Improving the sustainability of irrigation

A discussion of 'lessons learnt' from 10 years of research aimed at improving the sustainability of irrigation in Australia.[1]

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Abstract

The National Program for Sustainable Irrigation has created a Knowledge-base on the web to enable ready access to research findings from the last 10 years that are relevant to irrigation. The Knowledge-base summarises the relevance of the research to irrigation and categorises it, so that different user groups can find what they are most interested in, whether that be guidelines for on-farm irrigation or the economics of public policy decisions. Research relating to water use efficiency and the management of the off-site effects is outlined. Approaches to determining equity are discussed, in particular better ways of evaluating the contributions of the environment and the human economy. Some of the horizons of new research are mentioned, including desalination, advances in plant physiology, integration of regional models of sustainability, use of polyacrylamides and approaches to the comprehensive re-use of water on farm.

The Sustainable Irrigation Program Knowledge base

In 2003 the National Program for Sustainable Irrigation ("Sustainable Irrigation Program") commissioned work to collate and review the published research and 'grey' literature that informs the objective of enhancing the sustainability of irrigation.

The project commenced by looking at research commissioned by the Sustainable Irrigation Program, its program partners and its predecessor, the National Program for Irrigation Research & Development, and then moving out from this body of work to look more broadly at what is being done.

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The National Program for Sustainable Irrigation focuses research on the development and adoption of sustainable irrigation practices in Australian agriculture. The aim is to address critical emerging environmental management issues, while generating long-term economic and social benefits that ensure irrigation has a viable future. The Program has 14 funding partners who are: Land & Water Australia (Managing Partner); Sunwater, Queensland; Horticulture Australia Limited; Goulburn-Murray Water, Victoria; Cotton Research and Development Corporation; Harvey Water, Western Australia; Lower Murray Water Authority, Victoria; Wimmera Mallee Water, Victoria; Ord Irrigation Cooperative, Western Australia; Australian Government Department of Agriculture, Fisheries and Forestry; Department of Natural Resources and Mines, Queensland; Department of Primary Industries and Resources South Australia; Department of Environment Water and Catchment, Western Australia; and Department of Agriculture, Western Australia.

The review is still underway, and the next steps are to review journal articles, then develop a series of fact sheets and/or discussion papers.

As part of reviewing the literature, we asked "What is the relevance of this report to sustainable irrigation?"

To make this literature more accessible, we summarised the reports and have posted the summaries (and, where possible, links to the report) at the Sustainable Irrigation Program website (www.lwa.gov.au/irrigation/literature). Each report is discussed under one or more of the following headings:

- **Relevance to Irrigation**
- **Guidelines & Toolkits** – computer models and tools and any explicit guidelines
- **Efficiency & Profit** – on-farm practice
- **Environment** – off-farm research and practices
- **Public policy** – macro-economic issues & communication approaches

In addition, each report has been categorised as being relevant to one or more broad sectors of the irrigation community: Catchment, Horticulture, Broadacre or Extension & Knowledge Exchange.

These headings partially refer to the scale that the research is targeted towards, and the activity that it covers. Many research projects have aspects of one or more of these categories, and so are included under all relevant ones. A simple matrix of the above categories provides a fast way of getting to a relevant subset of research for an individual. Alternatively, an 'Author' or Keyword search may be undertaken.

The website represents then, a distillation of Australian irrigation research, with a particular focus on the 'grey' literature that often has a great deal of practical information that may not be suitable for refereed publications. The web address is www.lwa.gov.au/irrigation/literature.

The remainder of this paper describes some of the 'take-home' lessons found in this literature, and some of the areas that would benefit from further investigation or integration.

What is sustainable irrigation up against?

