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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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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);

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

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:

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

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.

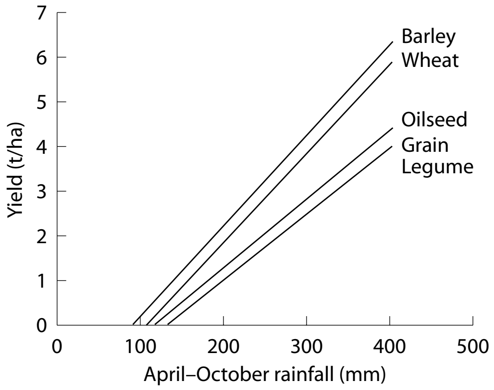

Figure 1 Relationships between potential grain yield and April–October rainfall (mm) for crops grown in South Australia (French 1995).

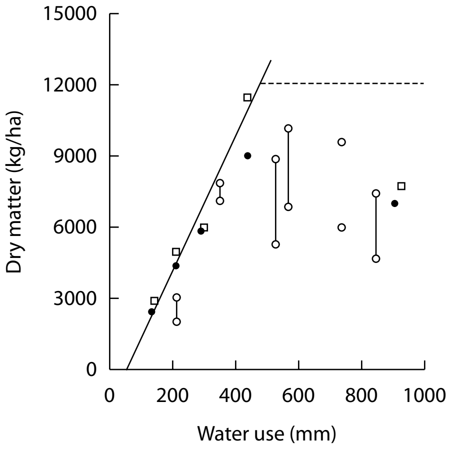

Figure 2 Relationships between growing-season water use (mm) and pasture dry matter production at experimental sites across Western Australia (from Bolger et al. 1993). Open squares represent values for maximum production systems (high fertiliser inputs, high seeding rates, good weed control); closed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

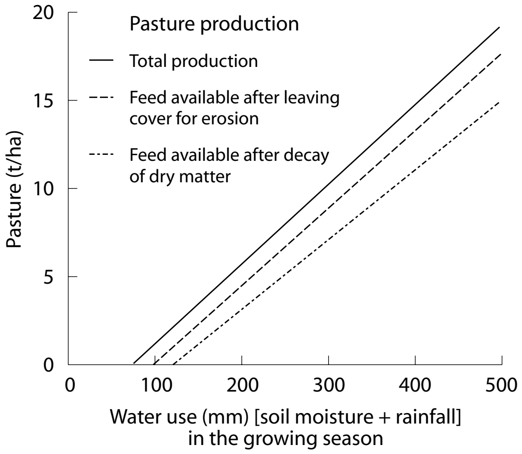

Figure 3 Relationship between water use in the growing season and pasture dry matter production in South Australia (after French 1992).

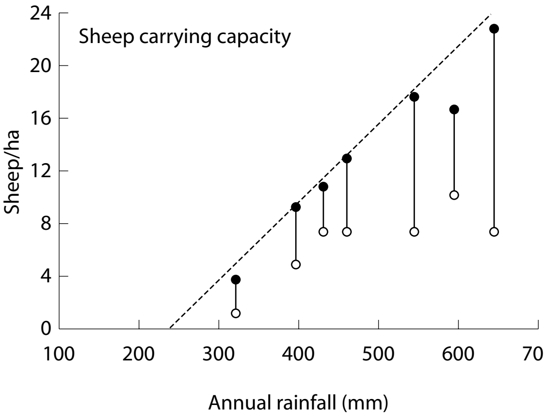

Figure 4 Relationship between annual rainfall and sheep carrying capacity derived from stocking rate experiments conducted at seven sites in South Australia (French 1992). Open circles represent minimum sheep carrying capacity; closed circles represent maximum sheep carrying capacity.

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.

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5

The Water Balance of Pastures in a South Australian Catchment with Sloping Texture-Contrast Soils

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Abstract

The water use of several pasture types was compared in a catchment in the Mount Lofty Ranges, South Australia. The study sites had sloping (less than 14%) texture-contrast soils. The aim was to delineate the water pathways (e.g. evapotranspiration, surface runoff, throughflow) in the catchment and to supply farmers with the best pasture option for minimising deep drainage.

Lucerne (*Medicago sativa* cv. Aquarius) produced more dry matter in summer and used more water than phalaris (*Phalaris aquatica* cv. Sirosa) on the mid- and upper slopes but was similar on the toe-slopes. The clay subsoils on the toe-slope were slightly saline, strongly sodic and sometimes affected by saline groundwaters in winter. After only one year's growth, the lucerne and phalaris pastures used more water than the existing cocksfoot (*Dactylis glomerata*) pasture on all parts of the slope. TOPOG-IRM modelling indicated that on all parts of the slope there was substantial deep drainage under the existing pasture (up to 29% of annual rainfall), with much-reduced deep drainage under phalaris and lucerne.

本文对比了几种牧草的水分利用壮况，以查明流域水分流失渠道(如蒸发蒸腾量，表面径流，壤中流等)，为当地农户找出最佳牧草种类，最大程度减少土壤水分深层渗漏。试验地点在南澳劳伏特山区，地面坡度<14%，土壤剖面质地不均，上层砂土或壤土，下层粘土。对比发现，苜蓿在夏季比苡草生产更多的干物质，在坡面的中上部也消耗更多的水分，但在坡面下部两者耗水量接近。坡下部的土壤粘土层有轻微盐化，严重碱化，冬季有时因地下盐

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水位升高而受到影响。在仅仅生长一年以后，在坡地的各个部位，苜蓿和苡草都能比当地原有的鸭茅草利用更多的水分。TOPOG – IRM 模型显示，鸭茅草下的土壤底层水分渗漏严重（可高达年降雨量的29%），而在苜蓿和苡草下面则大大减少了。

LAND degradation is widespread in the agricultural regions of Australia, affecting vast areas of potentially productive land. Most land degradation (e.g. dryland salinity, waterlogging and erosion) has been caused by the widespread clearance of perennial native vegetation and its replacement with mainly annual crops and pastures (e.g. Saunders and Hobbs 1993). This has led to a drastic change in the hydrology of agricultural landscapes. It is widely acknowledged that recharge under introduced annual crops and pastures is significantly greater than that which occurs under natural vegetation (e.g. Kennett-Smith et al. 1993).

Duplex soils, sands or loams over clays occupy a large percentage of southern Australian agricultural regions (Chittleborough 1992). Their chemical and physical properties vary along a toposequence from crest to flat (Tennant et al. 1992). Duplex soils are particularly susceptible to land degradation when cleared for agriculture. Degradation on duplex soils is exacerbated by the development of rapidly fluctuating perched watertables on slowly permeable subsoil horizons (Cox et al. 1994; Cox and McFarlane 1995). On some sloping duplex soils, significant quantities of water can travel as throughflow on top of the B horizon (Cox and Fleming 1997; Fleming and Cox 1998). This can increase the risk of waterlogging on low slopes. On ‘leaky’ duplex soils, groundwater recharge can mobilise stored salts and bring them into the root zone, particularly in the toe-slopes and flats (Cox et al. 1996; Fitzpatrick et al. 1997). The chemical and physical properties of these duplex soils may change over time (Fitzpatrick et al. 2000).

It is apparent then that catchment water balances need to change so that less deep drainage occurs (Gregory et al. 1992). One option for achieving this may be changed agronomic practices. Lucerne (*Medicago sativa* L.), phalaris (*Phalaris aquatica* L.), and cocksfoot (*Dactylis glomerata* L.) are commercially available pasture species. Previous studies of these pasture species on flat land have shown considerable variation between species in their growth and soil water use (e.g. Whitfield et al. 1992; Crawford and Macfarlane 1995; Lolicato 2000).

The aim of this study was to compare the water balance under lucerne with that under phalaris in three parts of the landscape. In addition, the pastures were compared with the existing (cocksfoot-based) pasture. Although farmers are encouraged to sow perennial pastures as a means of recharge reduction, no study has looked at the differences in their water use on sloping duplex soils.

Materials and Methods

Site location, climate and soils

The experimental site was located in the Keynes catchment in the Mount Lofty Ranges, South Australia. The climate is Mediterranean and the mean annual rainfall is 544 mm, more than 75% falling between April and October. The catchment soils are typical of many in the > 500 mm rainfall region of the Mount Lofty Ranges (Fritsch and Fitzpatrick 1994; Cox et al. 1996). Slopes average 14%. The Overview provides background information about the area and Figure 5 of the Overview shows its location.

Pits were excavated along five toposequences in the catchment and soils were classified according to both Soil Survey Staff (1996) and Isbell (1996) criteria. Chemical properties of the soil horizons were measured on selected samples using standard techniques (Rayment and Higginson 1992). Saturated hydraulic conductivities (K_s) of the A, E and B soil horizons were measured at 12 sites in each of the upper, mid- and toe-slopes of the catchment, using a disc permeameter (Perroux and White 1988). At the same locations, intact cores (0.047 m diameter and 0.05 m height) were collected for measurement of soil water characteristics[1] and bulk density.

Experimental design

There were three pasture types: lucerne-based, phalaris-based, and the existing pasture comprising cocksfoot, subterranean clover (*Trifolium subterraneum* L.) and annual grasses and weeds. Each plot was approximately 0.2 ha. Lucerne (*Medicago sativa* cv. Aquarius) and phalaris (*Phalaris aquatica* cv. Sirosa) plots were sown in the first year of the trial (1996) and replicated at each of the three levels of the landscape (that is, there were two plots of each crop at each of the upper, mid-, and toe-slopes). The existing pasture surrounded the lucerne and phalaris plots; detailed measurements were collected from one plot location at each landscape level. Physical barriers prevented run-on; overland flow and throughflow were measured using v-notch weirs and tipping buckets installed in drains (Cox and McFarlane 1995). Further details are in Cox and Pitman (2001).

Measurement of soil water stored in the profile

Soil water storage was monitored regularly (2–3 times a week in summer, weekly in winter), from 1996 to 1997 using a neutron moisture meter (NMM) (CPN Corporation, California, USA). Readings were taken at 0.1, 0.2, 0.35, 0.5, 0.7, 0.9, 1.1, 1.4 and 1.7 m. The neutron probe was calibrated from measuring the water content of soil cores (623 cm^3) collected at various periods of the year. Cores were dried at 105°C for 24 hours; gravimetric soil water content was then calculated and linear regressions ($r^2 > 0.8$) established for each soil horizon. Probe readings were taken at the same time as core sampling for each access tube. The bulk density of each sample (and of samples from the soil pits) was calculated from the known core volumes; their respective volumetric water contents were then derived.

Plant production and root distribution

On four occasions, pasture was harvested for the calculation of pasture dry matter availability. About 18 months after lucerne and phalaris establishment, 10 soil cores were taken from each of the three existing pasture plots and from one lucerne and one phalaris plot at each of the three toposequence positions. One core from each site (taken from approximately 1 m downslope of the NMM access tube) was sectioned to correspond with the neutron probe reading depth, sealed in a plastic bag and used for additional NMM calibration. A second core was placed on a core tray, which was sealed and labelled for detailed profile description. The remaining eight cores were cut into 0.2 m sections and placed in plastic bags that were sealed, labelled, and stored for root washing. All samples were stored at < 4°C prior to analysis.

Roots were washed using the hydropneumatic elutriation method described by Smucker et al. (1982); this method reportedly recovers 15–25% more root dry weight than careful handwashing techniques (Mackie-Dawson and Atkinson 1991). The technique requires two sieve sizes (0.5 mm and 1.0 mm) to retain the roots. Further soil pits were excavated to allow analysis of root growth and distribution, including a qualitative description of root growth and penetration down the profile.

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[1] Needed for the water balance modelling but not discussed in this paper.

Morphological measurements of length, area and root length density (RLD) were determined from scanned samples in the WinRHIZO™ package (Regent Instruments Inc., Quebec, Canada), using the method of Tennant (1975).

