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**Improving Irrigated Agriculture:
How Far Can We Go?**

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Paper prepared for presentation at the “Water For Irrigated Agriculture And The Environment: Finding a Flow for All” conference conducted by the Crawford Fund for International Agricultural Research, Parliament House, Canberra, Australia, 16 August 2006

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SESSION: FUTURE WATER AVAILABILITY AND IMPROVED AGRICULTURE

Improving Irrigated Agriculture: How Far Can We Go?

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The last decade has seen the nexus between increasing world population and the area of irrigated land broken, indicating that further population will need to be fed by improved water productivity rather than through increased irrigated area. But how much improvement is possible?

This paper systematically considers irrigated agriculture from the plant through to a catchment, and from production and natural resource use perspectives.

While there is some evidence of improvement in transpiration productivity (yield per unit of transpired water) of our common irrigated crops, it seems we have reached the limit of potential improvement. Opportunity still exists to increase economic yield while containing seasonal water use through manipulation of vegetative and reproductive growth phases. For crops, the opportunity for improving water productivity largely involves decreasing soil surface evaporation relative to crop transpiration. There are still gains to be made in this area from both improved irrigation system design and agronomic practice. Farm layout, distribu-

tion and application systems can be significantly improved to increase water use efficiency. However, given the relative costs of water, earthworks, labour and equipment, there is often little financial incentive to reduce total water use for marginal gains in yield. Audits of many distribution systems show considerable opportunity for improvement and also highlight the inadequacy of current measurement systems. There is generally good opportunity to decrease water losses in these distribution systems but a significant limitation is securing the immediate and ongoing financial resources needed to upgrade.

Given the demand for water and the constraints on availability, we need improvement in financial and ecological productivity. Our purpose is therefore to seek increased multi-purpose water use productivity. There is good evidence that this can be achieved through irrigated regional engagement and a much greater emphasis on irrigation within a business context.

Scope of this paper

While the heading of this paper infers an examination of the many facets of improving irrigated agriculture, I have chosen to focus primarily on those aspects concerned with water availability and use in irrigated systems. In particular, and consistent with the title of this conference, there is an emphasis on describing our understanding of water use in irrigated plants, crops, farming systems and regions. This has been done with a view to identifying where improvements are possible and hence where less water may be used to produce more food and fibre for a demanding world. This means that considerations of salinity, drainage, alternative production and ecosystem layouts, commodity marketing and processing, and institutional arrangements are not considered even though these have an important place in improving irrigated agriculture.

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World irrigation context

Irrigated agriculture is practiced on nearly 250 million ha around the world, with most in India, China, the USA and Pakistan. Upward of 40% of world food is generated by either full or supplemental irrigation from 15% of the arable land area. For the period from 1960 to 1990, the development of irrigated land kept pace with increasing population, with a remarkably stable 22 people per hectare. The 1990s has seen a disjuncture; new irrigation development has slowed, population growth continues unabated and the connection between irrigated production and the supply of food is increasingly dependent on improved productivity rather than increased area. Add to this the increased demand for water for urban and industrial use and for ecosystem maintenance, and the pressure is on for increased irrigated agricultural productivity. But how much improvement is possible?

Irrigation as a system

Irrigation practice is an energy-, water- and skill-intensive activity that requires a systematic analysis if potential improvements are to be identified. This paper considers the irrigated system from the plant through to a catchment, and with both production and use of natural resources perspectives. A unifying concept in achieving this system description is to focus on improving water use productivity using a framework proposed by Molden *et al.* (2003). Adopting this assists our thinking about water across the range of scales, from plant to catchment. It also minimises the confusion associated with inappropriately-applied 'efficiency' terms.

Improvement in plant water use

Starting at the photosynthetic level within plants, there is little evidence that the amount of dry matter (carbon) fixed per unit of water transpired can be changed within a species. We know (Ehlers and Goss 2003) that there are differences between species, particularly between those with different photosynthetic pathways, e.g. C₃ and C₄, but within these groups and within a species this is not a productive area of improvement. As summarised by Keller and Seckler (2005), 'most authorities range from deep scepticism (Tanner and Sinclair 1983) to slight optimism (Bennett 2003) on the potential for substantial advances in this direction'. Without fundamentally changing the photosynthetic chem-

istry there may be little further improvement to be gained.

