or B toxicity in some sodic soils. This limits water uptake from these toxic soil layers to the detriment of crop yield and allows more drainage. Plants vary considerably in tolerance to Al and B offering scope for overcoming this constraint. While improvement by breeding and selection have been effective in species where variation for tolerance exists, eg A1 tolerance in wheat or phalaris (Fisher and Scott, 1993; Oram et al., 1993) or B in cereals (Moody et al., 1993), improvements in other species are being sought through identification of mechanisms and isolation of responsible genes (Delhaize and Ryan, 1995).

Manipulation of nitrate assimilation

Molecular analysis of the genes encoding nitrate reductase and nitrite reductase have provided valuable information on the genetics of the nitrate assimilatory pathway (Hoff et al., 1994). Analysis of the regulation of the pathway at the molecular level has revealed evidence for the involvement of nitrate, light and/or sucrose, and reduced nitrogen in the regulation. Identification of regulatory genes and structural elements involved in transport and storage of nitrate, or in the biosynthesis of cofactors of nitrate and nitrite reductases, will be required to improve nitrogen use efficiency in plants.

Osmotic stress tolerance

A major mechanism that underlies the ability of some plants to better tolerate water deficit is their capacity to accumulate solutes in response to the stress. The functional roles of these solutes are thought to provide protection by either osmotic adjustment directly, or by acting as compatible solutes, thereby allowing the biochemical machinery to continue to function at lower water contents (reviewed by Bohnert and Jensen 1996; Hare et al., 1998). Plants have been engineered by introduction of plant or bacterial genes to produce the same range of osmotically active solutes, such as mannitol, trehalose, glycinebetaine, proline, and fructans as occur normally in highly tolerant plant species. In most cases the concentration of the accumulated osmotic solute appears too low to be effective for osmotic adjustment. For optimum function, tight regulation of osmolyte production would seem a necessary requirement, with induction of accumulation only under the stress condition (drought, salinity, high water loss). Despite this, beneficial responses of modified transgenic plants under drought stress have been reported. An early demonstration of this approach was the synthesis of mannitol in tobacco leading to an increased ability to tolerate high salinity. Mannitol accumulation in chloroplasts may also provide a degree of tolerance to oxidative damage. Osmoprotectant compounds, such as fructans (Pilon-Smits et al., 1995, 1999; Nuccio et al., 1999) have been introduced into plants that do not normally accumulate them. The plants are reported to have increased water stress tolerance. In sugar beets, fructan producing plants attained up to 35% higher total

dry weights than wild-type plants under drought-stressed conditions, without significant differences under well watered conditions (Pilon-Smits et al., 1999). In the absence of clear evidence of osmotic adjustment, alternative beneficial effects of the introduced solutes must be invoked, such as protection of protein structure, preservation of membrane integrity, or possibly protection against oxidative damage. Exogenous application of glycine betaine, which accumulates in water-stressed plants, was also found to maintain better water status during water stress treatment than the untreated plants, and overcame the adverse effects of water stress on leaf CO2 absorption and growth (Xing and Rajashekar, 1999).

In alternative attempts to increase water use efficiency an abscisic acid responsive gene from barley called HVA1, increased root, shoot and total growth and biomass productivity under moderate water deficit conditions. Water use efficiency value increased significantly from 0.53g kg^{-1} to 0.66g kg^{-1} (Sivamani et al., 2000).

Salinity tolerance

Plants transformed with the yeast regulatory genes, HAL1 (regulates cation transport) and TPS1 (regulates sugar metabolism), which affects the expression of a number of stress-related genes, have been shown to have improved salt tolerance and salt and drought tolerance, respectively (Serrano et al., 1998). Suppression of osmoprotectant degradation, such as suppression of proline degradation (Nanjo et al., 1999) has been shown to improve tolerance to freezing and salinity through accumulation of higher levels of proline. Possible beneficial effects of mannitol accumulation on salinity tolerance were mentioned earlier. Improved salinity tolerance has also been associated with over-expression of the gene Alfin1 in alfalfa, which encodes a putative transcription factor (regulatory protein) linked with salt tolerance in this species (Winicov and Bastola, 1999).

Flood tolerance

Flood tolerant Arabidopsis thaliana plants have been produced by expressing the gene encoding isopentenyl transferase, a rate limiting enzyme in the cytokinin biosynthesis pathway. Flood tolerant plants appeared normal but were consistently more tolerant to flooding than wild-type plants. It is suggested that increased endogenous cytokinin in the transgenic plants reduced senescence induced by flooding (Zhang et al., 2000). Flood-tolerant clones of poplar (Populus deltoides Marsh.) with reduced senesence have also been identified by selection (Cao and Conner, 1999). The physiological and molecular basis of the flood-tolerance remains to be elucidated but the manipulation of cytokinin level could be useful for increasing leaf duration.

