



Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems

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Abstract

Yields of dryland (rainfed) wheat in Australia have increased steadily over the past century despite rainfall being unchanged, indicating that the rainfall-use efficiency has increased. Analyses suggest that at least half of the increase in rainfall-use efficiency can be attributed to improved agronomic management. Various methods of analysing the factors influencing dryland yields and rainfall-use efficiency, such as simple rules and more complex models, are presented and the agronomic factors influencing water use, water-use efficiency, and harvest index of crops are discussed. The adoption of agronomic procedures such as minimum tillage, appropriate fertilizer use, improved weed/disease/insect control, timely planting, and a range of rotation options, in conjunction with new cultivars, has the potential to increase the yields and rainfall-use efficiency of dryland crops. **It is concluded that most of the agronomic options for improving rainfall-use efficiency in rainfed agricultural systems decrease water losses by soil evaporation, runoff, throughflow, deep drainage, and competing weeds, thereby making more water available for increased water use by the crop.**

Key words: Crop management, fertilizer use, harvest index, modelling, rotations, tillage, transpiration efficiency, water use, water-use efficiency.

Introduction

While the Green Revolution resulted in the development of new cultivars of wheat and rice suited to high inputs of fertilizer and water, many regions of the world still rely on dryland (rainfed) farming for food production. The advent of

increasing water scarcity in this century (Seckler *et al.*, 1999; Turner, 2001), particularly for agriculture, and the already scarce availability of new land for agriculture will see less irrigated land available for crop production than in the past. While supplemental irrigation can benefit yields and water-use efficiency in water-limited environments (Oweis *et al.*, 2000; Turner, 2004), the potential for even limited supplemental irrigation is decreasing, with competition for water for urban and industrial uses and in order to maintain environmental flows. Thus, agriculture will become increasingly dependent on rainfall as its sole source of water, and maximizing the efficiency of its use to produce a crop will be paramount. What, then, are the possibilities of increasing crop production in dryland farming systems without further inputs of water; that is, what are the possibilities of increasing the rainfall-use efficiency of dryland crops?

An analysis of the yield trends of wheat production in Australia showed that yields have increased by an average of 12–13 kg ha⁻¹ year⁻¹ over the past six decades (Turner, 2001), despite rainfall not changing and irrigated wheat contributing only a very small proportion to total production. A more recent analysis of wheat-yield trends in Australia and the various states of Australia has shown (Fig. 1) that since the early 1980s there has been a more rapid increase in yield of over 30 kg ha⁻¹ year⁻¹ (Stephens, 2002). In Western Australia, where wheat is not irrigated and rainfall has probably declined over the last 25 years (Indian Ocean Climate Initiative, 2002), the increases shown in Fig. 1 arise solely from increases in rainfall-use efficiency. In Syria the increases since the early 1980s of 60 kg ha⁻¹ year⁻¹ have been even more dramatic (Turner, 2004), but such increases are not inevitable as increases in wheat yields in Morocco over the same period have been very modest (Turner, 2004).

A comparison of the genetic improvement in yields arising from the release of new cultivars in Western