Three big challenges for achieving sustainable irrigation are:

1. Routinely achieving excellent water use efficiency (WUE) across whole catchments and commodity sectors.
2. Managing the environmental impacts of irrigation i.e. reducing the amount of excess surface and subsurface drainage water and the associated salt, nutrients, chemicals and soil losses.
3. Achieving equitable distribution – we are yet to implement methods that best achieve equitable distribution of water for sustainable crop production as well as catchment and river needs. The current mechanisms struggle to evaluate and allocate 'benefit' between 'environmental' uses and agricultural uses, and between urban and regional use.

These three challenges are discussed below, as well as

4. On the Horizon – interesting research underway that may provide knowledge breakthroughs

1. IMPROVING WATER USE EFFICIENCY

1.1 Water Use Efficiency & Water Balance

Water Use Efficiency (WUE) is a label given to a whole tool box of indicators of whether water is being used in the most efficient and effective manner. To be able to ensure WUE, an understanding of all contributing factors is required. A sound understanding of water balance, for example, is necessary. Water balance is the process of identifying the water inputs to a defined crop, farm or catchment (irrigation + rainfall + groundwater) and the outputs (crop water use, evaporation, surface run-off and deep drainage).
The central document for understanding developments in water use efficiency is the Irrigation Insight compiled by Fairweather, Austin & Hope (2003). The fundamental rationale behind work to define appropriate measures of water use efficiency is that 'Managing irrigation at the field scale can be improved by quantifying the water balance. Understanding where savings can be made in this water balance is a necessary step to achieving improvements in application or irrigation efficiency'. (p.37). The report recognises that water use efficiency (WUE) needs to be measured at a variety of scales, from Storage, Conveyance/Distribution, Field application and whole of system. Significantly, the report provides average, maximum and minimum measures for a range of Water Use Indices for different crops, providing a starting point for benchmarking (p.52).

1.2 New Techniques

New techniques for improving the effectiveness of water used are summarised by Fairweather et al. (2003) as follows:

- Centre pivots and linear move systems, which have been improved by moving the water outlet closer to the ground by using drop tubes.
- Partial rootzone drying, where part of the root system of grapevines and pome and stone fruit is slowly dried and the remaining roots are kept well watered (see Kriedemann & Goodwin, 2003 and Loveys et al., 1999)
- Development of integrated real-time irrigation scheduling systems.
- Irrigation scheduling methods using remotely sensed crop temperatures.
- Deficit irrigation, which is the practice of finishing irrigation prematurely before the end of the crop cycle, or applying less water than required to replenish the soil moisture deficit at each irrigation.
- Alternate furrow irrigation on non-cracking clay soils.

1.3 Achieving WUE across commodity sectors

Beynon et al. (2002) identified that there are many structural challenges to be addressed to ensure that water use efficiency is comprehensively adopted at all levels of the irrigation and water industries. Commodities such as cotton, rice, horticulture and winegrapes have invested in research and extension programs to significantly reduce the average input of megalitres per hectare. In the report by Marsden Jacob (2003) it is noted that the Cotton industry has been active in developing and promoting best management practices in water application. This has seen a reduction in average application rates to an industry standard of 8 ML/ha, wide use of recycling systems from tailwater drains, and further research into shorter season varieties and use of low-level drip irrigation systems.

Water use in rice growing has dropped substantially over the past 10 years due to industry wide initiatives. Average application rates of 20 ML/ha have dropped where the large majority of growers now operate around the industry target of 12 ML/ha.

The wine-grape sector has seen a significant reduction in water application rates. The sector traditionally applied 8-10 ML/ha when using flood and furrow, depending on the characteristics of the soil and slope. Conversion to trickle irrigation has reduced this application rate to 5-6ML/ha. A development with great potential across a number of winegrape varieties is the partial root-zone drying techniques, where watering only half the plant's rootzone can produce more fruit. Again, science is able to make real breakthroughs for production and the environment.

The Marsden Jacob report summarises the priorities required to drive adoption of greater WUE. With dairying, the range of water use efficiency from farm to farm is very great, and there is a need for an industry program to improve this. The Dairy industry has developed an environmental strategy and is working on an industry-wide approach to irrigation sustainability. The pasture-based irrigation industry (for livestock fattening) does not offer the returns to merit the investment in major improvements in WUE. The likely scenario is that water will be transferred to higher-value uses that involve lower rates of watering.

