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Assessing Rainfed and Irrigated Farm Performance Using Measures of Water Use Efficiency

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Abstract

The aim of sustainable farming in both Australia and China is to achieve high water use efficiency (WUE), high profitability and minimal damage to the environment. High WUE is needed to minimise the overuse of scarce water resources. In this chapter, we review the many definitions of WUE that are in use in Australia and China. For example, in rainfed and irrigated zones of southern Australia, WUE or 'potential yield' is used as an index of production efficiency and its industry surrogates, whereas in China WUE is estimated as part of water-saving agricultural practices. We also look at why current measures of WUE are not appropriate for some cropping systems in Australia such as those in 'leaky' landscapes, where the crops cannot intercept and use all the water that reaches the root zone. A more encompassing measure of plant WUE may need to be developed for these systems and advocated to farmers. To maximise adoption by farmers, WUE must be based on easily measured parameters.

高效农业的目标是提高水分利用效率（WUE），增加收益，最大程度缩小植物水分低效利用对环境造成的不良影响，减少过度使用稀缺水资源。本文对中澳两国所采用的WUE的许多概念作了介绍和对比。例如，在南澳旱作和灌溉农业区，WUE或潜在产量常作为产出效率指数，而在中国则是节水农业实践的一部分。本文也说明了目前这种WUE的计算对某些农作系统，如易渗漏地，并不适用，因为植被未能全部截留、利用到达根部的水分。对于这些系统，应有一个更周全的WUE计算方法，推荐给农民。其中的参数要易于测量，便于农民们采纳。

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Cox, J.W., McVicar, T.R., Reuter, D.J., Huixiao Wang, Cape, J. and Fitzpatrick, R.W. 2002. Assessing rainfed and irrigated farm performance using measures of water use efficiency. In: McVicar, T.R., Li Rui, Walker, J., Fitzpatrick, R.W. and Liu Changming (eds), *Regional Water and Soil Assessment for Managing Sustainable Agriculture in China and Australia*, ACIAR Monograph No. 84, 70–81.

SHORTAGE of water may restrict future regional agricultural productivity in both Australia and China. As the demand for high-quality irrigated produce increases in Australia and overseas, there is increasing competition for water between agriculture, urban users and the environment, where 'environmental river flows' are necessary to maintain aquatic and riparian ecosystems (Young 2001). In China, the demand for water is driven by industrialisation of the economy and rapid urbanisation of the population, particularly over the past two decades (Anderson and Peng 1998; Brown and Halweil 1998; Rosegrant and Ringler 2000). This competition for water puts the agricultural sector under pressure to maintain and increase production using less water. In spite of serious water shortage in both countries, large amounts of water are wasted due to poor irrigation methods, although in Australia this wastage has partly been addressed by the introduction of irrigation quotas. Hence, the agricultural sector must increase its water use efficiency (WUE). Where agricultural practices must change in response to new policies, regulatory bodies require methods for monitoring WUE and mechanisms for conflict resolution such as litigation, legislation, negotiated agreements and market mechanisms (Deason et al. 2001).

In China, the regional distribution of water resources does not match agricultural demand for irrigation. While some 44% of the population and some 58% of the cultivated land are in the northern and northeastern provinces, only 14% of the total water resources (surface runoff and groundwater) are found in those regions (Brown and Halweil 1998). Agricultural water consumption accounted for over 80% of the total water use; thus, 'water-saving agriculture' (the term used in China) is of great significance. Stanhill (1986) identified three main components of water-saving agriculture: reducing delivery losses in irrigation systems; improving transfer of water (from either irrigation or rainfall) to a depth where roots can access the water; and maximising WUE by crops.

Farm productivity (yield per hectare) and disposable farm income (net profit per hectare) are two parameters used widely to assess and compare the relative performance of farming enterprises within and between regions. In rainfed agriculture these two annually derived measures are highly variable, because production is dominated by prevailing weather conditions during each growing season. Economic returns from farming are also affected by commodity prices and other fluctuating economic variables, such as interest rates. Where irrigation is efficient, the impact of climate is less pronounced, because soil water deficits are prevented and production targets can be reached. On the other hand, overuse of irrigation water can depress yields and returns, and in the longer term can contribute progressively to insidious environmental risks, such as the rising saline groundwater levels found in parts of Australia (Walker et al. 1999).