Sub-optimal temperature tolerance

Tolerance to low temperatures may require a composite suite of protection against freezing, dessication, ice envelopment, photoinhibition, flooding and pathogen attack. While this would be expected to involve an array of genes, a common feature of many of these damaging conditions is that they lead to oxidative stress, manifested as an increase in free radical production and superoxide. Recognition of this common property has indicated that prevention of oxidative stress, by the introduction of oxidant degradation mechanisms may be beneficial for cold tolerance. Transgenic lucerne plants have been produced which over-express various forms of superoxide dismutase (McKersie et al., 1997). A number of these plants have been demonstrated, in Canada, to achieve greater winter survival than controls, and these results have now been confirmed over several years of field trials. The specific biochemical changes induced in the transgenics which allows this winter survival is under study (McKersie et al., 1999)

The ascorbate-glutathione cycle is considered to play a major role in defending plant cells under stress conditions, by detoxification of reactive oxygen species (Foyer et al., 1994). The capacity to engineer stress tolerance in trees via an increase in antioxidant capacity would be of great benefit to forestry and the environment. Poplar plants expressing the bacterial gene for biosynthesis of the enzyme glutathione reductase (GR) were studied to determine whether an increased capacity for glutathione biosynthesis and metabolism led to an increase in the tolerance of plants to environmental and man-made stresses. Over-expression of GR in the chloroplast, caused an approximate doubling of both foliar glutathione and ascorbate. The plants showed a lower sensitivity to the photoinhibitory conditions of low temperature and high light than the non-transgenic control plants.

Endogenous glycine betaine levels show potential to induce cold tolerance. Studies with strawberry that had raised glycine betaine levels in leaves in response to abcisic acid application to unhardened plants increased cold tolerance by two-fold within 72 hr of application and improved freezing survival and regrowth (Rajashekar et al., 1999).

Heavy metal tolerance and soil remediation

Major genes have been shown to be responsible for heavy metal tolerance in natural plant populations eg. in *Silene* (Schat et al., 1996). Metallothionein and phytochelatin genes have been cloned from a number of plant species and shown to be involved in protection from heavy metals such as Cd, Cu and Zn (Zhou and Goldsbrough, 1994; Rausser, 1995; Foley et al., 1997; Clemens et al., 1999). It has been possible to achieve heavy metal tolerance in

Brassica by the transfer of a yeast metallothionein gene (Hasegawa et al., 1997). Likewise Cd tolerance has been achieved by over-expressing glutathione S-transferase or *E.coli* gamma-glutamylcysteine synthetase in Indian mustard (Zhu et al., 1999 a and b). Ni tolerance was achieved in transgenic plants with the expression of a calmodulin-binding protein (Arazi et al., 1999).

Transgenic plants with the potential to detoxify soil contaminants that limit plant growth have been produced (Newman et al., 1998; Gleba et al., 1999). In addition, two plant-based biotechnologies that take advantage of the ability of plant roots to absorb or secrete various substances have been recently developed. They are (i) phytoextraction, the use of plants to remove pollutants from the environment and (ii) rhizosecretion, designed to produce and secrete proteins from roots aimed at improving soil-root interactions.

8.4 Priorities and Capacity

Lucerne already has many attractive features including its deep-rooted trait, availability of drought-tolerant summer-active types, perenniality and high nutritive value as a pasture and fodder species. Lucerne offers the opportunity in many recharge areas to lower the water table while making economically viable use of the land. A major weakness of this species is its susceptibility to acid soils, a problem that should be tractable by gene technology. It is possible to transfer genes to lucerne, but we need one or more genes to confer tolerance to high levels of aluminium.

Australia has strong capacity in gene technology particularly in the ability to transfer genes to many crop, pasture and fibre plants. New genes are becoming available through the plant genome projects. The next hurdle is understanding which genes are critical to water and nitrogen use. Although genes are available for nitrate and ammonium transporters, for nitrate and nitrite reductases as well as for aquaporins we now need to understand the regulation and expression of these genes so as to put them to effective use.