There is scope for further investigation into the roles of regulation, incentives for new technology, and finding the right mix of benchmarking, training, and government and private extension services. To this end, there are a number of current projects and programs including Queensland's Rural Water Use Efficiency program, Victorian Dept. Primary Industries social research and the new CRC Irrigation Futures commitment to managing knowledge. The Sustainable Irrigation Program has a current research project in partnership with Cotton CRC in the northern Murray Darling Basin titled "Knowledge Management in Cotton and Grains".

Particularly useful references for equipment that can help with improving WUE include the Irrigation Insight 'Soil Water Monitoring' (Charlesworth et al., 2000, with 2004 edition just released), and the 'Know the Flow' project that describes various water meters and their applications (AIC, 1999 and http://www.ancid.org.au/ktf/).

1.4 Strategies to manage water-holding capacity of the soil

One of the major developments for reducing evaporation from irrigated ground has been to use various forms of sub-surface irrigation. Charlesworth (2002) investigated Capillary Rootzone irrigation (a laminar sheet of geofabric protected on top by weed matting and underneath by polyethylene to transmit water horizontally under the crop) and Drip Tape. He found that subsurface drip irrigation (SDI) generated greater returns to management but that the investment decision is sensitive to the system's useful life, the initial investment and the relative crop yields. SDI is a conservative technique that is desirable where water is being supplied from over-allocated or finite aquifers.

There is a vital and on-going role for the use of mulching as a means of increasing the amount of soil carbon and retaining soil moisture. The *use of strategic cover crops* in orchards and vineyards is particularly relevant. Field trials are currently being implemented as part of the CRC Vitculture's Viticare program (http://www.crcv.com.au/viticare/) to look at water use by different cover crop species. Trials will 'investigate 4 cover crops (barley, fescue/ryegrass mix, medic/ryegrass mix and Wallaby grass) with a bare soil control, for their usage of soil water and their impact on vine productivity and quality'. The management of cover crops was also recognised as being an unknown, again from weed control and water usage perspectives. To address this, barley, beans, pasture mix and fescue will be sown as a three replicate trial, then either rolled, mulched, herbicide or bare soil cultivation in spring.' At another site triticale will be compared with chickory, subclovers, fescue and canola. (Penfold, 2004)

1.5 Managing evaporation from storages

The main developments in managing evaporation in storages are summarised in Fairweather et al., (2003, p. 19) where they describe the use of chemical 'skins' on water storages (monolayers), and various floating barriers to reduce evaporation. All but the most expensive options appear to be vulnerable to wind. Aquacaps (Burston & Akbarzadeh, 1999) are floating plastic domes, to reduce evaporation from small storages. Aquacaps have the potential to reduce evaporation from water storages by an annual average of 70% when they cover 80% of the water surface. They also reduce water temperatures and water turbidity. An alternative approach is the use of E-Vap Cap which consists of a unique, multi-layered black and white polyethylene membrane 450 micons in thickness that contains its own buoyancy cells. (Evaporation Control Systems, 2004).

2. MANAGING THE IMPACTS OF IRRIGATION

2.1 Understanding what we can't see

Models of water use suggest that the quantity of water is not necessarily the limiting factor to achieving sustainability. Issues such as rising water tables need to be understood so that impacts on qualities such as ecological values can be assessed. Models of surface water flow, of distribution systems, of groundwater systems and of crop water usage and salinisation have all developed to a stage where they can be used with some confidence to predict the consequences of particular actions, thereby enabling better understanding of causes and effects of irrigated agriculture on production and the environment. A model enables everyone to 'speak the same language' about a process or change that is occurring in the farming systems or the landscape, and helps to quantify the change, so that assumptions can be tested.