In both rainfed and irrigated agriculture, farm yields and financial returns are also governed in the short to medium term by other factors, including:

- the quality of soil and land resources on the farm;
- the systems of land use and rotations that best suit the land resource and the climate; and
- how much money is invested in optimising economic returns and adopting improved farming practices to overcome constraints on yield.

In this chapter we assemble and evaluate practical indicators for assessing farm or field performance against benchmarks linked to the availability of soil water for plant growth — the factor that is the most yield limiting. Such indicators, which can be viewed as measures of WUE achieved during the growing season, have been prepared for rainfed and irrigated agriculture in both Australia and China. In this study we also assess landscapes where some of the seasonal rains bypass the soil–plant system due to overland flow, lateral flows in subsurface soil horizons or drainage past the root zone. The relative importance of the processes operating within these systems are discussed in more detail in Chapters 1 and 5 of this volume.

Definitions of Water Use Efficiency

Stanhill (1986) defined WUE both hydrologically and physiologically; here we introduce the additional concept of economic WUE. Hydrological WUE is the ratio of evapotranspiration to the water potentially available for plant growth. It is expressed as a percentage or fraction (0–1). Physiological WUE measures the amount of plant growth for a given volume of water; it can be defined for different measures of 'plant growth' and 'volume of water'. Turner (1986) noted that care is needed when defining WUE. For example, 'plant growth' may be measured in units of net biomass (including roots) (Ritchie 1983; Tanner and Sinclair 1983; Turner 1997) or as crop yield (Tanner and Sinclair 1983; Turner 1997). Similarly, 'volume of water' can be measured as total transpiration (Tanner and Sinclair 1983; Turner 1997; French and Schultz 1984a,b), total evapotranspiration (Ritchie 1983; Tanner and Sinclair 1983; Turner 1997), total water input (Sinclair et al. 1984) or total growing-season precipitation plus initial soil water at the time of sowing (French and Schultz 1984a,b). Economic WUE attempts to gauge the value of different agricultural commodities by expressing WUE in units of wealth generated per volume of water used. Armstrong et al. (2000) developed a measure of WUE for dairy cattle farms, with the units being kilogram milk fat plus protein per millilitre of irrigation water applied. The different measures of WUE have different applications; for example, economic WUE is useful for regional planners, hydrological WUE is relevant to irrigation engineers and physiological WUE is valuable for those involved in plant, soil or atmospheric sciences.

Sinclair et al. (1984) introduced different timescales for several definitions of WUE, ranging from an instant to a day or a growing season. These temporal scales have now been linked to a range of spatial scales, which extend from a single leaf, through a canopy, field or farm to a region (see Table 1, Chapter 18). The scales are linked: leaf WUE (in the order of tens of square centimetres) will usually be measured over a short time (e.g. from one second to one day), whereas regional WUE (in the order of thousands of square kilometres) will usually be measured over a longer time (e.g. from one day to one growing season). To date, very little research has focused on farm-level or regional assessments of WUE; a study by Tuong and Bhuiyan (1999) is one of the few examples of a farm-level assessment. A report of regional monitoring of WUE over the North China Plain for 13 years is given in Chapter 18.

As there are a large number of current uses for the term WUE, all indexes of WUE need to be clearly defined. While some of these indexes are directly related to water use, others are indicators of production performance based on crop response to water supply. For a WUE index to be of practical value, it should be based on easily measured parameters such as volume of water delivered from headworks, river pumping station or farm bore; water volumes delivered at the farm gate; area of crop or pasture irrigated; commodity yield; and rainfall. A WUE index will be more precise if it includes measurements of soil water and crop water use.