8.5 Timelines, Risks and the Future

One of the greatest hurdles to be faced in designing better plants for an economic and environmentally responsible agriculture is our poor understanding of the gene activities involved in the basic processes of water and nitrogen uptake and assimilation. New genomics-based approaches will help elucidate these processes provided resources are directed toward gaining this much needed knowledge. This is long term basic research which may require 10–20 years to provide useful outcomes. In the meantime there are some promising candidate structural and regulatory genes in hand with potential to provide tolerance to multiple stresses. For instance, a regulatory gene encoding a dehydration-responsive-element binding protein conferred drought, salt and freezing tolerance on transgenic plants by activating a cascade of at least six endogenous genes involved in stress protection (Kasuga et al., 1999). This concept could be evaluated in crop plants in the field within 3–5 years.

There are risks associated with the use of gene technology. These include public acceptance and environmental safety concerns about the use of GMOs. Although these concerns are mostly not based on scientific evidence, there is no denying the fact that the perceptions are very powerful. A further risk is whether access to genes is limited by proprietary rights to intellectual property. The issue of freedom to operate with affordable licences is one which requires due diligence prior to any major research undertaking that is likely to lead to a commercial outcome such as a new cultivar.

A top priority is understanding the physiological, biochemical and molecular bases of plant responses to nitrate, water and abiotic stresses and the associated feedback regulation mechanisms. There are complex interactions between different stress-signaling cascades induced under different abiotic and biotic stress conditions (Shinozaki and Yamaguchi-Shinozaki, 2000). This means that we need to evaluate the effects of introduced anti-stress transgenes on metabolite fluxes and pool sizes and their effects on stress-signaling pathways. Other strategies such as manipulation of the levels of membrane fatty acids to enhance water and nutrient transport, and to increase the rate of scavenging of reactive oxygen intermediates also warrant investigation.

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9. Opportunities for the Development of Oilseeds Adapted to Control Deep Drainage and Nutrient Leakage

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9.1 Introduction

Phase one of the Redesigning Agriculture for Australian Landscapes (RAAL) R&D program indicated the characteristics required to control deep drainage and nutrient leakage. The clear direction from the briefing paper is to identify crops that will provide a vascular linkage to soil water and then transpire that water through a large and actively growing canopy when vapour pressure deficits are high. High biomass, ramified root systems and extended vegetative development are implicit in this model. Current annual agricultural oilseed crops display some of these characteristics and have potential to contribute to the task of controlling deep drainage and nutrient leakage.

The majority of the water leakage, and recharge, is likely to be occurring in winter when annual crops (and even perennials) are growing and transpiring more slowly, thus using less water. Enhancing water use over winter would therefore also seem to be a significant feature in the control of deep drainage and nutrient leakage, combined with enhancing growth during the high water use conditions over summer.

This review evaluates the characteristics of the current oilseed species and the potential to enhance their usefulness through further breeding. In addition, it considers alternative options to address this problem.

9.2 Species of Interest

The characteristics of the annual oilseed crops safflower (*Carthamus tinctorius*), *Brassica* species (*B. napus* and *B. juncea*), niger (*Guizotia abyssinica*) and sunflower (*Helianthus annus*) make them the most likely annual candidates for the control deep drainage and nutrient leakage. The potential of niger (Getinet and Sharma 1996) and safflower (Dajue and Mundel 1996) to be developed as grain crops for arable farming systems have been recently reviewed.

There is a range of other less exploited oil producing species that could be considered either as crops or as a source of novel genes. These include perennial stock (*Matthiola incana*), Morama (*Tylosema esculentum*), *Eruca sativa*, *Sinapis alba*, *Crambe abyssinica* and *Borago officianalis*.

Perennial oil producing plants such as jojoba (*Simmondsia chinensis*) and olive (*Olea europeae*) are quite widely adapted to low rainfall situations, but both require freely drained soils with a low probability of water-logging (Naqvi and Ting 1990, Tous and Ferguson 1996).

9.3 Root Growth and Water Use

Safflower, *Brassica* species (*B. napus* and *B. juncea*) and sunflower are tap-rooted species with a relatively high water use. Root growth has been reported to 2.4m for safflower, 2.2m for sunflower and 1.7 to 2.1m for *Brasssica*, compared to 1.5m for cereals and 4.2m for lucerne (Soil Conservation Authority 1978). Beech and Leach (1989) reported that safflower (375mm) extracted almost twice as much water as wheat (212mm) from the top 2m of soil in southeast Queensland. Further, a three year rotational study on the Great Plains of central USA using a range of pulses, cereals and oilseeds showed that safflower and sunflower used more water than other crops and effectively drained the soil profile (Aase and Pikul 2000). Neilson (1998) reported that summer grown sunflowers extracted water from lower soil depths than canola and *Crambe*.