The development of models as regionally-applicable tools is a major step forward as the sustainability of the catchment can only be determined by simulating the interaction between paddocks and neighbouring influences such as channel seepage, and lateral flow between paddocks.

Two research models that explore crop production and the issues of irrigation and drainage that have developed a sizeable literature are the SWAGMAN series of models (Khan et al., 2000) and the APSIM group of models (McCown et al., 1996). In addition there are a large number of more specific models that were reviewed by Malano (2000).

Khan et al. (2004) have undertaken similar analyses using the combined abilities of MODFLOW, APSIM and SWAGMAN to identify areas of recharge, discharge and lateral inflow and outflow in the Colleambally Irrigation Area (CIA). Water budget results for 5 zones showed a consistent pattern of groundwater recharge during the irrigation period and groundwater discharge during the non-irrigation period. They identify a need for the whole CIA to reduce total recharge by around 20,000 – 25 000 ML/year, so that groundwater levels do not continue to rise. The modelling has enabled the recharge area (about 30% of the region) to be identified, so that on-farm and regional management options for the groundwater discharge zones can be developed, including the rational sharing of costs between the net groundwater recharging and discharging farms. Similar work in the Murrumbidgee Irrigation Area (Khan et. a., 2004b) provides evidence of some decline in watertables, due to improved irrigation practices and dry years, and the report shows the possibilities of presenting various scenarios for the development and management of the area and what the implications are likely to be, thus providing a quantitative underpinning for a regional discussion of sustainable practices.

The development of models of adequate complexity, and the stratification of the catchment in terms of the behaviour of the groundwater systems, have been crucial to achieving effective management goals.

2.2 Deep Drainage

Ringrose-Voase & Cresswell (2000), working in the Liverpool Plains area of northern NSW, identified the following needs to improve the estimation of deep drainage (recognising that this critical indicator of sustainability can not be directly measured):

- develop more efficient methods of implementing the sampling methodology including the estimation of soil hydraulic parameters.
- validation and truthing of the model.
- investigation of lateral transfers of water within the landscape
- quantify root-zone interactions with groundwater.

Problems in evaluating deep drainage have been identified by Humphreys, Edraki & Bethune (2003), who reviewed the Australian situation. They found :

‘ great variability in deep drainage determinations for similar landuse and irrigation management on the same soil types, reinforcing ...that there is a need for a systematic and comprehensive approach to understanding deep drainage for a range of soil types, landuses and management practices – both its quantification in relation to a defined set of measured soil and site parameters, and determination of what level of recharge is acceptable taking into account the local and regional hydrogeological conditions.
Strategic planning and policy development in the major irrigation areas is increasingly relying on the assessment of water use efficiency, deep drainage and net recharge using water balance models. The review shows that there is lack of good quantitative data for components of the water balance across the range of crops, climatic regions, site and seasonal conditions and management. Clearly it is impossible to carry out comprehensive determinations for all but a few situations, and water balance models must be used to estimate crop water use requirement and deep drainage for the range of situations. Such models need to be evaluated against quantitative data across a range of environments. However, there are few studies that have closed the water balance and which would allow rigorous testing of water balance models.’

Part of this problem is being addressed through the workshop that was documented by Carmichael (NPIRD, 2002) which aims to *standardise calculations of reference evapotranspiration* (through the use of both pan evaporation measurements and calculation using the Penman-Monteith equation) and in determination of crop water use reference factors (Kc) that adjust the reference evapotranspiration according to the physical characteristics of each crop. This may also represent an opportunity to move towards integration of models, while maintaining their modular nature, so that results from different models and different areas are more readily comparable.

Currently, the Sustainable Irrigation Program is helping to fund a coordinated approach to deep drainage research in the northern Darling basin. Working with peak stakeholders, the aim is to identify gaps in knowledge and to overcome them.