Hydrologic WUE

Hydrologic WUE is determined by spatial considerations (e.g.the distance water is conveyed) and by the type of irrigation infrastructure used to deliver water to the farm gate (e.g. open channels or a piped system) and onto the irrigated area. Hydrologic WUE is expressed as a percentage or a fraction (0–1), without dimension. It is closely related to water saving during conveyance and irrigation, and thus is important in research into field water balance, field water redistribution, canal seepage prevention, water conveyance works and new irrigation techniques.

The field water balance can be estimated from the following equation (Chen 1985):

$$E + T = P + I + U + W_1 - (R + D + W_2)$$

where P is precipitation; I is irrigation water supplied; E is soil evaporation; T is crop transpiration; evapotranspiration (ET) is the sum of E and T; U is upward capillary water; W_1 is the initial soil water storage at crop sowing; R is the surface runoff; D is deep drainage of soil water; and W_2 is the soil water storage when crop harvesting.

Three types of WUE indicators can be used to assess the efficiency with which irrigation water is diverted from a water source, transported and applied to a field.

Conveyance efficiency (Eff_c) takes into account channel seepage, spillage, and evaporative and any other water losses that occur during transport from the source to the point of delivery in the landscape. It can be expressed as:

$$Eff_c = (\mathrm{V_s}/\mathrm{V_d}) \times 100$$

where $\mathrm{V_s}$ is the total volume of water supplied to the target land area and $\mathrm{V_d}$ is the total volume of water diverted from the regional water body to the target land area.

The second indicator is termed distribution efficiency (Eff_d). It relates to the proportion of water received at the field inlets compared with the total outflow from the supply system and can be defined as:

$$Eff_d = \mathrm{V_r}/\mathrm{V_{out}}$$

where $\mathrm{V_r}$ is volume of water received at field inlets and $\mathrm{V_{out}}$ is the total outflow from the supply system.

The third indicator is application efficiency (Eff_a), which relates to the targeted land area.

$$Eff_a = \mathrm{V_{ap}}/\mathrm{V_{wa}}$$

where $\mathrm{V_{ap}}$ is the volume of water available within the plant-rooting zone (the volume supplied minus the sum of drainage, evaporative losses and nonrecycled tailwater) and $\mathrm{V_{wa}}$ is the volume of water applied from irrigation and rainfall. Application efficiency assumes that irrigation water is applied uniformly either by flood or pressurised systems.

Hydrologic efficiency can be measured on regional, farm or paddock scale; therefore, the scale should be made clear when efficiency estimates are reported. Efficiencies can also vary temporally and can be applied to single irrigation events or to longer periods such as months, growing seasons or years.

Hydrologic efficiency (Eff_h) of irrigation systems can be given as:

$$Eff_h = Eff_c \times Eff_d \times Eff_a$$

Having separate, yet interrelated, indicators of hydrologic WUE for an irrigation system allows managers to better monitor the system.

Physiological WUE

General

Physiological WUE is commonly used at several different levels: from molecular, through single leaf, canopy and field to regional levels. It can be called 'crop WUE'. As the spatial scale of the molecular level is outside the emphasis of this chapter, it will not be discussed further.

Single leaf level

At the single leaf level, WUE is defined as the net CO_2 uptake by leaf per unit of transpiration. It is expressed as the ratio of leaf photosynthesis rate to leaf transpiration rate, and could be the upper limit value for crop WUE. The water vapour and CO_2

fluxes can be expressed as the concentration gradient and diffusion resistance, which can be measured with gas exchange equipment. Thus, assuming that CO_2 and water vapour take identical paths between the leaf cell walls and bulk air, the WUE at this level could be calculated as follows (Fischer and Turner 1978);

$$WUE = \frac{\Delta c \times D_c\left(r_a + r_s\right)}{\Delta e \times D_e\left(r_a + r_s + r_i\right)}$$

where Δc and Δe are the leaf-to-air concentration gradients for CO_2 and water vapour, respectively; D_c and D_e are the diffusivities of CO_2 and water vapour, respectively; and r_a, r_s and r_i are the boundary layer, stomatal, and internal resistances to diffusion, respectively.