However, if we change external conditions such as the water vapour pressure of the air (its 'humidity') or the concentration of CO₂, or we change the configuration of the plant in say vegetative relative to reproductive phase duration, then over a season the transpiration 'productivity' (harvested yield per transpired water) can change. In general, growing and irrigating plants in more humid environments or in conditions of elevated CO₂ concentration will increase the dry matter yield per unit of water transpired. Ironically, the increased levels of atmospheric CO₂ and more humid conditions associated with climate change are conducive to increasing transpiration productivity.

In some crop plants, especially perennial horticultural species, we have used the separation of vegetative and reproductive growth phases to influence economic yield while containing the seasonal use of water (Kriedemann and Goodwin 2003). This is what the process of regulated deficit irrigation (RDI) tries to do — increase the economic yield relative to total dry matter. For peaches, the claim is that irrigation water use decreased by 30–50% while fruit yield was either similar or increased. Another variation of using plant physiological response to advantage is the development of partial root zone drying (PRD) by Loveys *et al.* (2000). The essential feature is that the roots of a plant are simultaneously exposed to both wet and dry zones in the soil. As Loveys describes, 'this results in the stimulation of some of the responses normally associated with water stress such as reduced vigour and transpiration but does not result in changes in plant water status.' Evidence with grapevines indicates a 30–50% reduction in the amount of irrigation water applied, with small to negligible decreases in grape yield (Kriedemann and Goodwin 2003, Table 5). Whether observations of reduced tree or vine vigour associated with these water controls result in long-term consequences or reduced plant longevity is still to be fully quantified.

In many cereal species, breeding programs have improved the harvest index (grain yield relative to total dry matter) which in turn would generally increase the harvested grain yield relative to the seasonal water use. As a general assessment, only marginal gains in water productivity of irrigated annual cereal species are likely unless water control, similar to that exercised on tree and vine species, could invoke similar physiological responses. This assessment is based on the observation that the rate of yield improvement for the major cereals

shows clear signs of slowing in the last decade (Tony Fisher, ACIAR, *pers. comm.* 2006), a factor very strongly related to the effective use of available water.

In summary, the opportunity to improve water productivity at the plant physiological level seems small and very challenging. At the whole-of-plant and over seasonal duration the opportunity to increase economic yield relative to total water use is still present but it seems increasingly difficult to envisage where quantum improvement can come from.

Improvement in crop water productivity

For crops, the opportunity for improving water productivity largely involves decreasing soil surface and intercepted water evaporation relative to crop transpiration. With agronomic practices that have increased plant density and decreased soil surface exposure a greater portion of the crop water use is through plant transpiration rather than soil evaporation.

A recent field study by Hanson and May (2006) on crop evapotranspiration of processing tomatoes in California compared the water use and yield of furrow and subsurface-drip irrigated crops. Further, they made a comparison between water use and yield of similar crops grown 30 years previously. There was evidence that use of the subsurface drip system decreased total water use by about 12% over the season (78 mm in a total of 650 mm) due to decreased soil surface evaporation in the establishment phase of the crop. However, this difference could be quickly overshadowed by poor management of the irrigation system or if agronomic practice increased the duration of the drip-irrigated crop. Hence, this advantage was not consistently recorded over three other seasons. The comparison with crops recorded 30 years previously indicated that the total water use was the same but fruit yield had increased by 53% (from 53 t/ha in 1970–1974 to 81 t/ha in 2000–2004).

Meyer (1997) made a comparison of yields and water use over a similar time duration for irrigated crops in the Riverina region of south-eastern Australia. Although this was based on district average data it shows (Table 1) that the energy yield of the commodities being grown relative to the water used had increased in the period 1960–1990.