Hydrological modelling

Rainfall, solar radiation, wind speed, temperature and humidity were recorded hourly at an automatic weather station located in the catchment. TOPOG-IRM (a hydrological modelling package based on terrain analysis) (Dawes and Hatton 1993) simulations were run using the climatic, soil and vegetation data until soil water changes, overland flow and throughflow were correctly predicted. Actual evapotranspiration was derived from Penman–Monteith type equations (Monteith 1981) within TOPOG-IRM (Dawes and Hatton 1993). Deep drainage was determined by difference using the water balance equation for texture-contrast soils (Gregory et al. 1992).

Results

Soil types

From crest to flat, the soils were a sequence of Typic Palexeralfs to Aquic Palexeralfs to Natraqualfs; elsewhere the sequence was red and brown Chromosols to brown Sodosols to brown Dermosols. On the mid- and upper slopes, the topsoils were acidic (pH 6.2–6.7), nonsaline ($EC_{1:5}$ 0.01–0.06 dS/m)[2] and nonsodic (ESP < 5%).[3] The subsoils on the mid- and upper slopes had variable pH (6.5–7.6), were nonsaline ($EC_{1:5}$ 0.021–0.045 dS/m) and were usually nonsodic (ESP < 6%) except at depth (ESP was 10% at 1 m). On the toe-slopes, the topsoils were also acidic (pH 5.8–6.9) and nonsaline (0.015–0.045 dS/m) but were sometimes sodic (ESP 3–15%). The subsoils on the toe-slopes also had variable pH (6.6–7.8) and were often slightly saline ($EC_{1:5}$ <0.2 dS/m) and strongly sodic (< 21%).

Bulk density of the topsoil (0–0.4 m) was similar (1.5–1.7 g/cm^3) and not significantly different ($P < 0.05$) at all positions on the slope (Table 1). Bulk density of the subsoil was significantly ($P < 0.05$) higher on the toe-slope (< 2.0 g/cm^3 at 0.9 m) and lower on the upper slope (< 1.9 g/cm^3 at 1.50 m) than elsewhere. The change in the bulk density of the subsoil with depth was similar on the upper and middle slope but different on the toe-slope.

Table 2 shows the average K_s values. In general, K_s on the toe-slope was significantly ($P < 0.05$) lower than on the mid- and upper slopes in the A and B horizons (average 0.9 and 0.05 m/day, respectively) but was significantly ($P < 0.05$) higher in the E horizon (average 0.18 m/day).

Table 1. Bulk density of soil in a toposequence.

Depth interval (cm)	Mean bulk density (g/cm^3)[a]		
	Upper slope	Mid-slope	Toe-slope
0–20	1.503 (1.417–1.589)	1.570 (1.395–1.735)	1.490 (1.439–1.677)
20–40	1.738 (1.705–1.793)	1.717 (1.434–1.892)	1.627 (1.491–1.765)
40–60	1.659 (1.405–1.838)	1.796 (1.712–1.948)	1.823 (1.689–2.020)
60–80	1.631 (1.312–1.824)	1.741 (1.657–1.868)	1.973 (1.755–2.242)
80–100	1.665 (1.439–1.887)	1.825 (1.769–1.983)	2.030 (1.802–2.508)
100–120	1.820 (1.659–1.920)	1.925 (1.810–2.008)	2.012 (1.775–2.248)
120–140	1.856 (1.683–1.946)	1.818 (1.813–1.823)	1.976 (1.764–2.134)
140–160	1.894 (1.720–2.014)	1.892 (1.881–1.904)	1.843 (1.698–1.984)

[a] Figures in brackets indicate the range

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[2] $EC_{1:5}$ is the electrical conductivity; dS/m = deciSiemens per metre.

[3] ESP is exchangeable sodium percentage.

Rainfall

The annual rainfall was 14% below average in the first year of the trial (when the lucerne and phalaris were sown), close to the average in the second year of the trial and 26% below average in the final year (Table 3). The rainfall from April to October followed a similar pattern, with a 12% reduction in the first year, a slight increase (3%) in the second year and a substantial (40%) decrease in the final year.

Soil water

Figure 1 shows the change in soil water content (SWC) over two years below three pasture types on the upper slope of the catchment (the darker the shading, the higher the SWC). The SWC of the A horizon (approximately 0–0.35 m) followed a similar pattern under all treatments, responding rapidly to rainfall events. The type of overlying pasture did not significantly affect SWC over time ($P < 0.05$) (Fig. 2). During each winter, a perched watertable developed to some degree on all treatments within the clay subsoil (at approximately 0.5–0.6 m depth).

Table 2. Average measured saturated hydraulic conductivity (*Ks*) used in the modelling of deep drainage (m/day).

Horizon	Toe-slope	Mid-slope	Upper slope
A	0.93	1.97	2.06
E	0.18	0.14	0.11
B	0.05	0.08	0.07

In the soil profile below 0.35 m, changes in SWC were more gradual, and less influenced by the weather conditions. Under cocksfoot-based pasture, SWC at 0.35–1.7 m increased over the period of study at all slope positions (Table 4), based on end water content minus the initial water content (the amount of water used by the plant or drained). Under phalaris, SWC decreased at all slope positions, with the greatest water uptake in the upper slope position, followed by the mid- and toe-slopes. Under lucerne too, SWC decreased most in the upper slope region, followed by the mid- and toe-slopes. This trend was confirmed by solving the water balance to 1.8 m depth (Table 5). Lucerne on the mid- and upper slope and phalaris on the upper slope dried the soil profile over a two-year period. Over the same period, the SWC increased in all landscape positions under the cocksfoot. Thus, the greatest deep drainage occurred under cocksfoot; there was substantially less deep drainage under phalaris, and there was an uptake of soil water from below 1.8 m by the lucerne in the upper and mid-slope positions. In the toe-slope position, deep drainage was similar under lucerne and phalaris (Table 5).

Dry matter production and root analysis

Lucerne-based pasture was significantly ($P < 0.05$) more productive than the phalaris-based or cocksfoot-based pasture in the upper and mid-slope positions. It was also more productive on the toe-slopes but not to the same degree. Toposequence position in this regard was highly significant ($P < 0.01$). Table 6 shows the summer

Table 3. Monthly rainfall at Keyneton township and seasonal rainfall for the Keynes catchment (mm).

	J	F	M	A	M	J	J	A	S	O	N	D	Total	Apr–Oct total
Average[a]	18	23	20	35	62	64	80	76	63	49	29	25	544	429
1996	48	15	13	37	37	67	121	9	48	58	9	5	467	377
1997	47	8	30	10	10	132	84	80	73	53	15	7	549	442
1998	10	61	2	7	56	24	12	85	73	0	35	39	404	257

[a] 78-year average data from Bureau of Meteorology

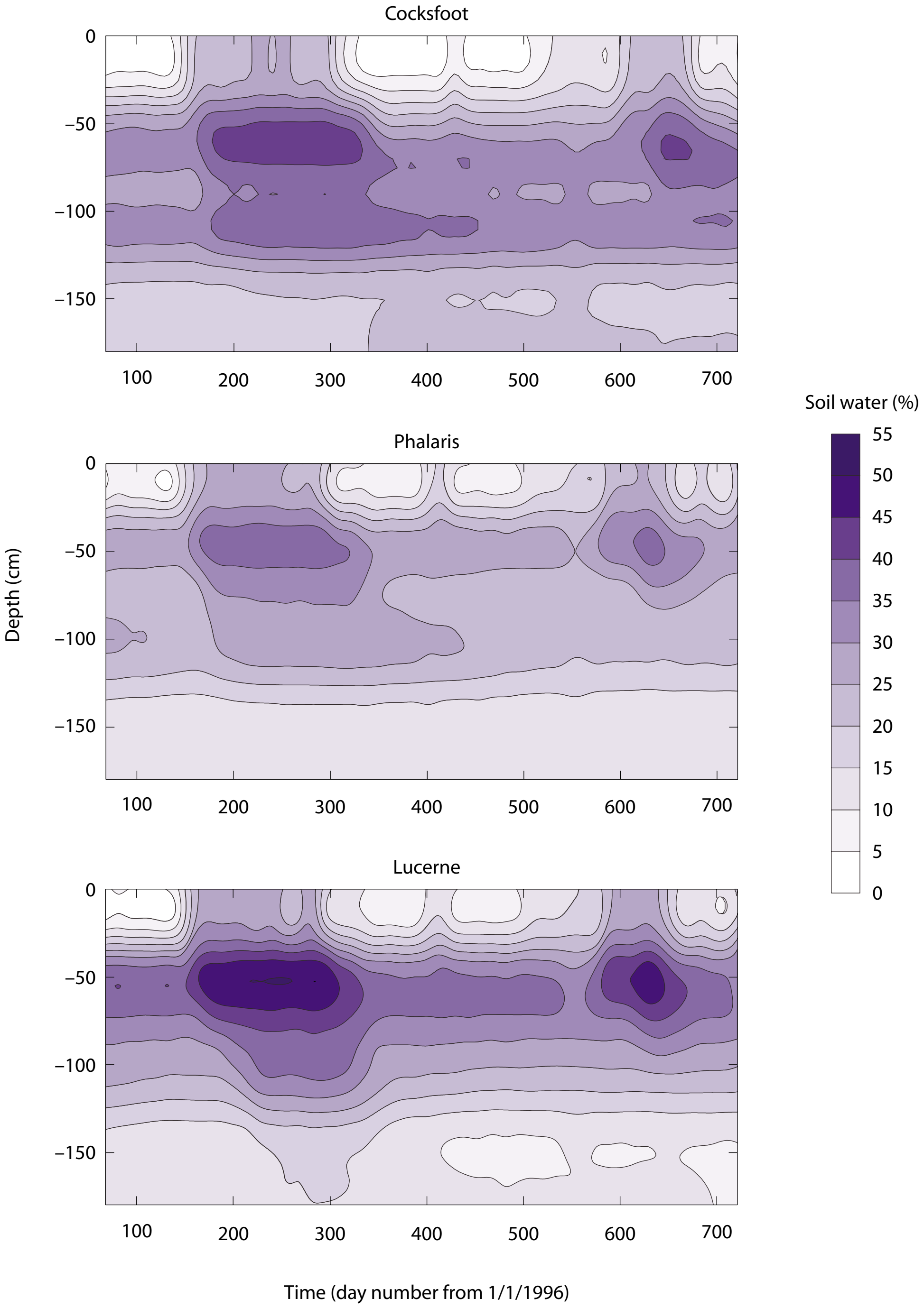

Figure 1. An example of soil water content (volume %) over a two-year period, under three pasture treatments on the upper slope, showing the development of perched watertables within the B horizon (average 35–75 cm).