Assuming that the CO_2 concentration at the chloroplast is zero, r_i includes photorespiratory effects as well as other apparent and actual internal diffusive resistances to CO_2. As a result, Δc equals the concentration of CO_2 in the atmosphere, 0.58 mg/L at 25°C. Assuming that D_c/D_e is 0.6:

$$WUE = \left(\frac{360}{\Delta e}\right)\left(\frac{r_a + r_s}{r_a + r_s + r_i}\right)$$

with WUE in units of $mgCO_2/gH_2O$ and Δe mg/L. The intercellular air spaces of the leaf are assumed saturated with water vapour at the leaf temperature. The highest WUE that might be expected under any conditions can be calculated by assuming that r_i is zero, meaning that there is infinitely high photosynthetic affinity. At a leaf and air temperature of 25°C, an air relative humidity of 50% and air saturation deficit of 12 mg/L, WUE would be 30 $mgCO_2/gH_2O$. In reality, with the exception of crassulacean acid metabolism (CAM) plants, WUE values are usually substantially lower than this (Fisher and Turner 1978).

WUE is affected by environmental factors including air saturation deficit, air temperature, incident irradiance, leaf orientation and leaf movement. WUE also varies with genotypes, the leaf traits r_a, r_s and $r_{i,}$, and leaf water potential ψ_{leaf}.

Canopy (community) level

At the canopy level, WUE is defined as the ratio of a crop community's net CO_2 assimilation to its transpiration; that is, the ratio of the canopy CO_2 flux to the water vapour flux for the canopy transpiration. It can be expressed as follows:

$$WUE = \frac{F_c}{T}$$

where F_c is the canopy CO_2 flux and T is the water vapour flux for the canopy transpiration. The gas exchange theory has been extended to measure the fluxes of CO_2 and water vapour. The unit for WUE at this level should be the same as that for the single leaf. The canopy WUE can also be expressed on temporal scales as instantaneous, daily and seasonal WUEs.

Field level

At the field level, WUE is defined as the yield gained per unit of water used. The yield can be expressed as the net biomass Y_b (including roots) or the grain yield Y_e ($Y_b \times HI$, where HI is the harvest index). Field-level WUE is calculated as:

$$WUE = \frac{Y}{WU}$$

where Y is the dry matter yield (Y_b) or the grain yield (Y_e) in kg/ha; and WU (water use in mm) can be the total evapotranspiration, the irrigation water added or the precipitation, depending on the purpose of the analysis. For example, to show the effects of irrigation or precipitation on the accumulation of dry matter, the unit for WUE would be kg/ha/mm.

Regional level

At regional level, WUE is defined as the ratio of a region's annual yield (t) to its annual water use (m^3). Calculation of regional WUE is relatively complex because there are usually several crops growing in the same period and different kinds of landscapes within a region. Chapter 18 discusses regional WUE indicators.

Economic WUE

This index applies especially to irrigated agriculture and is used for assessing and comparing the financial benefits resulting from irrigation. The indicator is usually defined as:

$$\text{Economic WUE} = \frac{\text{operating surplus for the irrigated area (\$/ha)}}{\text{total water supplied to the crop in rainfall + irrigation (mm/ha)}}$$

Gross income or profit at full equity for the irrigated area could replace operating surplus as the numerator. In either case, the indicator is expressed as $/ha/mm. Expressing WUE in these terms potentially allows economic policy to be the driving force for increasing WUE (Grimble 1999).

A ranking of sustainability indicators for assessing the economic performance of a farm business has recently been developed for Australia's cropping and pasture industries operating within rainfed regions (Pannell and Glenn 2000). In contrast, financially based indices are often volatile, being sensitive to changes in commodity prices and the effects of climatic conditions on crop yield and grain quality. Usually, data over several decades are required before trends can be discerned. However, an on-farm economic indicator has recently been proposed and assessed across major crop and pasture regions (Reuter et al. 1996). It links farm income per hectare ($/ha) to annual rainfall received (mm) and thereby seeks to dampen the seasonal effects on economic performance. A variant, not yet tested, could link farm income to growing-season rainfall. This indicator, sometimes termed $WUE in Australia, uses units of $/ha/100 mm of annual rainfall.