In both these examples, the improvement in water use productivity came largely from improvement in yield through both changes in varieties and more

importantly in agronomic practice. There is little evidence that the amount of water used has actually decreased, a conclusion reached in other recent studies of irrigated practice (Meyer 2005). Good agronomy together with careful water management continues to be the main ways of improving water use productivity.

This brings us to the perplexing discussion about the limit of increased water productivity and its implications for water requirements. Keller and Seckler (2005) argue that as we reduce the obvious inefficiencies in water supply and poor management practices that have given us significant improvement in crop water use productivity, any further increase will imply an increase in total water use. This is not the impression one gains from reading reviews by Wallace (2000) and Howell (2001) who maintain that there remains large potential for improved water productivity. Their starting basis is that ‘only about 10–30% of the available water (as rainfall, surface or groundwater) is used by plants as transpiration’ (Wallace 2000).

Let us try to understand these different positions and their implications. The basis for the Keller and Seckler position is represented in Figure 1 which assumes a linear relation between relative yield and relative available water³. The evidence that this is the case becomes much more convincing when yield data from different areas are normalised according to the water vapour pressure deficits of the areas as indicated by Tanner and Sinclair (1983). If we accept this premise, it implies that in crop canopies the ‘extinction coefficients’ of energy intercepted for photosynthesis and that for evaporation of water have the same relationship to leaf area index (LAI) (the area of green leaves per plant / ground surface area per plant).

³ Relative available water is total water from all sources (stored soil water, irrigation and rainfall) as a fraction of the water transpired by the crop plants grown to their genetic potential.

Table 1. Comparison of irrigated crop yields from data of mid-1960s and 1990s

Crop	Year	Yield (kg/ha)	H ₂ O (%) ¹	Protein (kg/ha)	Carbohydrate (kg/ha)	Total food energy		Water use ³ (ML/ha)	Energy system efficiency ⁴ (%)
						(MJ/ha) ²	(MJ/kg)		
Grapes (white)	1960 ⁵	25172 ⁶	81	146	1498	59483	2.36	10.7	0.23
	1990 ⁷	30000	81	198	5310	89100	2.97	8	0.45
Oranges (fresh)	1960	30206	86	121	2393	38277	1.27	12.2	0.13
	1990	40000	87	376	4680	78800	1.97	15	0.21
Rice (white)	1960	5096 ⁸	9	457	5057	95691	18.78	15.2	0.26
	1990	5850	12	415	4680	89447	15.29	12	0.30
Wheat (flour) ⁹	1960	911	12	100	663	11896	13.06	4.6	0.11
	1990	3750	12	386	2850	57188	15.25	5	0.47
Tomatoes (fresh red)	1960	50300	91	686	2000	41897	0.83	9.1	0.19
	1990	80000	94	720	3680	72000	0.90	8	0.37

¹The similarity of water content gives an indication that the form of food being compared between the two periods is similar.

²Food energy values for the 1990s were taken from USDA tables available on the WWW at address http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl

³Values for water use in 1990 were typical of total crop evaporation. Water added to satisfy this need would be both irrigation and rainfall.

⁴Energy system efficiency was calculated as:

1960 — (Calorific value of edible food per 1000 gallons × 100) / (1000 × 2662). In Hoare's original calculation he used a value of 4500 calories per gallon. I have used a value of 2662 calories per gallon to be consistent with the 1990 calculation and to use the correct value for the latent heat of vaporisation of water.

1990 — (Total food energy (MJ/ha) × 100) / (Water use (ML/ha) × 2450000 (MJ/ML))

⁵1960 are values from Hoare (1968) converted to metric units.

⁶Yield values are for white table grapes.

⁷1990 are values compiled from USDA food energy values with yields and water use from Water Force Victoria.

⁸1960 rice yields were 3.5 tonnes per acre (8.6 t/ha). This would have been a very high yield at that time, whereas the 1990 yield is based on an industry average of 9 tonnes per hectare. Both assume a 65% mill out return, paddy rice to processed white rice.

⁹The 1960 figures used dry-land wheat with a yield of 0.5 tonnes per acre (1.2 t/ha). 1990 are for an irrigated wheat crop yielding 5 t/ha of grain. Both used a mill return of 75%, whole grain to flour.