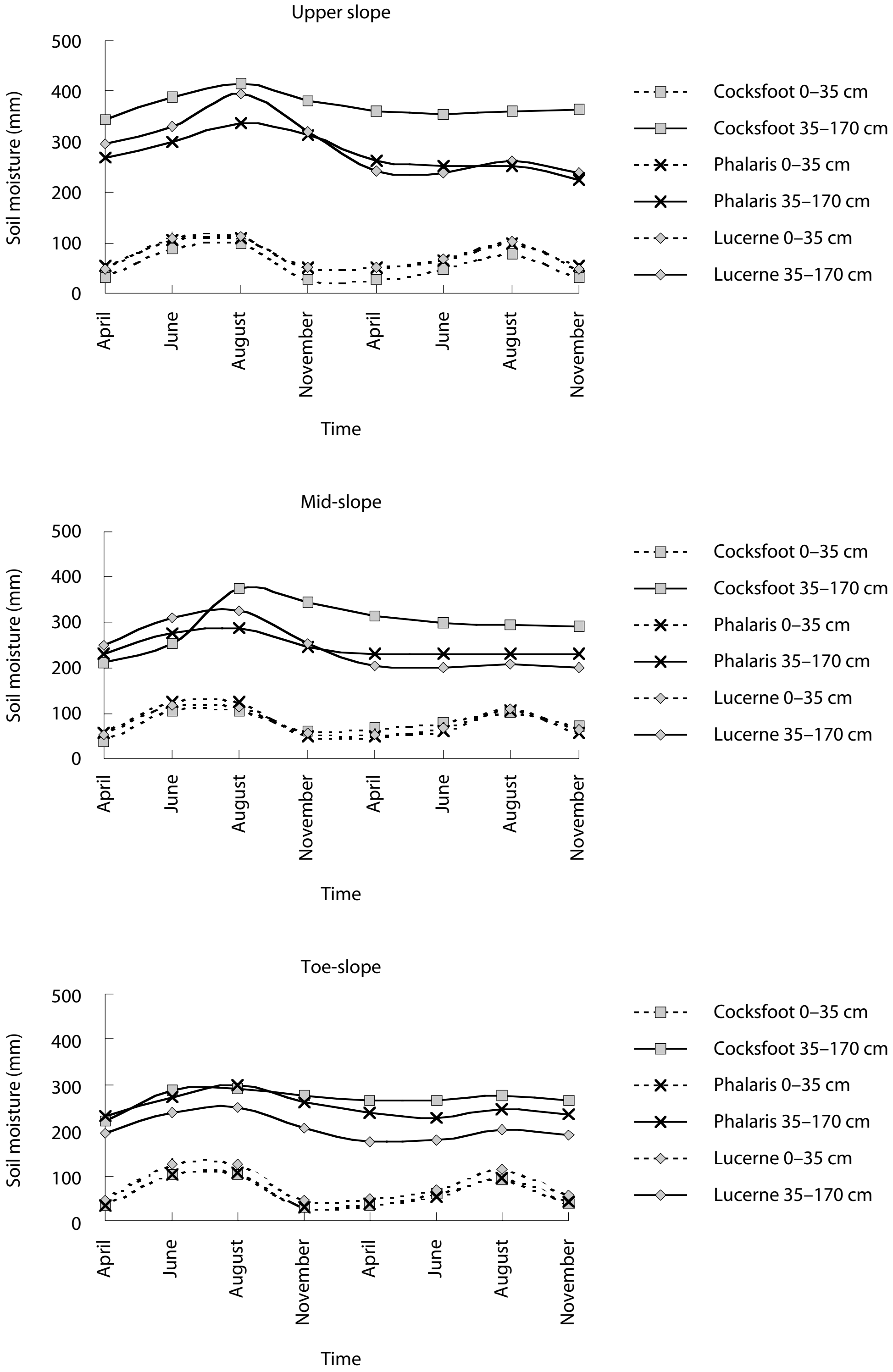

Figure 2. Average monthly soil water content (mm), from April 1997 to December 1998, under pasture.

growth advantage of the lucerne compared with the cocksfoot and phalaris-based pastures (the lucerne production in April 1997 was much higher than the other two pastures on all slope positions).

For all three pasture treatments, examination of roots in soil pits confirmed that most roots were in the top 0.3 m of the soil profile (Table 7); this is consistent with other studies (Evans 1978; Gregory 1998). Visual inspections revealed a dense mat of roots in the top 0.1 m under all treatments, but surface samples (0–0.1 m) were not analysed because it would have taken too long to prepare samples of such a large amount of extraneous organic material.

Table 4. Average change (initial–final) soil water content (mm), 35–170 cm soil depth, over a two-year period (1996 to 1997).

Pasture	Upper slope	Mid-slope	Toe-slope
Cocksfoot	14.9	81.8	48.9
Phalaris	58.0	11.2	1.8
Lucerne	74.8	57.8	10.5

Figure 3 shows mean data (from eight cores per treatment per slope position) for the scanned root samples. The cocksfoot samples were taken from the pre-existing pasture; the other samples were taken about 18 months after pasture establishment. Cores were taken to the maximum depth possible given soil conditions and the limitations of the drilling rig; most samples were no deeper than 1.4 m. As indicated in Figure 3, most of the cocksfoot and phalaris root material below approximately 0.9 m was dead.

Discussion

Soil water, deep drainage and water use

The soil water content of the A horizon was similar under all pasture types. In the autumn/winter of the first year of the trial, a perched watertable developed within the B horizon under all pastures and at all slope positions. By the autumn of the second year, the lucerne, and to a slightly lesser degree the phalaris, had begun to dry the profile below 0.35 m; this, combined with below average rainfall, reduced the development and duration of perching. Under the cocksfoot, the soil profile below 0.35 m had remained at a higher SWC; perching developed earlier and lasted longer than for the other two pasture treatments.

Table 5. Average water balance for different pasture/slope treatments (mm), 0–180 cm soil depth.

	Cocksfoot			Phalaris			Lucerne		
	Upper slope	Mid-slope	Toe-slope	Upper slope	Mid-slope	Toe-slope	Upper slope	Mid-slope	Toe-slope
Rainfall[a]	897	897	897	897	897	897	897	897	897
Evapotranspiration[b]	752	755	826	806	785	872	878	877	870
Surface runoff[a]	2	2	18	1	2	40	1	43	1
Throughflow[a]	8	18	74	8	44	14	13	13	29
Change in water storage[c]	–59	–141	–102	19	–32	–50	44	26	–49
Deep drainage[d]	194	263	81	63	98	21	–39	–62	46

[a] Actual measurements
[b] Actual evapotranspiration from TOPOG-IRM
[c] Initial–final soil water content
[d] Deep drainage is by difference in the water balance equation

Predicted deep drainage losses under cocksfoot were substantial over the two-year period, particularly in the upper and mid-slope positions. There was less drainage at the toe-slope position, because 73.5 mm of infiltration was removed via throughflow. Generally, throughflow increased downslope due to the increase in bulk density, and consequent lower porosities, of the sodic B horizon.

Deep drainage under the cocksfoot pastures ranged from 9% to 29% of annual rainfall over the two years. Under the phalaris treatments, deep drainage ranged from 21 to 98 mm, or 2–11% of the total rainfall for the period.

Phalaris persisted longer into summer than cocksfoot, broke dormancy earlier, had

Table 6. Mean dry matter production (kg/ha) of lucerne, phalaris and cocksfoot-based pastures, at three toposequence positions, over four time periods.

Slope	August 1996	October 1996	April 1997	October 1997	Total
Lucerne sites					
Upper	1211.6	2851.5	2393.9	2860.3	9317.3
Mid	1123.9	2954.2	1518.9	2461.1	8058.1
Toe	796.5	1871.2	1229.4	1796.7	5693.8
Phalaris sites					
Upper	1033.5	2732.4	936.1	2440.5	7142.5
Mid	902.2	2623.6	888.9	1491.4	5906.1
Toe	938.2	2618.4	905.0	1764.8	6226.4
Cocksfoot sites					
Upper	941.4	2904.6	552.1	1796.1	6194.2
Mid	902.8	2295.0	599.2	1667.1	5464.1
Toe	997.4	2098.6	767.9	1637.7	5501.6

Table 7. Root length densities at discrete depth intervals for the three pasture species tested.

	Root length density (cm/cm^3)		
Depth interval (cm)	Cocksfoot	Phalaris	Lucerne
10–30	3.7	6.0	6.5
30–50	0.9	1.8	1.9
50–70	0.5	0.8	0.7
70–90	0.2	0.4	0.5
90–110	0.2[a]	0.3[a]	0.3
110–130	0.1[a]	0.2[a]	0.3

[a] The bulk of root material in the cocksfoot and phalaris samples below 90 cm was dead

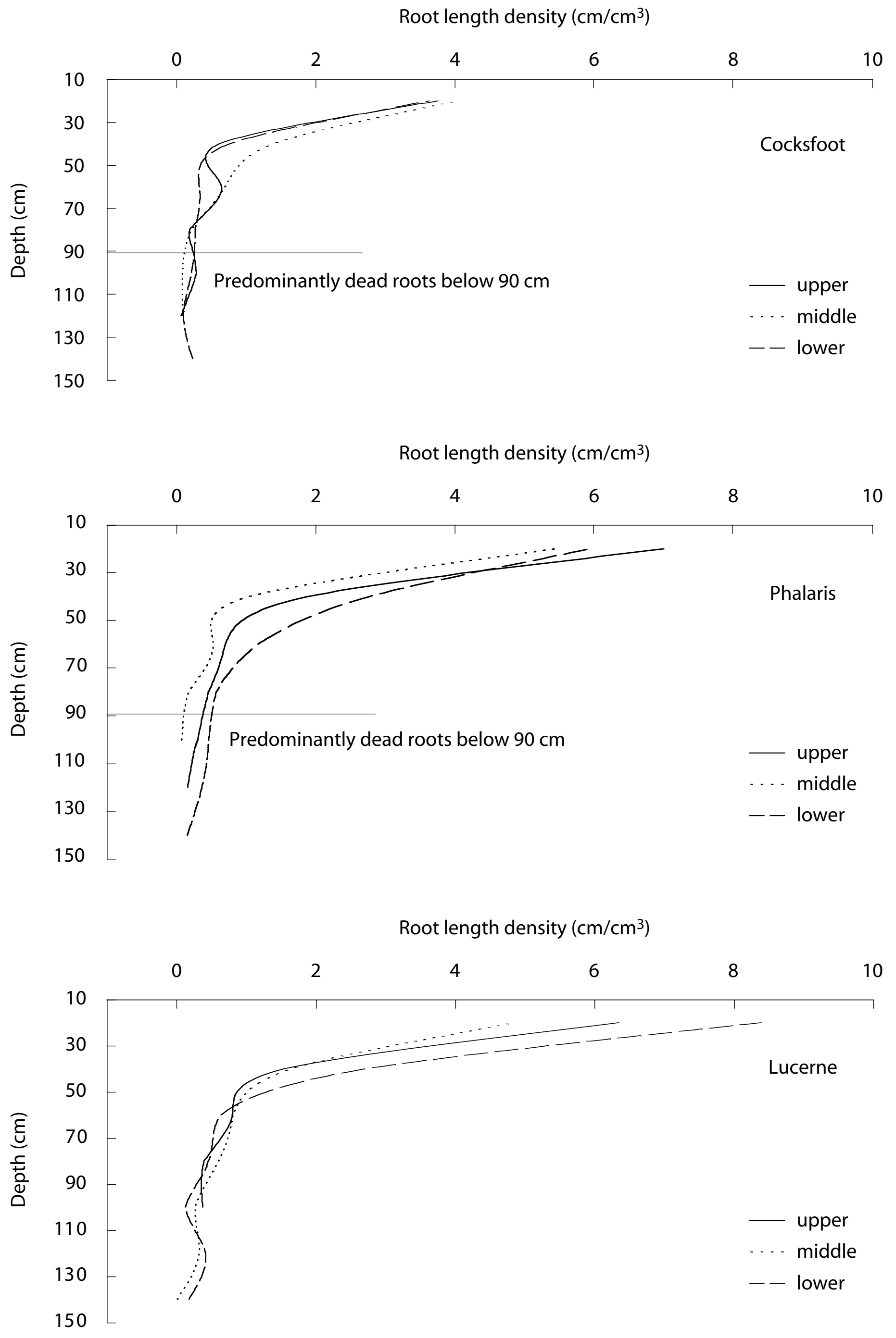

Figure 3. Root length density emphasising toposequence effects for cocksfoot, phalaris and lucerne.

proportionally more groundcover, and produced between 0.5 and 1.0 tonnes/ha more dry matter at each slope position. This additional growth resulted in increased evapotranspiration. These factors, and the substantially smaller increases in SWC under phalaris than under cocksfoot, suggest that farmers should be encouraged to sow phalaris rather than cocksfoot.