Factors affecting WUE

Crop WUE is an important indicator for weighting the relationship between crop matter production and crop water use. Thus, factors affecting crop yield or water consumption will be reflected in a change in WUE. Factors affecting crop WUE vary both spatially and temporally, and can be divided into four categories:

- species or crop variety grown, encompassing plant breeding (Li et al. 1995) and genetic modification;
- soil conditions (Gong and Lin 2000), incorporating soil erosion, sodicity and salinisation (Rozelle et al. 1997);
- agricultural practices involving the use of fertilisers (Garabet et al. 1998), efficient irrigation management (Zhang and Oweis 1999; Zhang et al. 1998; Liu et al. 1998), time of planting and crop rotation (Li et al. 2000), planting density (Karrou 1998) and the use of mulch (Tolk et al. 1999) or plastic film (Jin et al. 1999) to reduce soil evaporation; and
- atmospheric factors including levels of incoming solar radiation, wind-speed conditions and the relative gradients of water vapour, both internal and external to the leaf.

Over a longer time frame, estimation of WUE will also be affected by changes in climate (Smit and Yunlong 1996, Loaiciga et al. 1996), including precipitation patterns (Thomas 2000) and CO_2 concentration (Hunsaker et al. 2000).

WUE Indicators for Rainfed Agriculture in Australia

For rainfed agriculture, we define WUE as 'the efficiency of crops or pastures in any year to acquire and use available soil water derived from seasonal rainfall to produce harvested products'. In this context, 'harvested products' for annual crops refers to the grain or seed harvested at crop maturity, a measurement readily recorded by farmers. For grazed and ungrazed pastures, total pasture biomass can be estimated by a variety of procedures. The concept of potential yield, pioneered with wheat in the Mediterranean climatic zone of South Australia by French and Schultz (1984a,b), has proved to be a most innovative benchmarking system for ranking performance of rainfed farming crops and pastures. Their initial studies used 60 sets of data from field experiments and commercial crops, grown between 1964 and 1975, to relate grain in wheat to water use by the crop (French and Schultz 1984a).

Figures 1–4 show that crop water use increased as growing-season rainfall increased, resulting in a positive but variable trend between grain yield and crop water use. A boundary line (termed the 'potential yield line') was used to envelop all data points. For wheat, the intercept for this line was at 110 mm of water use, a value attributed to direct evaporative water losses from the soil surface and crop canopy. However, for hard-setting surface soils, evaporative losses were estimated to be higher (170 mm), because water infiltration into the root zone is slower, causing greater soil evaporative losses. The slope (20 kg/mm of water use) defined yield potential per millimetre of crop water use.

For practical reasons, farmers are unlikely to measure soil water changes between sowing and crop maturity; therefore, a surrogate estimate for crop water use has been determined (French and Schultz 1984b). The approach involved constructing relationships between grain yield and 'derived' growing-season rainfall (defined as April to October in South Australia). This term incorporated 30% of the measured rainfall falling in summer (i.e. before 1 April) and in late spring (i.e. after 31 October), based on the assumption that this rainfall increases grain yield. Through this step, farmers in any season could rank their crop yield relative to the potential benchmark yield from the simple equation:

$$\%\ \text{potential yield} = \frac{\text{actual yield}}{\text{potential yield}} \times 100$$

where the potential yield of wheat was defined as:

$$\begin{array}{c}\text{potential yield}\\ \text{(kg/ha)}\end{array} = \begin{array}{c}\text{(derived April–October}\\ \text{rainfall} - 110\text{ mm)} \times 20.\end{array}$$

We then derived guidelines for assessing potential yield estimates in any field or season. For example, a potential yield of > 80% was judged to be approaching optimal productivity, where few, if any, constraints were limiting yield. On the other hand, a potential yield of < 50% was taken to indicate that grain yield was being seriously restricted by one or more factors such as weeds, disease, nutrient disorders or frost. The nature of these yield-limiting constraints then needed to be identified, either through field observations or the use of diagnostic procedures that identify particular field problems. In subsequent studies, potential yield lines were derived for other field crops and for pastures grown in South Australia (French 1992, 1995), and researchers in other Australian states developed relationships for other crops and environments. These regional variants have been summarised by Reuter et al. (1996). In Western Australia, a computer program (PYCAL) was developed to permit farmers to calculate and annually rank per cent potential yield for a range of crops; the program took into account variations in regional environments.