2.3 Defining a Sustainable Irrigation System

A separate modelling stream of work that is yet to be brought together with that described above involves *ecological risk assessment* (Hart, 2002). This approach describes the effects of irrigation in terms of probabilities, rather than being deterministic. Currently Case Studies are being undertaken in the Murray Irrigation Region and the Lower Loddon that establish partnerships with the irrigation industries and state resource management agencies to develop capacity within these organisations to use ecological risk assessment and management procedures to improve the ecological sustainability of irrigation regions. .

Work by Lukacs (1999) identified ecological opportunities and limitations in the development of new irrigation schemes. A second paper (Lukacs, 1999b) recommends the development of Sustainability indicators that include:

- measures of biodiversity,
- nutrient and sediment targets,
- aesthetic and ecological values
- water quality,

as well as indicators of farm productivity.

The new CRC for Irrigation Futures will be further developing indicators of sustainability. Complementing this work are two Sustainable Irrigation Program projects being funded in partnership with many stakeholders. They are the Northern Australia Irrigation Futures project to consider an "Irrigation Framework" for policy makers, regulators, managers and investors to use to ensure any irrigation development in North Australia is designed and managed in a sustainable way; and the Goulburn-Broken Irrigation Futures project in the Goulburn Broken Catchment.

2.4 Various Approaches to Managing the Impacts of Irrigation

Engineering approaches to drainage

Within irrigation, the primary focus of work to reduce deep drainage has been in establishing drainage systems that prevent irrigation water entering water tables. For a review of the issues associated with drainage in each of the irrigation areas of Australia, the Irrigation Insight edited by Christen (2001) provides a very useful overview. Generally, the implementation of sub-surface drainage systems (as opposed to surface drains) has been limited by the associated costs, and the focus has remained on better irrigation practices, such as *getting water on and off the paddock quickly*. For example Standen & Roberts (1998) describe increasing adoption of 3 best practice benchmarks:

1. The irrigation system should have channels and channel structures capable of carrying the full flow of water available to the farm meter outlet.
2. Excessive irrigation water drains off without ponding or backing up on bays.
3. No irrigation water leaves the farm.

While there were improvements in all of the above areas, only 14% of all farmers surveyed in 1998 met all three benchmarks. It is predicted that this figure has susbstantially improved over the past 6 years and it would be an interesting exercise to repeat the 1998 survey.

Plant systems to manage drainage

Humphreys et al. (2003) suggested that there was a need to explore crop water use from shallow watertables to increase water use efficiency and/or control watertables by modifying irrigation scheduling. Research by Thorburn (2004) subsequently demonstrated that shallow fresh water tables can contribute significant amounts of water to crops, especially those with potentially deep roots like sugarcane, in northern Australia. In many cases, irrigation can be reduced, and in cases where the depth to the water tables is 1metre, irrigation may be unnecessary. However, water tables at 2 metres depth will supply little water to crops unless their roots are active close to the water table. Cropping system models can capture the impact of shallow water tables on crop response to irrigation and these models can give valuable insights into irrigation scheduling.

There has been a great deal of work undertaken to look at *cropping rotations that reduce the amount of recharge* that occurs below the soil. For example Asseng et al. (2001 a & b) working in the wheat belt of Western Australia, identified the high degree of recharge that was occurring under sandy soils. This could be improved through increased incorporation of organic matter or fertiliser addition to increase crop biomass, thereby achieving a fuller use of all incident rainfall. However, they found that there were only marginal reductions in deep drainage using this methodology and that it was more effective to use Eucalyptus, or lucerne to reduce deep drainage. Verburg et al. (2001) looked at including lucerne into the cereal rotation (phase farming), which was effective in drying out the soil profile and creating a buffer to limit deep drainage during the subsequent cropping phases. How quickly lucerne dries out the profile, and how quickly rewetting occurs under cereal crops depends on factors such as weather, soil type, and crop/pasture management. Edraki et al. (2003b) have demonstrated the merits of irrigated lucerne in drying out soils, so that rotations could be established that reduce recharge of deep aquifers. Similarly, in rice-growing areas, the use of winter crops such as wheat are being used to help use the moisture retained after a rice crop (Humphreys et. al., 2001). This represents a form of opportunity cropping (Stirzaker et al., 2000), which looks at seasonal conditions to determine when an additional crop can be planted. Stirzaker et al. (2000) also describe companion farming, where an annual cereal is sown into a perennial pasture system. These options have been described for managing dryland salinity, and consideration for helping to reduce recharge in irrigated systems will be based on economics.