Modelling showed that under lucerne deep drainage occurred only on the toe-slope. At this point on the toposequence, 46 mm (5% of the total rainfall) passed below the 1.8 m profile boundary; groundwaters were shallow, so it probably contributed to recharge. In both the upper and mid-slope positions, soil water (44 and 26 mm respectively) was depleted from below 1.8 m by the lucerne. Numerous other studies, at smaller scale, support the ability of lucerne to extend its roots to a considerable depth, extract soil water from deep within the profile and reduce deep drainage. This study demonstrated that lucerne significantly reduces deep drainage on duplex soils at a small subcatchment scale, particularly at the upper and mid-slope positions. The main advantage of lucerne over the other pasture species tested appears to be the ability to extend roots into the subsoil and extract soil water stored deep in the profile, which would otherwise contribute to deep drainage. Lolicato (2000) reached a similar conclusion in his comparison of lucerne with cocksfoot, phalaris and birdsfoot trefoil (*Lotus corniculatus*). At the toe-slope position, where there was poor drainage and increased salinity, lucerne and phalaris both performed similarly, allowing deep drainage of 27–29 mm, in comparison to 63 mm at that position under cocksfoot.

Dry matter production and root analysis

Lucerne produced more dry matter over two years than the phalaris or cocksfoot in the upper and mid-slope positions. This was largely due to the summer dominant growth of lucerne. Phalaris and cocksfoot generally showed similar dry matter production, although phalaris production was slightly higher than that of cocksfoot over summer. Lucerne production was consistently lower than phalaris and cocksfoot on the toe-slopes where soils were slightly saline.

The decline in root material below 0.3 m in the catchment was quite marked for all species. Ridley and Simpson (1994) reported a study on a duplex red soil with a similar A/B horizon at approximately 0.3 m; they found a more gradual decline, with substantial root length density (RLD) to 0.5 m (approximately two-thirds of that in the 0.1–0.3 m interval). The Keynes catchment data suggested that a restrictive A/B horizon may encourage root proliferation in the surface soil.

Visual inspection of soil pits indicated distinct differences in rooting depth between species: cocksfoot roots were observed to 1.2 m, phalaris to approximately 1.5 m and lucerne to more than 2.0 m. The cocksfoot had been established for many years, so had probably established a maximum rooting depth for that environment. Soil pits dug some 18 months after the establishment of the lucerne and phalaris pastures showed that root extension to 2.0 m had already occurred. Subsequent pits did not indicate that phalaris was increasing its penetration to any extent. The lucerne root system could not be excavated to the full extent as its taproots followed cracks into the underlying sandstone. Both the phalaris and the lucerne roots had taken advantage of macropores, cracks and other faults to extend into lower depths. There was little evidence of roots elsewhere in the soil matrix at depth.

Figure 3 shows root length for each toposequence. The relatively low RLD of cocksfoot in the 0.1–0.3 m range is obvious. In the 0.3–0.7 m section of the soil profile, cocksfoot RLD is 0.25–0.5 cm/cm^3, whereas phalaris and lucerne are closer to 0.5–1.0 cm/cm^3. Phalaris and lucerne have more roots in the 0.1–0.3 m region; phalaris appears to show differences related to toposequence position, with a higher RLD below 0.3 m, in both the upper and toe-slope positions. This is consistent with pasture growth trends for phalaris, with lower pasture cuts on the mid-slope. Lucerne RLD seems consistent below 0.5 m, at all toposequence positions; its main advantage over the other two pastures is that substantial live roots extend down the profile. At depth, many of these roots were still less than 1 mm in diameter compared to the fine, hair-like roots of both cocksfoot and phalaris. Decreases in SWC under the three pasture types are consistent with the densities and morphology of their root systems.

Conclusions

The results of this study show that both lucerne and phalaris will produce a higher amount of dry matter and use more water resulting in less deep drainage than the cocksfoot-based pastures that farmers are currently sowing. Lucerne is the best choice on mid- and upper slopes; phalaris is best for low slopes, where soil salinity and sodicity reduce the performance of lucerne.

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6

Simulation of Winter Wheat Yield and Water Use Efficiency on the Loess Plateau of China Using WAVES

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and Warrick R. Dawes[†]**

Abstract

Water availability is a major factor limiting crop yields on the Loess Plateau of China. As competition for water intensifies, it is essential to develop alternative irrigation schedules that maximise crop yield and water use efficiency (WUE) for a given level of water supply. A field experiment with winter wheat (*Triticum aestivum* L.) from 1995 to 1998 calibrated and tested a biophysically based model (WAVES) in terms of grain yield and WUE prediction. The data collected include water and energy balance components, biomass and grain yield. Comparisons between the measurements and the model predictions were made with three years of field data. Modelled grain yield and WUE based on biomass and harvest index were in better agreement with the measurements than those based on transpiration and harvest index. The model was sensitive to different irrigation treatments, and in reasonable agreement with field measured data. The highest irrigation treatment resulted in the greatest evapotranspiration but not the highest yield, so WUE was relatively low. Appropriately limited irrigation could improve the grain yield and WUE. Aiming only for maximum grain yield or for maximum WUE could lead to uneconomical irrigation management.

水分供应是黄土高原粮食产量的主要限制因素。由于用水竞争的加剧，选择能够在某一设定供水水平上，产量最高，水分利用效率（WUE）最高的灌溉方式就很重要。1995-98 年间进行的冬小麦田间试验，在作物产量和WUE 方面校正、检测了基于生物物理原理的 WAVES 模型。收集了水分能量

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平衡组分、生物量和粮食产量的数据，作了测量值和模型预测值的比较。以生物量和收获指数为基础预测的产量及 WUE 与实测值的吻合程度高于以蒸腾与产量指数为基础的数值。该模型对不同灌溉条件敏感性高，与实测值的吻合令人满意。灌溉最多，则蒸发最多，但产量不是最高，所以 WUE 相对较低，适当的有限灌溉能提高产量和 WUE。仅仅追求最大产量或最高 WUE 可能导致灌溉的经济效益不高。

THE LOESS Plateau, located in the middle reaches of the Yellow River, is one of the main agricultural regions in China. The Overview provides background information on this area; Figure 1 of the Overview shows its location. Winter wheat (*Triticum aestivum* L.) and summer corn (*Zea mays*) are the main crops in the area. Average annual rainfall ranges from 300 to 600 mm, with over 60% occurring from July to September. As rainfall is low and variable, water is the most important factor limiting agricultural production in the region. Crops are irrigated with water pumped from the Yellow River or from collected rainfall. However, the amount of available water in the Yellow River has declined rapidly in recent years, so there is an urgent need to reduce irrigation in order to sustain agriculture in this area (Kang and Li 1997). A challenge is to develop management techniques that increase water use efficiency (WUE) while optimising crop production. Chapter 4 discusses this in more detail.

When available water becomes limited, water deficits are unavoidable in some periods of the crop growing season. Irrigation scheduling then becomes more important and complex because irrigation decisions need to be based on the relationship between water use and grain yield and on WUE. This requires people to evaluate alternative irrigation schedules and choose a schedule that optimises crop yield and WUE for a given level of water supply. There are few detailed investigations on water use–grain yield relationships and WUE under different water supply conditions in the region, although many irrigation practices involve soil water deficit control.

In order to develop guidelines for farmers and/or decision makers to manage crop production, many irrigation practices under various conditions must be evaluated in terms of their effect on yield and WUE. Process-based models can provide useful information about different irrigation practices. For example, Hook (1994) and Kang et al. (1992) have used models to determine the best irrigation strategies. Models can also add value to decision making by transferring results from extensive field experiments to other areas (Cheeroo-Nayamuth et al. 2000; Cabelguenne et al. 1999; Jagtap et al. 1999; Sankaran et al. 2000; Alagarswamy et al. 2000).

Modelling crop yield and WUE is an important facet of crop water management and requires a good understanding of crop–water relationships. WAVES (water, atmosphere, vegetation, energy and soil) is an integrated energy and water balance model based on the biophysical processes in the soil–plant–atmosphere continuum (Zhang et al. 1996). A detailed description of WAVES can be found in Zhang and Dawes (1998) and in Chapter 1 of this volume. The model was successfully applied to the Loess Plateau to model the processes of water dynamics, crop evapotranspiration, and biomass accumulation (Huang et al. 2001), but was not tested for crop yield prediction.

The objective of this chapter is twofold: to evaluate two different methods for predicting crop yield and WUE within the WAVES model, and to evaluate optimal water management practices for improving crop yield and WUE under limited water supply on the Loess Plateau.

Field Experiments and Data

Site description

We conducted field experiments in Changwu, Shaanxi Province, during 1995–98. The Overview provides background information about the area; Figure 4 of the Overview shows its location. The study site has an elevation of 1206 m and has a semiarid to warm temperate climate with an average annual rainfall of 542 mm, concentrated from July to September. Annual averages are 2226 hours for sunshine duration, 9°C for temperature and 1552 mm for potential evaporation. The groundwater table is 50–80 m below the surface. The soil is a dark loess soil with a loam texture; it has been intensively cultivated over many centuries. Table 1 shows the major physical properties of the soil. The top 30 cm contains 1.55% total organic matter, 0.106% nitrogen (Bremner and Mulvaney 1982) and 0.095% available phosphate (Olsen and Sommers 1982). The lysimeters were 3 m × 2 m in area and 3 m deep, separated by waterproof concrete walls buried up to the soil surface.

The soil was irrigated, fertilised and well mixed in the top 30 cm before sowing. In each plot, an aluminium tube, 2 m long, was installed for moisture measurements. A mobile plastic rain shelter was installed above the lysimeters to control soil water status. Winter wheat (cultivar Changwu 89-134[1]) was sown in late September. Seedling density was controlled at 200 plants/m^2. There were seven treatments of irrigation deficit each year with three randomly designed replicates (Table 2). All plants were harvested in early July in the year following planting.

Measurements and statistical treatment

A neutron moisture meter (CPN503, United States) was used to measure water content every 10 cm to a depth of 2 m, with measurements taken weekly. In controlling soil water deficit, average soil water content for the top 40 cm and 60 cm was monitored using a time-domain reflectometer (Trase system, Soil Moisture Equipment Corporation, United States). When soil water content dropped to the lower limit of the designated range (see Table 2), the plot was irrigated to its field capacity. The amount of irrigation water in each lysimeter was recorded and used to calculate total water consumption. At the end of the winter growing season, plants were harvested and the dry mass and final grain yield calculated. All data were statistically analysed and treatments were compared using Duncan's multiple range test.

Meteorological data were recorded by a standard weather station located at the experimental site. Daily values of maximum and minimum temperature, maximum vapour pressure deficit and average wind speed were recorded.

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[1] This cultivar is widely used by farmers in the region.

Table 1. The particle composition and hydraulic properties of soils at Changwu.

Size	Particle composition									
(mm)	>0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001 mm	θ_s	θ_F	θ_{wilt}	γ_d
%	1.1	2.4	57.0	8.6	17.7	13.2	0.486	0.255	0.1	1.21

θ_s = saturated soil water content (cm^3/cm^3); θ_F = field capacity (cm^3/cm^3); θ_{wilt} = water content at permanent wilting point (cm^3/cm^3); and γ_d = mean bulk density (g/cm^3)

Table 2. Controlled minimum soil water content of different treatments in the winter wheat growing season.