The potential-yield concept is relatively simple, and readily accessible parameters are used for the model based on principles of plant water use. Because of these characteristics, the approach was rapidly adopted by the grain industry in southern Australia for ranking yield performance at field and farm scales. However, farmers probably estimate potential yield using rainfall from April to October, rather than 'derived' growing-season rainfall. An empirical index of plant water use remains an important cornerstone for site-specific management. The index can also now be linked to mapping of grain yield contours in fields using differential global positioning system (DGPS) grain yield monitors. The concept has also been used in South Australia to review and map temporal and spatial trends in cereal productivity, and the findings have influenced policy developments.

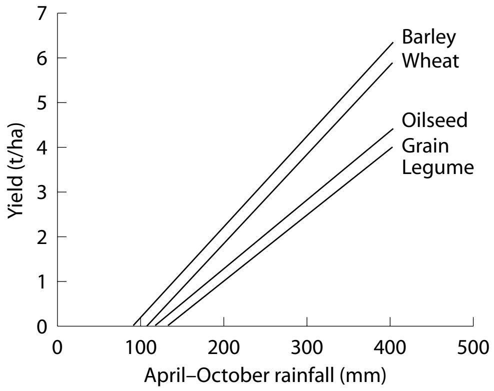

Figure 1 Relationships between potential grain yield and April–October rainfall (mm) for crops grown in South Australia (French 1995).

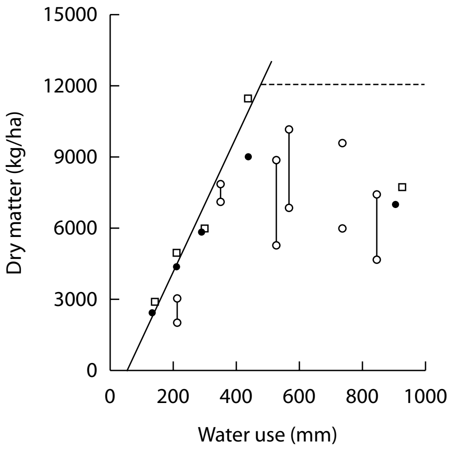

Figure 2 Relationships between growing-season water use (mm) and pasture dry matter production at experimental sites across Western Australia (from Bolger et al. 1993). Open squares represent values for maximum production systems (high fertiliser inputs, high seeding rates, good weed control); closed circles represent values for 'typical' production systems; open circles represent maximum and minimum values from Wesfarmers CSBP Ltd experimental sites.

Issues Arising from Estimating WUE under Irrigation

In irrigated agriculture, the aim of WUE is to optimise and sustain yield returns by matching water supply (rainfall plus applied water) to the amount of water needed by crops or pastures and to flush down salt accumulations within the root zone. In comparison to rainfed agriculture, irrigated

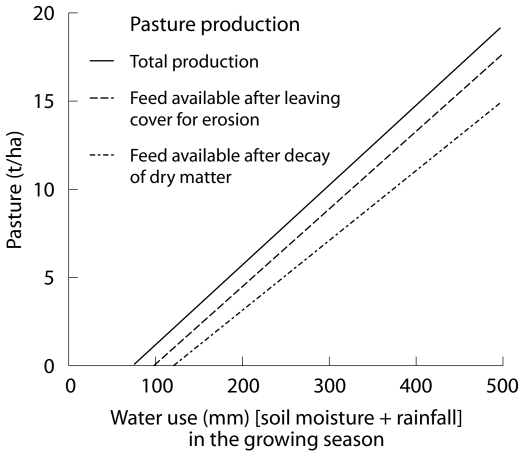

Figure 3 Relationship between water use in the growing season and pasture dry matter production in South Australia (after French 1992).