However, we know that as the LAI of crops approaches and exceeds a value of three, evapotranspiration has a quite flat response, that is it does not continue to increase as LAI increases. For photosynthesis, there is almost always plenty of total energy available but increasingly dense canopies have self-shading to the extent that there is little further gain in assimilative capacity. Canopy arrangements that minimise self-shading at high LAIs should increase dry-matter production relative to water use. This is likely to be hard to achieve, however, in non-trellised canopies and so

any opportunity for water productivity improvement through this means is likely to be small.

The relation of relative yield to relative available water, depicted in the transpiration (T) line of Figure 1, also implies that maximum crop water use productivity occurs when yield is equal to the maximum, fully watered yield⁴. Further, this im-

⁴ This occurs because of the offset of the transpiration line from the origin. In other words, there is always some water use before there is any dry matter yield, hence at any point

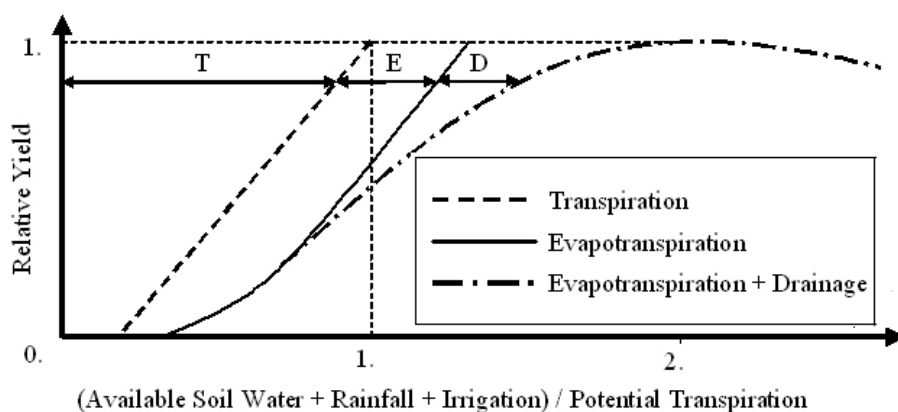


Figure 1. Generalised relationship between relative yield (actual yield / potential fully irrigated yield) and relative available water. Figure adapted from Keller and Seckler (2005).

plies that maximising crop water productivity requires full irrigation, and in situations of limited water it is better to fully irrigate a smaller area rather than irrigate a large area with less than full water addition.

The position taken by Wallace and Howell is more directed at increasing the total amount of the water resource that is available for transpiration. In Figure 1 this is represented as maximising T relative to evaporation (E) and drainage (D). In examining this we need to consider irrigation application and irrigation water delivery systems.

Improvement in farm distribution and application systems

It has been well established that there is a very large range in the volume ratio of irrigation water that enters the soil profile (and is available for plant use), and that entering the ‘farm gate’. The extensive world study by Wolters (1992) indicated that this application efficiency had a range of 30–70%. Farm layout, application system type and management can all contribute to improve application system efficiency significantly. A recent Australian study (Khan *et al.* 2004a,b; Pratt Water 2004) showed that, for on-farm application in the Murrumbidgee Irrigation Area, water savings of 60 GL (6% of annual water diversion) would require a capital outlay of \$150 million. This outlay would be associated with conversion of some existing horticultural surface irrigation systems to drip and some surface-irrigated annual crops to moveable sprinkler systems. Realising water savings through

along the line the ratio that is crop water productivity
 $Y_{rel}/ET < Y_0/ET_0$

improved application systems is not a linear response, however, since an additional \$173–\$377 million would be needed to achieve a further saving of 25 GL.