No.	Treatment[a]	Minimum soil water content maintained (% of field capacity) Seeding to before winter freezing	Regrowth to stem elongation	Booting to heading	Flowering to milk ripeness	Maturity to harvest
1	LLLLL	45	45	45	45	45
2	LLLHM	45	45	45	70	55
3	LHMLL	45	70	55	45	45
4	LMHMH	45	55	70	55	70
5	MMHHL	55	55	70	70	45
6	HMHHM	70	55	70	70	55
7	HHHHH	70	70	70	70	70

[a] The growing season was divided into five periods and soil water content in the top 60 cm (40 cm before the jointing stage) was maintained during different stages at one of three levels: high soil moisture content (H) (no soil water deficit); medium (M) (mild soil water deficit); or low (L) (severe soil water deficit). When soil water content approached the minimum values, water was supplied up to field capacity.

Using the WAVES Model

WAVES can be used to predict crop yield and WUE. Crop yield is estimated from the carbon balance, determined by calculation of evaporation and transpiration demand for a given day. These fluxes are based on the soil conditions at the start of the day. A portion of the energy balance is used to estimate the stresses on the vegetation (Zhang and Dawes 1998), and carbon balance is then used to calculate assimilation based on those stresses. Finally, evaporative demand is calculated using a conductance based on the assimilation rate. In this way a complete cycle between the atmosphere, soil and vegetation can be made. The WAVES plant growth model is a generic algorithm using rate-based equations, physical principles and empirical results (Wu et al. 1994). WAVES does not attempt to model discrete phenological growth stages or to predict yield. The model treats a plant as three separate carbon sinks representing leaves, stems and roots. Each of these is assumed to occupy the conceptual site fully (i.e. leaves are evenly spread across each square metre, stem numbers are not determined but are uniformly spread and roots totally explore the depths to which root carbon is allocated).

Engineering estimates of crop yield can be made from knowledge of above-ground biomass and actual and potential transpiration, based on empirical relationships (Charles-Edwards 1982). The simplest equation uses the harvest index:

$$Y = HI \times DM \qquad (1)$$

where Y is crop yield (kg/ha), HI is the harvest index, and DM is the total above-ground dry matter (kg/ha). Transpiration data can be used to make alternative yield estimates (de Wit 1958):

$$Y = HI \times m \frac{ET_a}{ET_p} \qquad (2)$$

where m is a crop factor dependent on variety and species (kg/ha), ET_a is actual transpiration, and ET_p is average potential transpiration rate over the growing season. Within WAVES, the values of ET_a and ET_p are stored and can be used for these calculations with a user-specified harvest index and m parameter.

Harvest index is related to water supply level (Austin et al. 1980; Perry and D'Antuono 1989; Siddique et al. 1989). Based on Kang et al. (2000), the harvest index for winter wheat was set to 0.25 (rainfed), 0.30 (limited irrigation), 0.40 (middle irrigation) or 0.35 (full irrigation). The crop factor *m* was set to 140 in all the simulations (Kang et al. 2000). Crop WUE was calculated as grain yield divided by seasonal evapotranspiration.

Calibration was done manually (i.e. without the use of software that optimises parameters for least squares or other error criteria). The calibration approach required a compromise between the degree to which a parameter could be adjusted for an individual plot, and the degree of parameter variation across plots. In order to obtain model parameters, the WAVES model was first run using the meteorological data between September 1995 and July 1996 and treatment 1 (full irrigation). Vegetation parameters for winter wheat were selected from the work of Zhang et al. (1996), with the accumulated temperatures and the maximum root depth adjusted according to local conditions. The soil in the experimental site has a fairly uniform profile and was assumed to have only one layer. The maximum rooting depth for winter wheat was set to 2 m under limited irrigation. The bottom of the soil column had a draining boundary with a maximum rate of 0.01 mm/day. This selection of the lower boundary condition is based on the specific characteristics of water balance with a winter wheat crop.

Results and Discussion

Grain yield prediction

Figure 1 shows a comparison of simulated and measured grain yield during the period 1995–98, using Equations 1 and 2 (Figs. 1a and 1b, respectively). Simulated grain yield using Equation 1 agreed well with the measurements. The best-fit slope through the origin was 0.97, with a correlation coefficient of 0.93. Grain yield simulated by Equation 2 also compared reasonably well with the measurements. The best-fit slope was 1.00 with a correlation coefficient of 0.82. These results indicate that grain yield can be approximated from estimates of above-ground dry matter and crop transpiration.

The harvest index and crop factor must be known to predict grain yield using the above methods. For winter wheat on the Loess Plateau of China, the harvest index varies from 0.25 to 0.40, depending on water availability (Kang et al. 2000). In water-limited crops that rely predominantly on stored water, the harvest index is roughly proportional to the amount of water available after anthesis (Nix and Fitzpatrick 1969). This is not the case for crops that rely predominantly on current rainfall (Passioura 1986). In other words, the harvest index varies with available soil water and other factors; it cannot be considered as an independent variable. The success of grain yield predictions using

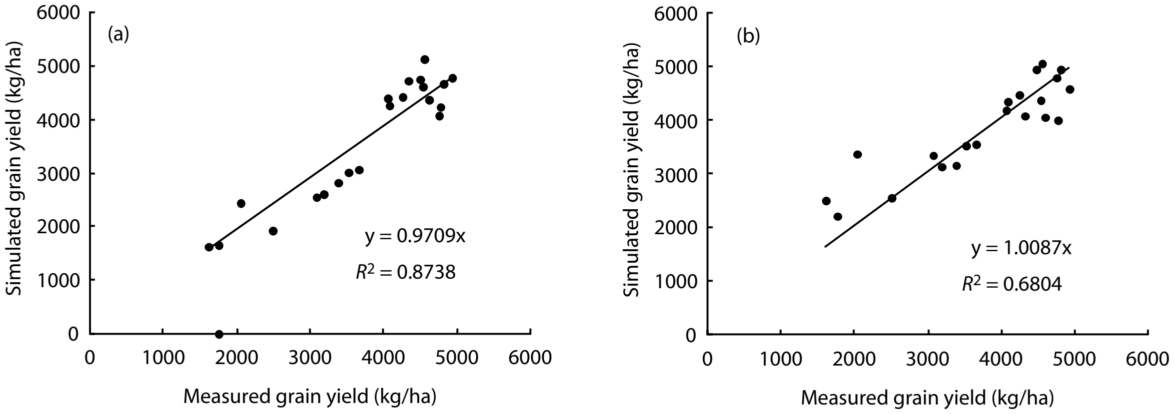

Figure 1. Effectiveness of WAVES in predicting grain yield for winter wheat, Changwu. (a) Prediction based on above-ground matter. (b) Prediction based on transpiration.

Equations 1 and 2 relies on accurate estimates of the harvest index. The results shown in Figure 1 support the findings of Zhang et al. (1999) and Wang et al. (2001), that the WAVES model can accurately simulate plant biomass under various soil moisture conditions.

The crop factor *m* is considered to be dependent only on variety and species (Hanks 1983). It can be applied to both water-limited and well-watered situations (de Wit 1958). We used a constant value in all simulations. Relationships represented by Equations 1 and 2 are attractive because they are simple; however, they are really useful only if we are able to estimate crop transpiration independently. This often means that a detailed model of a soil–crop–atmosphere system is required.

Water use efficiency

Figure 2 shows the comparison of the simulated WUE by the WAVES model and the measured values. The results obtained using Equation 1 agreed reasonably well with the measurements. The best-fit slope through the origin was 0.95, with a correlation coefficient of 0.75. The results using Equation 2 showed poor correlation with the measured values. Mathematically, WUE is estimated by dividing Equation 2 by actual evapotranspiration and shows the variation in potential evapotranspiration. Since this quantity is independent of crop growth, little correlation can be expected. Where potential evapotranspiration, and therefore atmospheric demand, becomes the most limiting factor in crop growth, the relationship shown in Equation 2 may yield better estimates of WUE.

Figure 3 illustrates how evapotranspiration relates to simulated grain yield and WUE, using the WAVES model. Grain yield and evapotranspiration increased simultaneously when evapotranspiration was below a critical value; the slope increased as evapotranspiration decreased and became negative when evapotranspiration was larger than the critical value (about 500 mm). However, the maximum WUE was reached when evapotranspiration was at 440 mm and did not correspond to the maximum grain yield. When evapotranspiration was relatively low, an increase in water use by a crop could result in large increases in both grain yield and WUE. However, at maximum WUE, an increase in crop water use could still lead to an increase in grain yield, but could only reduce WUE.

Simply aiming for maximum grain yield under limited irrigation will require too much water. However, aiming for maximum WUE will result in

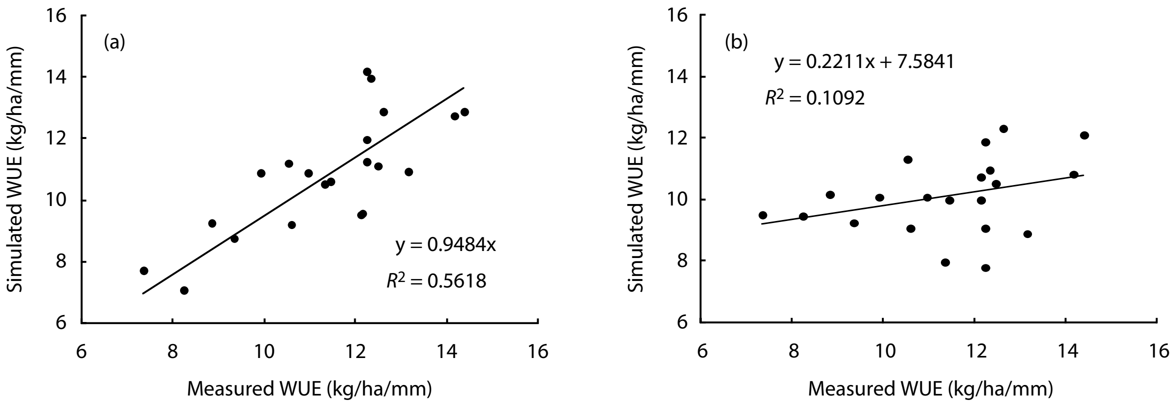

Figure 2. Effectiveness of WAVES in predicting water use efficiency (WUE) for winter wheat, Changwu. (a) Prediction based on above-ground matter. (b) Prediction based on transpiration.

a lower grain yield. Thus, it is necessary to consider both yield and WUE when irrigating. The association of high WUE with high yields has important implications for efficient use of water resources on the semiarid Loess Plateau of China.

Table 3 shows total evapotranspiration, grain yield, biomass and WUE calculated by summation of daily output from simulations over the whole growing season from 20 September to 2 July for three years, together with irrigation water use and rainfall. Simulated seasonal evapotranspiration varied between 234 and 526 mm. Simulated biomass was between 8800 and 12,600 kg per hectare (kg/ha). The simulated grain yield was 1600–5140 kg/ha, and 2200–5040 kg/ha, using Equations 1 and 2 respectively. Crop WUE was 6.16–12.87 kg/ha/mm and 7.78–12.33 kg/ha/mm for yield simulated by Equations 1 and 2 respectively.

Clearly, evapotranspiration, biomass and grain yield were lower under rainfed conditions than under irrigation. Evapotranspiration and yield depend on applied irrigation. Both evapotranspiration and biomass were maximised by full irrigation treatment, and were correspondingly lower without irrigation. However, the maximum grain yield occurred in treatment 5, in which applied irrigation water was 300 mm, reduced by one-third compared with the full irrigation treatment, with the deficit of evapotranspiration between 7% and 13%. The simulated results indicated that WUE of winter wheat could be improved by limited irrigation. Table 3 also indicates that the maximum WUE usually occurred in treatment 4. It suggests that the limited irrigation scheme has practical value for winter wheat production in this semiarid area.