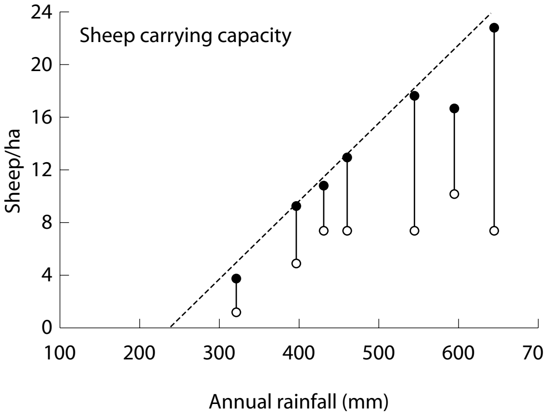

Figure 4 Relationship between annual rainfall and sheep carrying capacity derived from stocking rate experiments conducted at seven sites in South Australia (French 1992). Open circles represent minimum sheep carrying capacity; closed circles represent maximum sheep carrying capacity.

agriculture tends to have higher target yields and to use higher inputs such as fertilisers. However, the relative importance of factors such as crop water use, fertiliser requirements and salt accumulation will depend on the crop's root distribution, soil properties and the type of irrigation system used (e.g. flood, sprinkler, drip).

To obtain the full benefits from irrigation (by optimising WUE without adverse onsite or offsite effects), water management must be carefully controlled. Maximum production of dry matter, either per unit of water or per unit of land, is generally achieved through avoiding water stress by maintaining low water suction in the root zone. However, for some crops, one or more periods of water stress are necessary to maximise crop yield and product quality. In addition, an irrigation schedule that always maintains a fully charged root zone does not provide opportunities for taking advantage of rainfall and/or stored soil water. Also, if yields are to be maximised, irrigation must be managed to minimise salinity in the soil solution of the root zone.

Constraints to achieving high WUE in irrigated systems

With conventional flood irrigation systems, labour and operating costs are minimised by decreasing the frequency of irrigation. However, WUE and crop yields tend to be maximised when irrigation frequency is increased. Consequently, under irrigation, the most appropriate uses of land and water resources need to be balanced against economic feasibility and long-term sustainability.

Automated solid-set, centre-pivot sprinkler systems and trickle irrigation could increase WUE. Compared to flood irrigation systems, these systems offer opportunities to reduce water consumption without decreasing yield or income because they allow greater control of water application and require less labour. However, these benefits can only be achieved through increased capital costs and fuel consumption.

Flood irrigation systems can also be modified to permit closer control of water application. Laser-controlled precision land levelling allows better aerial distribution of water over the field and fewer applications of water. Combined with automation, major improvements in irrigation efficiency have been achieved in laser-level flooded systems. Closed conduits, rather than open waterways for lateral drains, allow for improved control and can make use of gravity to pressurise delivery systems or controls. In furrow-irrigated areas, furrow length can be reduced, intake distribution improved and tailwater eliminated.

Automated sensory systems for measuring soil and plant water status have recently become available. Often these systems incorporate data-loggers and sophisticated computing facilities, which can offer almost unlimited precision in controlling water supply. The benefit from such systems can be substantial and they offer scope for optimising WUE and product quality.

Numerous methods exist for modifying existing irrigation systems to increase WUE. However, to date, many of these have not found widespread application. One reason is lack of incentive, which can be linked to the pricing mechanism for irrigation water in Australia. Another problem is that many of these methods need adaptation and simplification to make them acceptable to growers. In addition, the basic irrigation infrastructure in many areas of Australia is old — a factor that often deters adoption of new technologies. Until capital inputs are available to revamp irrigation water delivery and handling systems, the potential for improving WUE will not be fully realised.