Harrigan and Barrs (1984) found differences in root length density between Australian safflower breeding lines in pot and field trials. They identified one line which had the highest root length density of all lines tested and proposed its suitability for dewatering. Phulari et al. (1986) found that the safflower cultivar with the greatest root development extracted the most water from the soil and had the lowest water use efficiency (WUE).

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Seiler (1994) reported the potential of sunflower wild progenitors to be used to genetically alter root growth patterns in cultivated sunflower. Although niger is not particularly deep rooted, it is adapted to tolerate waterlogging, and is extraordinarily tolerant of poor soil oxygen supply (Getinet and Sharma 1996). These characteristics could be extremely beneficial in the target situation.

As well as genetic differences, root penetration and water extraction have been modified agronomically in safflower (Abdurhahman et al. 1999) and canola (Norton 1993).

It is unlikely that simply selecting for higher biomass will result in larger root systems. The relationship between top and root growth depends on whether the limitations are above ground, such as temperature and radiation, or in the rhizosphere, including moisture, nutrient supply and disease (Chambers 1987). While the crops discussed all show differences in biomass production, breeding and management to achieve deep roots will also depend on overcoming the above and below ground limitations.

The ability to develop deep tap roots even in the presence of surface water could potentially enhance water use, as could extending the period of vegetative—and hence root growth—to outside the period where waterlogging occurs. Variation for waterlogging tolerance has been identified in *B. napus* (Niknam and Thurling 1995).

Subsoil salinity is a potential limitation to root penetration, and in those situations, salt tolerance would be important. Mild salinization has been reported to reduce water loss per plant and so increase water use efficiency (McCree and Richardson 1987). Safflower and canola are both moderately salt tolerant and both species show genotypic variation for tolerance (Patil et al. 1989, Francois 1994), so that more tolerant lines could be developed. Genotypic differences in tolerance to other subsoil constraints, including toxic levels of boron, manganese and aluminium, have also been reported (e.g. Hocking et al. 1999).

A further area of interest is the capacity of roots to capture nitrogen. There is very little data on N uptake by safflower, although significant genotypic variation has been reported for *B. napus* (Grami and LaCroix 1977).

A feature of robust root systems is pest and disease resistance and Kirkegaard and Sarwar (1998) have identified resistance in *Brassica* species associated with high levels of specific root glucosinolates. *Rhizoctonia* resistance has been found in some *B. napus* cultivars (Khangura et al. 1997) while safflower cultivars with increased *Phytopthora* tolerance have been released in Australia (e.g. Sirothora).

Biotechnology solutions may be required to overcome some of these constraints. There is also considerable potential for utilising bioremediation to reducing toxic levels of some compounds (Kumar et al. 1995).

9.4 Water Use Efficiency (WUE)

In its own right, altering WUE will not necessarily assist in dewatering. The direction would more logically be to identify species that use a lot of water during their growing season, and if they were also efficient at managing carbon assimilation then their productivity would be high. Identification of lines with lower levels of WUE could potentially lead to an increase in water use, provided that water use and WUE were both considered. Cultivar differences in WUE have been reported in *B. juncea* (Ghosh et al. 1994) and safflower (Phulari et al. 1986, Dhoble et al. 1992). Major differences in WUE can result from differences in phenology and temperature responses controlling flowering and maturity time.

Strategies to maximise crop growth in months where transpiration efficiency is lowest could enhance water use. Transpiration efficiency could be altered by canopy manipulation, as the micro-climatic conditions inside a crop canopy are likely to affect temperature, light distribution and vapour pressure deficit. Altering diffusive resistances by selection for leaf characteristics could also be of value (Stanhill 1986, Gutschick 1987). Similarly, exploiting differences in C3, C4 and CAM metabolic pathways, changing the spectrum of radiant energy and modifying stomatal physiology have been suggested as ways of altering WUE (Fischer and Turner 1978, Stanhill 1986, Gutschick 1987). Variation in osmotic adjustment between *Brassica* species (Kumar et al. 1984, 1987) and within *B. napus* lines (Clarke and McCaig 1982, Lewis and Thurling 1991) has been reported. There is variation in leaf waxiness in *B. napus* (Kadkol pers.comm.) and there is considerable morphological variation in a range of plant characteristics in safflower (Dajue and Mundel 1996) and niger (Getinet and Sharma 1996).

9.5 Perenniality and Phenological Development

Perennials develop a large root system over time to allow water extraction during summer. However, effective dewatering and lowering of water tables will result only where extraction is concurrent with a reduction in the volume of water entering the water table. In contrast to perennials, no single annual crop will be able to be used continually, so a suite of deep rooted annuals, including oilseeds, should be considered.