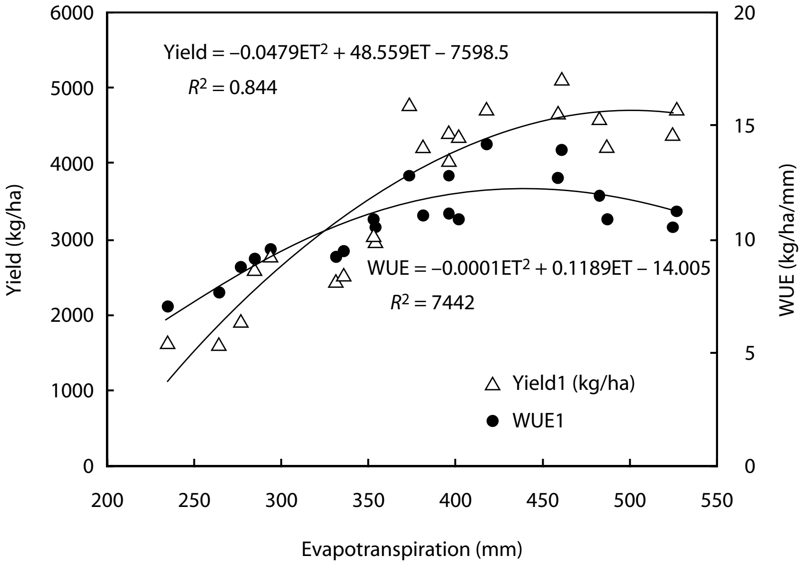

Figure 3. Effectiveness of WAVES in predicting the relationship between seasonal evapotranspiration (ET), water use efficiency (WUE) and grain yield for winter wheat in Changwu.

Table 3. Winter wheat evapotranspiration, biomass and grain yield simulated by the WAVES model, Changwu, 1995–98.

Years	Treatment no.	Rainfall[a] (mm)	Irrigation water (mm)	No. of irrigations	ET[a] (mm)	Biomass (kg/ha)	Yield 1 (kg/ha)[b]	Yield 2 (kg/ha)[c]	WUE1[d] (kg/ha/mm)	WUE2[e] (kg/ha/mm)
1995–96	1	239.6	0	0	234	8840	1660	2210	7.1	9.46
	2		100	1	284	10,400	2610	3120	9.2	9.09
	3		100	2	294	10,500	2810	3150	9.57	10.73
	4		200	3	395	11,175	4430	4470	11.21	11.32
	5		300	4	372	11,475	4790	4590	12.87	12.33
	6		400	4	380	11,438	4233	4003	11.13	10.52
	7		450	5	402	11,563	4375	4047	10.9	10.08
1996–97	1	137.0	0	0	263	10,000	1620	2500	7.7	9.50
	2		100	1	330	11,200	2450	3360	9.28	10.18
	3		100	2	335	11,167	2550	3350	9.52	10.00
	4		200	3	395	11,975	4070	4790	12.86	12.11
	5		300	4	458	12,400	4680	4960	12.76	10.83
	6		400	4	487	12,406	4255	4342	10.93	8.91
	7		450	5	523	11,938	4408	4178	10.53	7.98
1997–98	1	267.4	0	0	276	10,240	1940	2560	78.78	9.26
	2		100	1	354	11,767	3000	3530	10.6	9.98
	3		100	2	353	11,833	3070	3550	10.88	10.06
	4		200	3	417	12,373	4740	4949	14.2	11.86
	5		300	4	460	12,600	5140	5040	13.96	10.95
	6		400	4	482	12,500	4617	4375	11.98	9.08
	7		450	5	526	11,686	4736	4090	11.25	7.78

[a] ET and rainfall are evapotranspiration and rainfall in the growing season of winter wheat respectively

[b] Yield 1 is the simulated grain yield by Equation 1

[c] Yield 2 is the simulated grain yield by Equation 2

[d] WUE1 is the water use efficiency based on yield 1

[e] WUE2 is the water use efficiency based on yield 2

Conclusion

The WAVES model can be used to predict grain yield of winter wheat on the Loess Plateau. The simulated grain yield based on biomass and harvest index showed better agreement with the measurements than that based on transpiration and harvest index. The simulated WUE using grain yield from biomass and the harvest index agreed reasonably well with the measured values. However, when the grain yield obtained from crop transpiration and the harvest index was used to calculate WUE, the results estimated from the model showed poor correlation with the measurements. The model was very sensitive to different irrigation treatments. The harvest index is an important parameter for grain yield prediction. The model was developed with a constant harvest index for different irrigation treatments. However, the values of harvest index were similar but not constant for different irrigation treatments, and related water supply level.

WUE in this region can be improved by irrigation scheduling. Evapotranspiration was the highest when most irrigation water was applied, but WUE was relatively low. Appropriately controlled irrigation could improve the grain yield and WUE. Aiming only for maximum grain yield or for maximum WUE could lead to uneconomical irrigation management.

Acknowledgments

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7

Effects of Limited Irrigation on Yield and Water Use Efficiency of Winter Wheat on the Loess Plateau of China

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Abstract

Crop yields on the Loess Plateau of China are mainly limited by available water. A field experiment was conducted for winter wheat (*Triticum aestivum* L.) during 1995–98 to evaluate the effects of limited irrigation on crop yield and water use efficiency (WUE). The results showed that evapotranspiration, grain yield, biomass, WUE and harvest index depended on soil water content. The effect of irrigation on yield varied considerably due to differences in soil moisture content and irrigation scheduling between seasons. High moisture treatment gave the greatest evapotranspiration and biomass, but did not produce the highest grain yield and gave relatively low WUE. Appropriately controlled soil water content could improve grain yield, WUE and harvest index. Consistently high values of grain yield, WUE, and harvest index were obtained under conditions of mild water deficit at the seedling and start of regrowth to stem-elongation stages, with further soil drying at the physiological maturity to harvest stage. We therefore suggest that for winter wheat periods of mild soil drying in the early vegetative growth period together with severe soil drying in the maturity stage is an optimum limited-irrigation regime in this region.

黄土高原粮食产量很大程度上受水分供应的制约。在1995到1998年进行了冬小麦田间试验，以评价有限灌溉对作物产量和水分利用效率（WUE）的影响。结果显示土壤水分含量决定了水分蒸发量、粮食产量、生物量、WUE和收获指数。灌溉对产量的影响因不同季节不同的土壤水分含量和灌溉方式而有相当大的变化。水分多产生的蒸发多，生物量多，但是产量不是最

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多，WUE 相对较低。适当控制土壤水份含量能提高产量、WUE 和收获指数。在出苗、拔节初期轻度的水分亏缺，生理成熟至收获期再进一步的缺水可以获得高产量、高 WUE 和高收获指数。因此对于本地区的冬小麦而言，保持土壤在植物生长初期的轻度干燥和成熟期的严重干燥是一个合理的有限灌溉方式。

LIMITED irrigation means that the soil water deficit is controlled at certain stages of crop growth, a practice that has become more important in recent years in areas where water resources are limited. Water use efficiency (WUE) is defined here as the ratio between grain yield and total evapotranspiration during the growing season. For other definitions, see the review of WUE in Chapter 4. Studies on the effects of limited irrigation show that crop yield can be largely maintained and product quality can sometimes be improved while substantially reducing irrigation volume (Li 1982; Shan 1983; Fapohunda et al. 1984; Sharma et al. 1986; Singh et al. 1991; Zhang et al. 1999).

These studies also show that the relationship between crop yield and seasonal evapotranspiration can take different forms and that the empirical coefficients vary with climate, crop type and variety, irrigation, soil texture, fertiliser and tillage methods. The relationship between WUE and evapotranspiration or irrigation water use also shows large spatial and temporal variability. Aggarwal et al. (1986) reported that WUE decreased with increasing evapotranspiration, whereas Musick et al. (1994) found that WUE did not change with seasonal evapotranspiration. Under limited irrigation, reductions in grain yield due to restricted water availability depend on the degree, duration and timing of the imposed soil moisture deficit. The impact of soil moisture deficit on crop yield depends on the particular phenological stage of the crop, and the most sensitive stage can vary regionally (Singh et al. 1991). Because these differences relate to regional variability in environmental and agronomic practices, region-specific information is needed for developing and refining limited irrigation schemes.

The Loess Plateau is a vast arid and semiarid area with average annual rainfall ranging from 300 to 600 mm. Rainfall distribution is uneven, with more than 60% occurring from July to September. Total annual rainfall also varies significantly from year to year. Winter wheat (*Triticum aestivum* L.) and corn (*Zea mays*) are the main crops in the region. Available water is the most important factor limiting crop yields. During the last decade, irrigation water has been pumped from the Yellow River or from surface dams, and average crop yield has substantially increased. However, recently there has been a rapid decline in available water resources from the Yellow River; consequently, there is an urgent need for more efficient water use in order to sustain agriculture in the area (Kang and Li 1997). The Overview provides background information on the region; Figure 1 of the Overview shows the location of the Loess Plateau.

When the available water supply is severely limited, water deficits will be unavoidable during some periods of crop growth. Scheduling of irrigation times is then more complex because irrigation decisions must be based on the relationships between grain yield, crop growing phase and crop water use. Alternative irrigation schedules must be evaluated to determine which schedule maximises crop yield and WUE for a given level of water supply.

We lack adequate information on the relationships between grain yield and WUE under different irrigation regimes on the Loess Plateau; we also lack information about the degree of soil water deficit at different stages of growth, although many irrigation practices involve the control of soil water deficit.

The aim of this chapter was to study the effect of limited irrigation on crop yield and WUE for winter wheat in the field. The objectives were to:

- examine the impact of limited irrigation on crop yield;
- determine an optimum soil water deficit scheme under limited irrigation; and
- establish relationships between crop yield, WUE and the harvest index.

It was expected that the results of the study could be used to provide guidelines to farmers and irrigation managers on how to minimise water use while maintaining high wheat yields in the region.

Materials and Methods

Plant material and experimental design

The field experiments were conducted in Changwu, Shaanxi Province (see Figure 4 of the Overview) during 1995–98. The site is at an altitude of 1206 m, and has a semiarid, warm temperate climate with an average annual rainfall of 542 mm, falling mainly from July to September. Annual sunshine duration is 2226 hours, annual average temperature is 9°C and annual potential evaporation is 1552 mm. The groundwater table is about 50–80 m below the surface. The soil is a dark loess soil with a loam texture, which has been intensively cultivated over many centuries. Its major physical properties are given in Table 1. The top layer of the soil (30 cm) contains 1.55% total organic matter, 0.106% nitrogen (Bremner and Mulvaney 1982) and 0.095% available phosphate (Olsen and Sommer 1982). The experiments were carried out in lysimeters 3 m × 2 m in area and 3 m deep. Irrigation and fertiliser were applied to the top 30 cm before sowing. Each lysimeter had an aluminium tube 2 m in length installed for moisture measurements. During storms, a plastic rain shelter was installed above the lysimeters to control soil water status. Winter wheat (cultivar Changwu 89-134) was sown in late September. Seedling density was controlled to 200 plants/m^2. In total, 15 treatments of soil water deficit were included (Table 2) with three replicates. All plants were harvested in early July in the year following planting.

Measurements and statistical treatment

A neutron moisture meter (CPN503, United States) was used to measure water content every 10 cm to a depth of 2 m. Measurements were taken at weekly intervals. In controlling soil water deficit, average soil water content for the top 40 cm and 60 cm was monitored using time-domain reflectometry (Trase system, Soil Moisture Equipment Corporation, United States). When soil water content dropped to the lower limit of the designed range (see Table 2), the lysimeter was irrigated to its designated upper limit. The amount of irrigation water in each lysimeter was recorded and used to calculate total water consumption.

Table 1. Physical properties of the soils at Changwu.[a]

	Particle composition (mm)							
Size	>0.05	0.05–0.005	<0.005	Bulk density (g/cm^3)	Total pore space (%)	Field capacity (cm^3/cm^3)	Initial infiltration rate (mm/min)	Final infiltration rate (mm/min)
% in size class	3.5	65.6	30.9	1.21	50.6	0.255	5.9	1.6

[a] Data are the average value in the top 60 cm soil layer

A portable gas-exchange recording system (CID-301PS, CID Inc., Vancouver, WA, United States) was used to measure diurnal variations in the rate of photosynthesis and stomatal resistance on some clear days. The measurements were taken at hourly intervals from 7 a.m. to 7 p.m. At the end of each growing season, plants were harvested for estimation of dry matter in shoots and roots, and final grain yield.