Given the relative costs of water, earthworks, labour and equipment there is often little financial incentive to reduce total water use for marginal gains in yield. This situation highlights that, while there are appar-

ently significant gains to be made in water application efficiency and hence improved total water productivity, there is often little financial incentive to do so. Indeed it is often the case that optimum farm efficiency in financial and labour terms occurs when crop water productivity is not at the maximum value. This recognition helps explain why irrigators do not necessarily apply ‘full’ irrigation to their pastures or crops. Similarly it can be argued that greater irrigation water productivity could be obtained by growing different crops, and hence changing the seasonality or total size of water demand. However, the far bigger influence on crop choice is market access and potential commodity price, both factors that are generally outside the growers’ control.

In summary, maximum water productivity occurs when plants are supplied with just enough water to satisfy the potential transpiration in a given environment. If we were to manage water and crops to this level of precision, any further increase in yield will inevitably entail a commensurate increase in total water use. Prior to this state, there appears to be considerable opportunity to improve the proportion of water that is transpired relative to the total available, mainly through reducing evaporative and drainage losses. These losses occur during application (e.g. frequent ground surface wetting) and within the crop (e.g. sparse plant stand), with both these conditions increasing the proportion of non-productive evaporation. While it is recognised that increasing water productivity is important from a resource use and potential food production point of view, maximising water productivity is often not the most financially or managerially optimum thing to do in a farming situation. Care needs to be exercised in pursuing maximisation of crop water

productivity since this can entrain more total water than is financially optimal for a particular farm enterprise.

Improvement in distribution of surface irrigation water

Apart from irrigators who obtain most of their irrigation water from groundwater or are direct extractors from surface waters, many are supplied by delivery infrastructure with channels and control structures. With changes in responsibility for this distribution to more commercially-directed businesses, there is now an increasing vested interest in ensuring high delivery efficiency. Audits of many of these systems show considerable opportunity for improvement, and also generally highlight the inadequacy of current measurement systems. For example, the Pratt Water Initiative in the Murrumbidgee Valley (Khan *et al.* 2004a,b; Pratt Water 2004) indicated that significant water savings are possible in the irrigation water distribution system. This initiative highlighted deficiencies in the measurement systems on the river that could account for 10–15% of the total annual flow. With the irrigation area distribution system, more than 100 GL per year (or about 10% of total delivery) could potentially be saved through improved infrastructure control, reduced channel seepage and suppression of channel evaporation. Economic assessment indicated that controlling channel seepage to save up to 20 GL/year would cost from \$400/ML to \$2000/ML, depending on the methods used. To realise further water savings, the costs rise by an order of magnitude.

The greatest limitation to achieving significant water savings is the high capital costs associated with upgrading and changing the infrastructure. Governments are increasingly reluctant to have public investment in these schemes, and are increasingly forcing the costs back to the end users. This is a vicious cycle because older irrigation areas have infrastructure most in need of updating, but they are also the least able to raise the revenue needed to secure capital. There is generally good opportunity to decrease water losses in these distribution systems, but a significant limitation to secure the immediate and ongoing financial resources to upgrade. Again, caution is needed, for as Barker *et al.* (2003) point out, ‘Water savings do not necessarily lead to higher water productivity and, similarly, higher water productivity does not lead to greater economic efficiency.’

Improved water use in an irrigated catchment

At a catchment level we know that irrigation in more humid areas will have greater crop water productivity. We also know that smartly-timed supplemental irrigation can be very effective in providing particular yield quality and or quantity to take advantage of niche markets. But by their nature, niche markets are fickle and so it is a case-by-case proposition as to whether the capital cost of supplemental irrigation will continue to be viable in the long term.

Motivators for improving irrigation

A primary motivator for water policy reform at both Australian and state government level is to encourage more economic activity from the use of limited water supplies, that is more dollars per megalitre. On the surface this is interpreted as encouragement for production of high-value commodities like vegetables and fruit. At the irrigation enterprise level, however, the major motivator is generation of greater profit, especially if this is accompanied by lower risk from production and market volatility. There is thus a fundamental difference between the motivators of policy and the irrigated enterprise — a difference that needs to be appreciated by policy makers. In the longer term, though, there is a happy coincidence between profitable irrigated enterprises, total economic activity, community well-being and the need for resource maintenance.

Where do irrigator interests lie?