Improving water quality

Many of the issues associated with improving river and drain water quality are addressed through better management of irrigation itself, as this reduces the volume of water that is draining from the paddock after irrigation. Similarly, close attention to the timing of irrigation events after fertilisation can dramatically reduce the high 'spikes' of nutrients (such as nitrogen) that can be washed off the paddock immediately after it has been fertilised. This is now standard practice for irrigated pasture practice, particularly in the dairy industry. Where water does leave the paddock, most farmers now see that water as an asset to be managed via *on-farm re-use dams*. These can use the water as is, or if it is too saline, this water can be shandied with fresh irrigation water or groundwater (see, for example, the case study in the Colleambally Irrigation area by Prasad et al., 2001). There are some problems with conjunctive re-use however (Surapaneni & Ohlsson, 2002) so there is a vital role for other mechanisms of nutrient extraction and reduction. The Sustainable Irrigation Program, with project partners, has commissioned research into the use of reclaimed effluent water in Australian Horticulture.

There have been a number of studies that have looked at using plant ecosystems (such as native wetlands, artificial wetlands, and vegetation with channels) to reduce the nutrient loads. For example, work done by Hunter & Lukacs (2000) showed that artificial wetlands are effective at reducing suspended solids, but were not particularly helpful in removing Nitrogen. The concentration of Phosphorus (P) went up. In their review of relevant studies they concluded that:

- There are highly variable daily and seasonal nutrient concentrations entering wetlands
- The wetlands acted as both sinks and sources

Therefore, the effect of the wetland is somewhat limited and may not be the most effective way of managing nutrients in drainage water.

However, there are still questions about how 'fully functional' the constructed wetlands were at the time of the studies, and whether the full complement of vascular plants, algae, fungi and invertebrates were on site to fully utilise available nutrients. Possibly there would be the option of harvesting fish or yabbies from these sites and that this would assist in moving nutrient off site. *There may also be opportunities to improve the effectiveness of artificial wetlands through a combination of engineering structures and simple chemical treatment of waters leaving the wetland sites,* thereby keeping the benefits of the habitats that are created but avoiding the deposition of spike loads of nutrients into rivers.

An example of simple chemical treatment using polyacrylamide (PAM) has been described by Soyka & Surapaneni (2000). Polyacrylamide is a product used for stabilizing and flocculating soils, reducing irrigation-induced erosion and enhancing infiltration. It can substantially improve runoff water quality by reducing sediments, soluble Nitrogen and Phosphorus, pesticides, weed seeds and microorganisms. Rates of between 1 kg/ha for furrow irrigation and 4 kg/ha for sprinkler irrigation have been used. U.S. research has shown no adverse effects on soil microbial populations. While cationic and neutral PAMs have toxicities that warrant caution, anionic PAMs are safe when used at prescribed rates. Significant negative impacts have not been documented for aquatic macrofauna, edaphic microorganisms or crop species. *The potential of polyacrylamide (PAM) needs to be highlighted and evaluated in industry case studies.*