Meteorological data — air temperature, air humidity, wind speed and rainfall — were recorded at a standard weather station located at the experimental site. Maximum and minimum temperature, maximum vapour pressure deficit and average wind speed were also recorded each day, as was daily potential evapotranspiration from an evaporation pan with a diameter of 601 mm.

All data were statistically analysed; Duncan's multiple range test was used to compare treatments.

Estimation of evapotranspiration, water use efficiency and harvest index

Crop evapotranspiration between two soil moisture content measurements or in the whole growing season was estimated from the equation:

$$ET = \Delta W + I + P + S_g - D - R_f \qquad (1)$$

where ET is crop evapotranspiration, ΔW is the change in soil water storage between two soil moisture content measurements, I is irrigation, P is rainfall, S_g is capillary rise from the water table to the crop root zone, D is downward drainage from the crop root zone and R_f is surface runoff from the lysimeter.

Because the water table was below 50 m, capillary contribution from the groundwater can be ignored (Zhang et al. 1995). During heavy storms, a mobile plastic rain shelter eliminated runoff from the

Table 2. Controlled minimum soil water content of different treatments in the winter wheat growing season.

		Soil water content maintained (% of field capacity)				
Treatment no.	Treatment type[a]	Seeding to before winter freezing	Regrowth to stem elongation	Booting to heading	Flowering to milk ripeness	Maturity to harvest
1	LLLLL	45	45	45	45	45
2	LLLHM	45	45	45	70	55
3	LHMLL	45	70	55	45	45
4	HLMHM	70	45	55	70	55
5	MMMMM	55	55	55	55	55
6	LMLLM	45	55	45	45	55
7	MLLMH	55	45	45	55	70
8	MHLLH	55	70	45	45	70
9	MHMLL	55	70	55	45	45
10	HHLML	70	70	45	55	45
11	LMHMH	45	55	70	55	70
12	HHHHH	70	70	70	70	70
13	HMHLM	70	55	70	45	55
14	HMHHL	70	55	70	70	45
15	MMHHL	55	55	70	70	45

[a] The growing season was divided into five periods and soil water content in the top 60 cm (40 cm before the jointing stage) was maintained during different growth stages. When soil water content approached the minimum value, water was supplied up to field capacity. H = high soil moisture content (no soil water deficit); M = medium soil moisture content (mild soil water deficit); L = low soil moisture content (severe soil water deficit).

lysimeters. The measured rainfall during such events was applied as irrigation and allowed to infiltrate. Since irrigation water was applied to the topsoil and moisture content was controlled below field capacity (Table 2), deep drainage was assumed to be negligible.

Crop water use efficiency was calculated as grain yield divided by seasonal evapotranspiration. Harvest index was estimated as grain yield divided by total biomass.

Results and Discussion

Evapotranspiration, grain yield and biomass

Table 3 lists the average values of evapotranspiration, grain yield and biomass for different treatments in 1995–98. The growing season reference evapotranspiration calculated by a modified Penman equation was 534.2, 429.9, and 479.3 mm for the respective growing seasons. Actual evapotranspiration was considerably lower than for winter wheat in the Southern High Plains of the United States (Howell et al. 1995; Schneider and Howell 1997) or the North China Plain (NCP) (Zhang et al. 1999). The differences may be due to different climatic conditions.

The plants in treatment 1 were grown in rainfed conditions, with no irrigation in the growing season. Seasonal evapotranspiration varied from 213 to 267 mm. In 1996 and 1998, evapotranspiration was balanced by the growing-season rainfall. However, because of drought in 1997, 80 mm of stored soil water was used in addition to the seasonal rainfall. Grain yields varied between 1612 and 2493 kg/ha under rainfed conditions. In the irrigated treatments, seasonal evapotranspiration ranged from 227 to 519 mm and grain yield from 1771 to 4920 kg/ha, depending on the amount of water applied and the time of irrigation. Evapotranspiration and yield depend on the level of soil water deficit at different growth stages. In treatment 12 (high soil moisture), seasonal evapotranspiration was 358–519 mm during the three years of the study. These high values may have been due partly to relatively high soil evaporation resulting from more frequent wetting of the soil surface, especially early in the season, when crop cover was low.

The high soil moisture treatment did not produce the highest grain yield. In fact, the highest grain yield was attained in treatment 15, which was subject to mild water deficits at the seedling, regrowth and stem-elongation stages, followed by soil drying during the period from physiological maturity to harvest. Seasonal evapotranspiration in this treatment was 7.4–24.9% less than that in the high soil moisture treatment. Hence, this treatment combines the benefits of reduced irrigation water (7.4–24.9%) and higher grain yield (0.4–18.0%). The results are only a first indication for a single area, but they support the idea that water resources can be conserved through a process of mild soil drying in the early vegetative growing periods followed by severe soil drying in the maturity stage. This can assist in developing sustainable agriculture and may help in preventing further depletion of water resources. Thus, limited irrigation may be of real value in making winter wheat production part of a program of sustainable agriculture.

Table 4 shows that the regulated soil water deficit reduced leaf and stem development and stimulated root development. An advantage of smaller shoots is that crops consume less water. Canopy transpiration is largely a function of net energy absorbed by the leaves when available water is not limiting (e.g. Monteith 1981), and smaller leaf area will reduce light interception. In addition, soil water deficit may reduce water loss through physiological regulation, such as by reduced stomatal conductance (e.g. Davies and Zhang 1991). The data indicate that total water consumption was reduced by both smaller leaf area and lowered rate of leaf transpiration.

Table 3. Total evapotranspiration (ET), grain yield, harvest index and water use efficiency (WUE) of winter wheat plants, 1995–98.

Year	Treatment	Rainfall (mm)	Irrigation (mm)	ET (mm)	Biomass (kg/ha)	Grain yield (kg/ha)	Harvest index	WUE (kg/m^3)
1995–96	1	239.6	0	213	6000	1750	0.292	0.822
	2		97	300	9250	3180	0.344	1.060
	3		107	278	10251	3375	0.329	1.214
	4		269	385	11401	3905	0.343	1.014
	5		167	359	10451	3570	0.342	0.994
	6		183	291	10526	3505	0.333	1.204
	7		241	338	11426	3870	0.339	1.145
	8		281	387	13726	4020	0.293	1.039
	9		216	323	11901	4080	0.343	1.263
	10		268	389	12401	4230	0.341	1.087
	11		302	403	14551	4245	0.291	1.053
	12		408	519	16726	4200	0.251	0.809
	13		302	420	14051	4600	0.327	1.095
	14		383	383	12976	4775	0.368	1.247
	15		390	390	14351	4920	0.343	1.262
1996–97	1	137.0	0	220	6598	1612	0.244	0.734
	2		60	277	8294	3060	0.369	1.105
	3		112	231	7794	2039	0.262	0.883
	4		246	232	5598	1771	0.316	0.765
	5		158	310	9181	4079	0.444	1.315
	6		197	235	7984	2040	0.256	0.869
	7		280	296	8225	3060	0.372	1.036
	8		302	285	8026	2788	0.347	0.978
	9		235	254	9223	3076	0.334	1.212
	10		293	285	10746	3852	0.358	1.353
	11		284	227	6982	2045	0.293	0.902
	12		391	358	13001	4060	0.312	1.133
	13		306	330	12016	4749	0.395	1.439
	14		378	340	12717	4811	0.378	1.417
	15		361	329	10732	4792	0.447	1.458
1997–98	1	267.4	0	267	8726	2493	0.286	0.933
	2		88	308	8727	3520	0.403	1.143
	3		120	304	8409	3089	0.367	1.018
	4		217	310	9293	3533	0.380	1.138
	5		174	301	8126	3060	0.377	1.016
	6		198	339	9974	3506	0.352	1.035
	7		271	356	10314	3441	0.334	0.966
	8		296	370	10653	3659	0.343	0.990
	9		204	362	9860	3672	0.372	1.014
	10		253	305	9180	3680	0.401	1.205
	11		267	292	9066	3294	0.363	1.130
	12		350	399	13860	4533	0.327	1.135
	13		297	354	11334	4325	0.382	1.223
	14		324	367	11106	4485	0.404	1.224
	15		319	370	10314	4553	0.441	1.232

Under the rainfed conditions of treatment 1, minimum total above-ground biomass was 6000–8726 kg/ha (see Table 3); the maximum biomass was recorded in the high soil water conditions of treatment 12 (13,000–16,726 kg/ha). The linear curve fit through the data in Figure 1 indicates that early-season soil evaporation was about 28 mm. With limited irrigation and a controlled soil water deficit, the biomass was lower than with a high soil water content. However, the reduction in biomass was small in treatment 15 and even less in treatments 13 and 14 in 1997 and 1998. This was due to a compensatory effect of photosynthesis after rewatering under controlled soil water deficit (Table 5). Soil water deficit at the seedling stage substantially reduced leaf photosynthesis, but it recovered a few days after rewatering, suggesting that stomatal inhibition was the main reason (Cornic 1994). Further soil water deficit between the start of regrowth and stem elongation had less effect on the photosynthesis rate in treatment 15, especially for plants subjected to soil water deficit at the seedling stage. This could be related to a larger and deeper root system (Table 4) following soil drying at the seedling stage. A deep root system is beneficial under water-limited conditions as it allows water to be extracted from depth. Studies on dryland crops have shown that utilisation of water deep in the profile may be limited by root density (e.g. Jupp and Newman 1987; Zhang and Davies 1989; Kang et al. 1992; McIntyre et al. 1995).

Regression analysis shows that the relationship between grain yield and seasonal evapotranspiration is a quadratic function (Fig. 1). Grain yield did not increase when seasonal evapotranspiration exceeded a critical value: in this study about 434 mm, or approximately 84% of the measured maximum evapotranspiration. However, biomass increased linearly with evapotranspiration. Both biomass and grain yield showed good correlation with evapotranspiration (Fig. 1), but not with the amount of irrigation water applied (Table 3). These results suggest that the effect of irrigation on grain yield varied considerably due to differences in the soil moisture content and irrigation scheduling between seasons. A high soil moisture content throughout the season required a high water consumption but did not lead to higher grain yields. In some cases, high soil moisture content even resulted in lower grain yields (Table 3). Similar relationships have been reported for wheat, corn and cotton in Northwest China (Kang and Dang 1987), wheat in India (Rajput and Singh 1986;

Table 4. Distribution of root, stem, and leaf dry mass (%) at different development stages of winter wheat grown in the field under different treatments,[a] 1995–96.