Another impediment to improved on-farm WUE is often the off-farm water distribution system. Typically, in most irrigated areas in Australia, water is distributed through large canals feeding laterals that deliver water at the farm gate. The design and operation of the canal system dictates that (at best) water must be ordered some days in advance of supply, or (at worst) water is delivered on a fixed rotation scheme. Efficient on-farm water use requires an adequate supply of water, delivered on demand. This can also help schedule irrigations to individual fields, and provide sufficient feedback to improve the operation of the delivery system.

Need for efficient drainage systems

WUE will also be adversely affected by waterlogging. Excess application of irrigation water must be avoided. Therefore, irrigation systems should incorporate drainage systems that remove irrigation water applied in excess of crop needs and avoid excess salts accumulating in the root zone. Drainage systems must also minimise water entering adjacent fields through seepage from leaky canals and excess irrigation. Natural soil drainage rates need to be taken into account and supplemented by artificial drainage installations. Although flushing salts past the root zone is important to the long-term viability of an irrigation area, the increase in water volumes to either local or regional groundwater systems can cause other environmental problems, such as salinity, in areas removed from the primary area of irrigation.

Salinity and sodicity are major threats to optimum WUE in Australia. To avoid yield reductions from salinity, the downward flux of water through the root zone must be sufficient to avoid concentrating salts in the soil solution of the root zone. This flux is generally termed the ‘leaching requirement’ — the fraction of the total surface-applied water that must percolate through the root zone to prevent salinity levels in root zones from reaching harmful levels.

For typical irrigation water with an electrical conductivity of 1.8 dS/m (1,000 mg/L of dissolved solids), the leaching requirement for most crops is 0.05. In theory, this leaching requirement is easily met, even with the most efficient irrigation management, provided that there is uniform aerial distribution of irrigation water. However, in practice, uniform distribution is not easily achieved because some parts of a field always receive too much water and others do not receive enough water. Thus, drainage requirements are closely related to on-farm irrigation management and to the seepages and spills from the distribution system.

Estimating WUE in ‘Leaky’ Catchments

The term ‘leaky catchment’ refers to the lateral and vertical transport of water (and solutes) moving off-site from catchments (Cox and Fleming 1997; Cox and Pitman 2001). By definition, rainfed catchments harvest and partition seasonal rainfall into that which is available for plant growth and that which flows from the land into streams and subsequently into regional water bodies (Cox and Ashley 2000). Rain not intercepted and captured by the soil–plant system may move via overland and throughflow pathways towards streams, and by deep drainage to groundwater. Such losses to the soil–plant system are likely to be greater in areas of higher rainfall and in landscapes with sloping topography.

Where there are duplex soils, lateral transport of water and soil solutes is likely to be significant (Cox et al. in press). This may contribute to transient perched watertables and areas of waterlogging and salinisation, which develop, persist and expand within the landscape (including discharge and ponded areas at lower points in a catchment) (Cox and McFarlane 1995).

These processes have a definite seasonal incidence and may unbalance a catchment’s hydrology. In any given year, the resident time of water (and solutes) varies at different points in the landscape (including the recharge and discharge areas). Within a growing season and in the longer term, cumulative effects may progressively occur that impact on catchment hydrology and hence on the spatial use of water by plants.

Given the mobility of water within catchments, there is scant hope for using only growing-season or annual rainfall to estimate and compare WUE under different land management practices (e.g. comparing WUE under set-stocking or rotational grazing at varying grazing pressures). A more sophisticated model is required to quantify spatial contributions to catchment water balance. Such a model could in turn be used to estimate the proportion of rainfall that is intercepted or used by the soil–plant system.

In other words, we need to quantify the total environmental losses of water (i.e. water not intercepted or used by plants) before we move towards calculating WUE for a given farming system. We also need to recognise that WUE estimates are likely to vary spatially within a given catchment, and with the type of farming system used.

Conclusions

Various WUE indicators employed in China and Australia have been discussed. The type of WUE indicator used must be clearly stated because some are used to indicate production or economic performance rather than water use. To be widely adopted, an indicator of WUE must be practical and based on easily measured parameters.

Acknowledgments

This research was supported by contributions from ACIAR to Project LWR1/95/07, conducted by CSIRO Land and Water and the Chinese Academy of Sciences.

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