3.0 Achieving Equitable Distribution of the available Water Resource

There is an evolving need to find approaches that assess the relative benefits of different water-uses in different parts of the catchment landscape. While the market reforms will assist in ensuring that water is traded to achieve fuller usage, there is not necessarily evidence that the commodities that are produced are necessarily the most appropriate, as the full array of environmental costs may not be fully evaluated in the existing trade. Recent work by Reeves (2004) has attempted to evaluate the contribution of Australian irrigated agriculture to the Australian economy, and to estimate the economic impacts of recent and future water reforms at the national level. In a market-based approach to water allocation, water trades from industries with the lowest marginal value for water (e.g. grazing) to those with higher marginal values for water (e.g. vegetables). Such an approach may be highly affected by varying transport costs of produce, so that while it may be more water-efficient to use water close to its source, it may be less transport-efficient than to send the water downstream so that produce is grown as close as possible to its final markets. Added over the top of this are constraints on the availability of land and productivity of different crops in different climate zones and the relative ecological benefits of water used in different parts of the riverine ecosystem. River red gums, for example, may benefit significantly from increasing river flows at particular times of the year. Therefore, while it is beneficial to put the correct economic drivers in place to enable water to be used for the most profitable industries, it is also important that all of the physical and ecological constraints, benefits and trade-offs are understood as well.

The current trend towards the separation of water rights from land rights, with the consequence of allowing non-users of water to own the water, has implications for the achievement of a just and equitable allocation of water. While it might mean that the water goes to the most efficient producers, until those commodities are truly valued in terms of the water embodied in those products, in the context of the national physical trade account, there will be no substantial way of determining which commodities should be prioritised for national support. There is a trade off between the amount of water used by particular commodities and the load that they place on the national water system, and the overall national return, expressed both monetarily and energetically; as well as environmentally.

Foran and Poldy's (2002) study entitled 'Future Dilemmas' discusses equity and the allocation challenge.

Land & Water Australia and the Sustainable Irrigation Program are currently exploring future research approaches to biophysical and social questions that take into account the complexities in landscape change.

4. On the horizon

Desalination technology

An overview of *desalination technology* and its application in Australia is given by Winter et al. (2001). Since that time desalination plants have been set up to supply drinking water for a number of areas in Western Australia. While the use of such plants for supplying irrigation water appears to be a long way off, as plants can tolerate far higher levels of brackish water, the effect of these desalination plants is to reduce some of the competitive pressures for water between urban and rural uses. A conference is being held on this subject in 2005

Physiology of plant water use

There are many fundamental areas of plant physiology that can potentially contribute to more sustainable irrigation (irrigation using less water to produce more). Amongst these, there are possibilities to 're-design' photosynthesis so that more carbon is produced per joule of energy supplied by sunlight (Davidson, 2003). To effect these changes into crop use would involve plant-breeding and genetic modification of the plants. There are other possibilities in these arenas, that fundamentally shift the energy use of the plant from a broad array of uses, particularly reproduction, growth and maintenance respiration, so that the plant's energy is used more for a particular outcome.
There is also the whole series of possibilities of application of irrigation water more precisely at certain phases in the plant's development (such as has been demonstrated by Regulated Deficit irrigation), that can save substantial amounts of water. The dynamics of root growth and the propagation of valuable organisms such as the mycorrhizal fungi, that expand the ability of the root to harvest water are still poorly understood, particularly in the context of ensuring that soil conditions remain suitable for the growth of these other species.
Meyer observed that *the precise effects of saline water on plants needs further research* (in van der Lely, 1999), and there is the possibility of achieving satisfactory plant yields through precisely deployed saline water i.e. by timing the delivery of water according to physiological phases of the plants' growth or by delivering water to only part of the plant.

Stronger genetic selection for species water use efficiency

Work is on-going to develop rice varieties that are cold-tolerant, which would allow shorter periods of ponding and thus reduce water use (Dennis, 2004). *There are also possibilities for genetic modification of plants to trade off the evolutionary development of resilience within plants for greater efficiencies of photosysnthesis.* These approaches would necessitate controlling the environment within which the plant grows, for example by managing temperature ranges or the competition that the plant is exposed to. The overall benefits of these developments will need to be evaluated using energy accounting approaches, to determine if they are worthwhile.

Interspecies broadacre cropping and drying phases in rotations.