For irrigation to prosper in the long term, there needs to be continuing access to sufficient water of adequate quality, with low salt content being the primary quality concern. There is thus a coincidence of irrigator and river environment concerns with respect to managing salinity in the rivers. Beyond this, irrigators do not have a primary vested interest in the condition of the river or the dependent riverine ecosystems. Their engagement in the public discussion on the state of the rivers is to ensure that their interest in water supply is maintained through access and allocation policy. The public discussion is largely centred on the perceptions of the net benefits of using water to maintain river and near-river ecosystems relative to irrigated production. Apart from tourism and recreational

activities, the attributes being promoted are aesthetic and cultural — values that can be held equally by irrigators and non-irrigators alike. To assure continuity of supply, irrigators need to win the hearts and minds of the voting public so that there is a shared sense of fair and equitable balance of water access and benefit opportunity. To this end, irrigators will need to become more involved as managers of the rivers, where management is more than ensuring the supply of water for irrigation.

Significant improvement is possible

This review has indicated that the opportunities of improving irrigation to help ‘provide water for all’ lie mostly in improving water distribution systems, farm distribution and application systems, careful attention to crop agronomy and only limited opportunity through genetic manipulation of plant photosynthetic chemistry. There is enough evidence to indicate that every irrigated crop and pasture can improve its median water productivity. The focus should be on improving the productivity of the top third of producers, with the expectation of significant improvement in the performance of the middle third. The increasing value and tradability of water in the Australian context will provide opportunity for poorly-performing producers to realise their asset value and leave the industry. Increased water productivity is clearly of significant benefit to regional communities, especially if this is accompanied by increased diversity of commodity production and associated service industries. The opportunity provided by irrigated production lies in retaining and increasing diversity, flexibility and adaptability, that is increasing resilience. Increased productivity needs to be stimulated and accompanied by greatly improved water distribution systems. Excessive losses need to be fixed. Small-volume, long earthen channels need replacing with pipes and some uneconomic areas need to be retired. Modified systems must be designed to increase flexibility of supply through combinations of greater control, some pressurised with water on demand and with on-farm and near-farm storage. Conversion of application systems on many crops can free up 30–40% of current water use and provide opportunity for expansion or trading for environmental or production uses. The benefits of increased control and measurement in water distribution and application include the capability to target evaporative, seepage, drainage and overflow losses.

There is therefore considerable opportunity for increased production, increased water productivity and a balance between water use for production and that for maintenance of environmental values. The very significant improvements in irrigated practice and productivity in the Riverland and Sunraysia of the Murray River (Meyer 2005) over the last decade or so were realised through combined improvements in distribution systems, on-farm application and management, and much institutional support. Realising the opportunities cannot be achieved through a piecemeal, incremental process, it requires collective action at a regional level so that irrigators, delivery system performance and institutional arrangements work together.

Improved irrigation within a regional irrigation business partnership

The experience of major change and improvement in irrigated practice and productivity, and accompanying improvement in community well-being, comes from concerted actions of irrigated districts or regions. The most successful improvements have been associated with self-identifying communities who identify an imperative to act and manage to line-up changes to practice, skills, service levels, institutional arrangements and legislative backing. Regions are much more likely to improve than well-meaning but dispersed actions of commodity groups, especially at national level (i.e. a non-local level).

Improved multi-purpose water use productivity

The title of this conference, ‘Water for Irrigated Agriculture and the Environment – Finding a Flow for All’, has the implication that there is enough for all. Within southern Australia it is increasingly evident that there is not enough water to retain an ecological system that is similar to that of the past ideal. Hence we have decided to focus our attention on particular ecological ‘icons’ in the river and riverine system, and to try to find compromises with our other uses. In essence we are seeking improvements in financial and ecological productivity within the available water constraint. Our purpose is therefore to seek increased multi-purpose water use productivity. Evidence suggests that this can best be achieved through concerted action within community-identified irrigated districts or regions. This is also more likely to succeed where a directed business approach is adopted that effectively taps into the primary motivations of

both irrigation water distribution companies and irrigated farm enterprises.

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