The task of converting the current annual oilseed crops into perennial crops that use water and nutrients all year

round is likely to be extremely difficult. A more achievable objective might be to extend the effective growing season of the annual crops through manipulation of phenological characters and sowing time.

If *Brassica* crops with an obligate vernalisation requirement (e.g. forage rape) are sown in spring, they will grow all through the summer and not flower until the following spring. While genes for winter habit already exist in *B. napus* populations, they are not available in *B. juncea*. Flowering time in *B. juncea* is controlled by daylength (Kirk and Oram 1978), so a vernalisation gene would need to be incorporated. A similar situation would arise in safflower, where flowering is also under strong daylength control. Where the required genetic variation is not available within these particular species, they will require a biotechnology solution.

9.6 Growth Temperatures

The extension of the effective growing season of the annual crops is likely to require enhanced heat tolerance in safflower and *Brassica* species. *B. juncea* is considered to be more tolerant of heat stress than *B. napus* (Kirk and Oram 1978). Developing sunflower cultivars with enhanced cold tolerance will permit the crop to be sown earlier and achieve a higher biomass before flowering. Work to select sunflower lines that germinate at low temperatures has been undertaken (Downes pers.comm). Again, where the required genetic variation is not available within the particular species, it will require a biotechnology solution. The difficulty of incorporating genes for both heat and cold tolerance into one species would need to be considered.

9.7 Priorities

Extension of the effective growing season of the existing annual oilseed crops (particularly *B. napus*, *B. juncea*, safflower and sunflower) through manipulation of phenological characters and sowing time is likely to be the more readily achievable means of enhancing water and nutrient use in the short term than conversion of these species to perennials. Better adapted and higher yielding safflower cultivars for use within arable farming systems. Hybrid safflower cultivars offer some opportunities and are currently being tested in the Victorian Wimmera. An assured, widescale market for the products is essential for the targeted species.

9.8 Capacity, Timelines, Confidence and Risk

Considerable work would be required to develop oilseed species with extended growing seasons that are highly adapted to reducing deep drainage and nutrient leakage. The development of such annual oilseed species would require additional genes for developmental responses, enhanced root development, tolerance to high and low temperatures, tolerance to subsoil constraints and pests and diseases etc. While Australia has some capacity to identify and transfer the appropriate genes, it would be an extremely long term and costly process. The identification of specific genes in alternative species and the cloning and transfer of the genes are difficult and time consuming tasks. With so many changes required, the likelihood of success of such an approach is limited. Risks include the difficulties of identifying the appropriate genes and ensuring their successful expression once transferred to other species.

9.9 Future Directions

There are no easy solutions to the problem. Progress in converting current annual winter crops into perennial crops that use water all year round is likely to be extremely limited. The extension of the effective growing season of some annual oilseed crops through manipulation of phenological characters and sowing time may enhance water and nutrient use to some extent. This approach also has significant limitations.

There is a need therefore to consider other options. Alternative management options include the use of tap rooted oilseeds intercropped into lucerne based systems. Options such as lucerne/*Brassica* or lucerne/safflower mixtures, may provide more reliable and achievable benefits. Similarly, the use of existing perennial species (e.g. *Eucalyptus*, *Melaleuca*) to produce specialty/ essential oils, especially on marginal cropping country, may be a more efficient way to reduce water recharge.

9.10 References

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Appendix 1

Workshop Participants

The following people participated in a one-day workshop in Canberra on Friday 23rd June 2000, to discuss the Scoping Study.

Name	Organisation
Joe Baker	Queensland Department of Primary Industries
Warren Bond	CSIRO Land & Water
David Clarke	Redesigning Agriculture for Australian Landscapes R&D Program
Wallace Cowling	University of Western Australia
Ross Downes	Innovative Plant Breeders Pty Ltd
Bob Gault	CSIRO Plant Industry
TJ Higgins	CSIRO Plant Industry
David Jordan	Queensland Department of Primary Industries
Brian Keating	CSIRO Tropical Agriculture
Chris Louis	Land & Water Resources Research & Development Corporation
John Passioura	CSIRO Plant Industry
Phil Price	Grains Research & Development Corporation
Richard Price	Land & Water Resources Research & Development Corporation
Peter Randall	CSIRO Plant Industry
Richard Richards	CSIRO Plant Industry
Phil Salisbury	University of Melbourne
John Williams	CSIRO Land & Water