The development of rotations to assist in drying out rice growing areas (Humphreys et al., 2001) illustrates the possibilities for managing recharge and leakage from irrigation areas using an approach where the paddock is soaked and then dried out with different plant rotations. This would assist in 'drawing down' high water tables. A more comprehensive application of these approaches, or more strategic approach to the use of these drying regimes could make a big difference to the recharge within irrigation areas. *The disincentives to the application of these approaches need to be explored and evaluated*. The work of Thorburn (2004) has significantly added to our knowledge of plant water use in shallow fresh water tables.

Open hydroponics

Open hydroponics refers to an approach to fruit and vegetable culture, where the soil is regarded simply as a substrate to anchor the plant, and all the plant's water and nutritional requirements are supplied precisely via a drip irrigation system. The root system of the plant is pruned and restricted so that the plant's nutrition is tightly controlled, and so that the plant spends less energy on root growth. Some results suggest that yields may be increased by about 20%, with a 15-20% reduction in water use (du Plessis, 2004). There is still a need to define guidelines for fertigation treatments. The approach that is being used in some situations involves irrigation at times of maximum evapotranspiration, so that photosynthesis is not limited by heat or water stress (Edwards, 2004). The trade-off being productivity and water use efficiency deserves further exploration. *The Sustainable Irrigation Program is commissioning further research on this topic.*

Integrated re-use farming systems and Serial Biological Concentration (SBC)

Serial biological concentration (SBC) approaches to managing saline water are a useful way to manage and utilise increasingly saline water. A more comprehensive knowledge of the options and interactions between various sequences of usage would be helpful. Work is currently underway at CSIRO Land and Water in Griffith to look at the production of high value crops in the first 2 stages, followed by salt tolerant crops (stage 3), fish farming (4), evaporation basins (5) and a solar pond to generate energy (Humphreys et al., 2001).

Integrated human/natural systems accounting

The term 'triple-bottomline' accounting is a reminder of how our current economic framework is still to acknowledge that it operates within a finite framework of global resources, and that substitution between commodities is not always possible. Far more comprehensive approaches have been developed, but are yet to be widely adopted. The best of these is the EMERGY approach developed by Odum (1996), but the Stocks and Flows model used by Foran & Poldy (2002) is a useful step, with the development of formalised accounting approaches for physical resources. *Further work is needed to develop conventions for using EMERGY accounting techniques, particularly where economic measures have to be converted to energy equivalents.*

Conclusions

Achieving a durable, sustainable irrigation industry is the purpose of many public and private sector organisations that have invested in research over the past 10 years. The ideal of a robust and sustainable irrigation industry is still some way off, as the industry learns from past mistakes and adapts practices to integrate new knowledge.

Particular commodities have made substantial gains in efficiency and effectiveness of water use. There are a number of research projects, new technologies and possibilities for plant breeding that hold out the promise that water use efficiency gains can continue to be made. Products such as Polyacrylamide demonstrate significant potential that warrants further evaluation.

Understanding and managing the impacts of irrigation on the environment is even more complex than the challenges of water use efficiency. There are still many parts of Australia that do not have sufficiently *integrated regional groundwater models*, that are built from robust datasets. The stream of work that is being done on *ecological risk assessment*, and the introduction of a stochastic approach to modelling, is yet to be brought together with the likes of the SWAGMAN models to manage environmental risks. Similarly, evaluation of the environmental benefits of particular regional water-use options have not been included in models; nor have mechanisms for undertaking trade-off analyses of environmental benefits been undertaken. However, the tools to understand and monitor the health and sustainability of different irrigation systems are now reaching a level of sophistication that can account for regional groundwater modelling and the economics of growing particular crops and rotations of particular crops.

Improvements in water use efficiency, coupled with the strong focus on reducing the off-site effects of irrigation, mean that there can be a sustainable future for irrigation. Our challenge is to find better ways to evaluate, analyse and present the trade-offs in the different uses of water.

The development of the Sustainable Irrigation Program's Knowledge-base is a small contribution to the process of ensuring that the issues and the development of solutions are rapidly promoted and adopted.

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