Sampling date	Root			Stem			Leaf		
	LLLLL	MMMMM	HHHHH	LLLLL	MMMMM	HHHHH	LLLLL	MMMMM	HHHHH
4 Nov	22.6	22.6	22.6	38.0	38.0	38.0	39.4	39.4	39.4
6 Dec	19.6	12.3	10.1	35.8	40.0	34.8	44.6	47.7	55.1
6 Jan	19.9	14.2	12.0	45.6	42.6	32.0	34.5	43.3	56.0
6 Feb	16.3	15.2	13.8	40.8	39.7	34.1	42.9	45.1	52.1
13 Apr	14.6	14.9	14.1	53.2	49.2	49.1	32.1	35.9	36.8
21 May	12.4	11.0	8.7	69.2	67.6	73.5	18.4	21.4	17.8
29 May	13.4	12.0	7.2	60.6	61.8	58.9	10.4	11.9	12.0

[a] Table 2 shows details of treatments

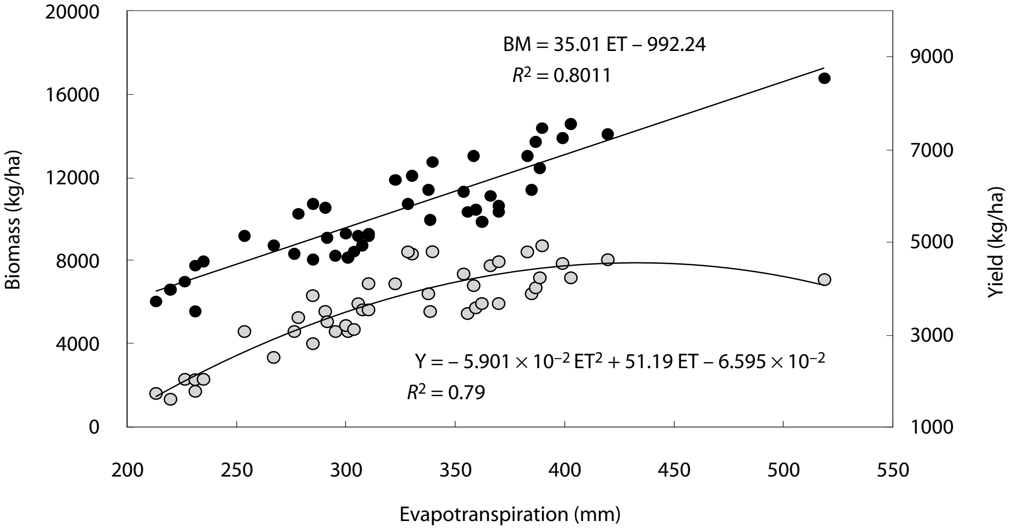

Figure 1. Relationships between growing season evapotranspiration (ET) and biomass (BM) and grain yield (Y) for winter wheat at Changwu.

Table 5. Photosynthesis rate (P_n) and relative photosynthesis (RP_n)[a] of winter wheat plants under different treatments.[b]

		Date (day/month)								
Variable	Treatment[c]	17/4	29/4	6/5	10/5	11/5	18/5	23/5	29/5	9/6
P_n (μmol/m^2/s)	LLLLL	3.90	4.52	6.31	3.33	3.01	7.64	5.19	3.95	4.45
	MMMMM	6.10	6.67	8.27	5.12	5.49	8.04	6.26	4.25	4.95
	HHHHH	6.20	6.97	8.74	4.85	4.74	7.94	5.71	5.32	4.81
	HMHHL	6.01	6.37	7.12	4.85	5.03	8.53	6.40	5.93	4.71
	MMHHL	6.10	6.26	7.44	4.80	4.94	8.41	6.47	5.82	4.60
RP_n (%)	LLLLL	62.9	64.9	72.7	68.7	63.5	96.2	90.9	74.3	92.5
	MMMMM	98.4	95.7	94.6	105.6	115.8	101.3	109.6	79.9	102.9
	HHHHH	100	100	100	100	100	100	100	100	100
	HMHHL	96.9	91.4	81.5	100	106.1	107.4	112.1	111.5	97.9
	MMHHL	98.4	89.8	85.1	99.0	104.2	105.9	113.3	109.4	95.6

[a] Relative photosynthesis is the ratio of photosynthesis rates in each treatment to the rate of the control treatment (HHHH)

[b] Data are the daily average value of measurements in 1996. Values are means of replicates for each treatment.

[c] See Table 2 for details of treatments

Kumar and Khepar 1980), cowpea and corn in Nigeria (Fapohunda et al. 1984), and sorghum in Northeast Brazil (Sharma and Alonso Neto 1986).

It can be deduced from Figure 1 that grain yield required a minimum evapotranspiration of 152 mm for winter wheat. This value is lower than the 206 mm for dryland and irrigated wheat reported by Musick et al. (1994), and higher than the 84 mm for winter wheat on the NCP (Zhang et al. 1999), but very close to the 156 mm for wheat in the Mediterranean region (Zhang and Oweis 1999).

The relationship between grain yield and biomass is fitted with a quadratic function in Figure 2. Grain yield increased with biomass until it reached a value of 15,000 kg/ha, and then remained more or less constant, in line with the data in Figure 1.

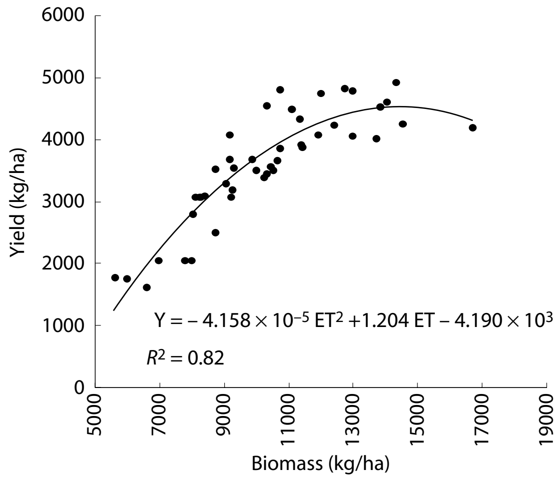

Figure 2. Relationship between biomass (BM) and grain yield (Y) for winter wheat at Changwu.

These relationships also indicate that the highest biomass was associated with maximum evapotranspiration, but not with the highest grain yield, which was reached by appropriately controlling soil water content and limiting evapotranspiration and biomass.

Water use efficiency and harvest index

WUE ranged from 0.73 to 0.93 kg/m^3 under rainfed conditions (Table 3) and from 0.77 to 1.46 under the irrigated treatments. The level of WUE depends on the controlled ranges of soil water deficit at different stages. WUE in the high soil moisture treatment (12) ranged from 0.81 to 1.14 kg/m^3 but the highest WUE values were recorded in treatment 15 (1.23–1.46 kg/m^3 over the three years of the study), as expected from the information on yield and seasonal evapotranspiration. The lower values for treatment 12 arose because seasonal evapotranspiration was the highest recorded in any treatment, but yield was not.

WUE values in our study were higher than those for winter wheat (0.40–0.88 kg/m^3: Howell et al. 1995; Schneider and Howell 1997) and for irrigated wheat (0.82 kg/m^3) in the US Southern Plains (Musick et al. 1994), but close to those (1.08–1.19 kg/m^3) for winter wheat in the Mediterranean region (Zhang and Oweis 1999) and for winter wheat (0.84–1.39 kg/m^3) on the NCP (Zhang et al. 1999).

The harvest index was 0.24–0.29 under rainfed conditions and 0.25–0.45 under irrigated conditions, meaning that appropriate irrigation and controlled soil water content can increase harvest index. Maximum harvest index was recorded in treatment 15. However, under treatment 12 (a high soil water treatment), the harvest index was only 0.25–0.33, much lower than under other irrigation treatments. This treatment resulted in high above-ground biomass (Table 4), causing lodging in the late growing stage, with adverse effects on grain filling. Sheng and Wang (1985) found that high soil moisture content during the grain-filling stage may result in lower 1000-seed weight and grain yield. Other investigators (e.g. Zhang et al. 1998) have reported similar results; it has been well established that remobilisation of carbohydrate reserves from the stem and the leaf sheath is a key factor for grain filling. In wheat, low soil moisture content during grain filling may lead to better use of the carbon reserves in stems and sheaths (Palta et al. 1994; Ricciardi and Stelluti 1995).

Regression analysis indicated a quadratic relationship between WUE and seasonal evapotranspiration (Fig. 3). WUE reached its maximum value at a seasonal evapotranspiration of 354 mm, then started to decrease with evapotranspiration. However, maximum WUE did not correspond to maximum grain yield (Figs 1 and 3). When evapotranspiration is relatively low, water availability is the limiting factor for grain yield and an increase in evapotranspiration results in significant increases in both grain yield and WUE. However, the rate of change starts to decrease as evapotranspiration further increases. Once WUE reaches its maximum value, an increase in total crop water use could still lead to a marginal increase in grain yield, but WUE would decrease. For example, at the maximum WUE the grain yield was 4134 kg/ha; a further increase of 20% in total crop water use would increase grain yield by only 8%. In economic terms, grain yield response to total crop water use is a diminishing-return function. Therefore, aiming for maximum grain yield under limited water resources is not economical and should not be encouraged. These results also indicate that it is possible to maintain relatively high grain yield and WUE by limiting the duration and severity of plant water stress under limited irrigation.

The relation between harvest index and seasonal evapotranspiration is also nonlinear (Fig. 3). Maximum harvest index, like maximum WUE and grain yield, did not coincide with maximum seasonal evapotranspiration but was recorded when the seasonal evapotranspiration was about 346 mm. Therefore, the maximum value of the harvest index is attained under an appropriate evapotranspiration deficit.

The nonlinear curves fitted through the data in Figure 3 also indicate that WUE increases linearly with harvest index, in agreement with results from other studies (Austin et al. 1980; Perry and D'Antuono 1989; Siddique et al. 1989). Passioura (1977) and Fischer (1979) have suggested that in water-limited conditions a relatively high harvest index is needed to obtain high WUE. In our study, the highest harvest index occurred when evapotranspiration was about 70% of its maximum; the index then started to decrease with increasing evapotranspiration (Fig. 3). Improving the harvest index led to improvement in WUE under limited irrigation conditions.

Conclusions

Evapotranspiration, grain yield, biomass, WUE and the harvest index of winter wheat were all affected by controlled ranges of soil water content during growing seasons. Grain yield response to irrigation varied considerably due to differences in soil moisture content and irrigation scheduling between seasons. Evapotranspiration was highest under continuous high soil moisture conditions, as was above-ground biomass. However, grain yield was not the highest in these conditions, and WUE was relatively low due to inefficient use of the stored soil water. Maximum values of WUE and the harvest index occurred under appropriately controlled soil water conditions. WUE appears to increase linearly with harvest index; improvement in WUE under limited irrigation conditions is thus the consequence of an increased harvest index.

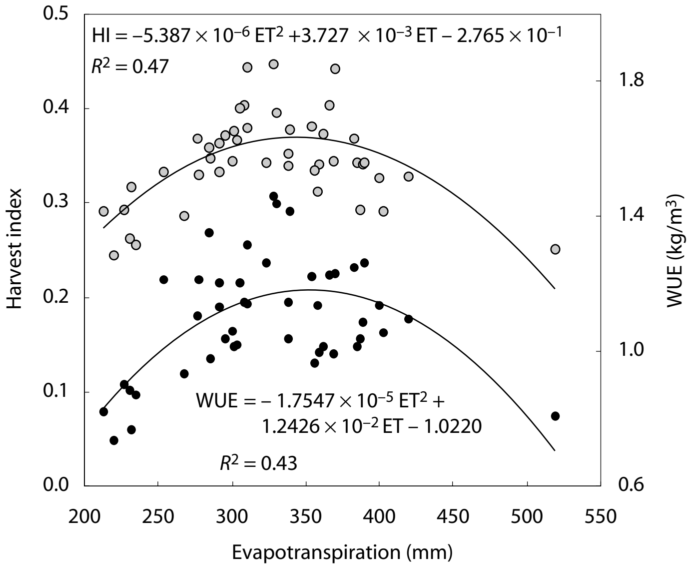

Figure 3. Relationships between seasonal evapotranspiration (ET) and water use efficiency (WUE) and harvest index (HI) for winter wheat at Changwu.

Appropriately limited irrigation and controlled soil water content level could lead to higher grain yield, WUE and harvest index. Compared to high water treatment, this practice has the advantage of lower above-ground biomass before flowering, greater net photosynthesis rates during grain filling, and larger grain yield. Hence, mild soil drying in the early vegetative growth period and severe soil drying in the maturity stage of winter wheat is an optimum limited irrigation regime in the Loess Plateau of China.

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