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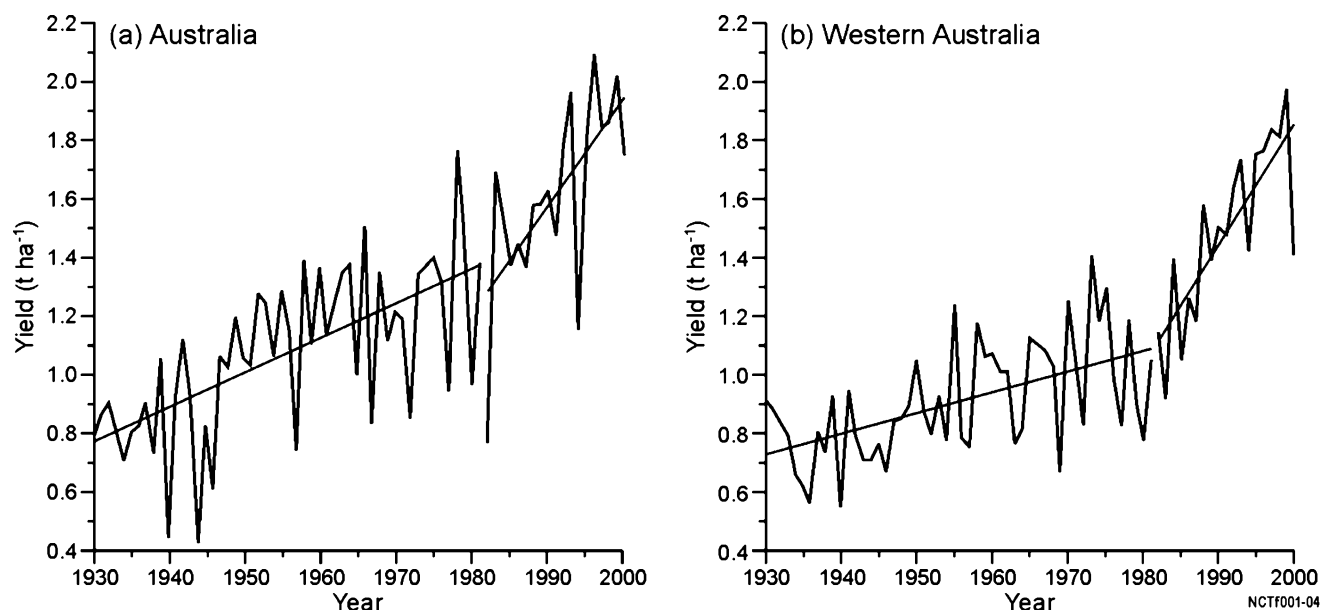


Fig. 1. Changes with time in the yield of wheat over the past seven decades in Australia and Western Australia (adapted from Stephens, 2002, with permission from the Department of Agriculture of Western Australia).

Australia (Perry and D'Antuono, 1989) and England (Austin *et al.*, 1980, 1989) suggested that about half of the increase over the past 12 decades, up to the early 1980s, was from the introduction of new cultivars and half from improved management (Turner, 1997). Stephens (2002) suggested that two-thirds of the rapid increase in wheat yields in Australia since the early 1980s has been due to improvements in management and one-third to improved genotypes. Indeed, Turner (2004) has suggested that, as in the case of the Green Revolution, it has been the combination of improved agronomy coupled with suitable genotypes that has led to the increased yield trend and increased rainfall-use efficiency in Australia's wheat production since the early 1980s. While Mifflin (2000) and Araus *et al.* (2003) argue that genetic improvements are likely to bring the greatest increases in yield, and hence rainfall-use efficiency, in water-limited environments in the twenty-first century, the role of management in increasing yield in the past and in the future should not be overlooked. Thus, this review will focus on the agronomic factors that have the potential to increase yields and rainfall-use efficiency in dryland farming systems that rely entirely on rainfall as their source of water. The role of genotypic improvements in yield can be found elsewhere (Turner, 1997, 2003; Richards *et al.*, 2002; Araus *et al.*, 2003).

Dryland farming environments

Before considering agronomic options for the improvement of yield and rainfall-use efficiency in dryland farming systems, it is necessary to know the environmental conditions under which the dryland crops are grown and the likely incidence(s) of water shortage. In Mediterranean

dryland farming systems, annual crops are generally sown in the autumn when rainfall commences, grow during the cool wet winters, and set seed in spring and early summer as temperatures and vapour-pressure deficits rise and rainfall decreases (Fig. 2). High temperatures and lack of rainfall preclude any significant summer cropping without irrigation in Mediterranean-type climates. Although the winters are wet and rainfall usually exceeds evaporation (Fig. 2), cool temperatures and low incoming radiation because of cloud cover often limit growth in these months. In more continental, Mediterranean-type environments, frost is also common. One of the features of Mediterranean-type climates is that rainfall is more reliable than in other semi-arid environments (Turner, 2004). For example, the standard deviation for annual rainfall in the Mediterranean-climatic region of south-western Australia is 23–25% compared with standard deviations of 30–33% in the area of northern New South Wales that has a similar annual rainfall, but predominantly summer rainfall (Asseng *et al.*, 2003). Nevertheless, even in Mediterranean cropping regions the growing-season rainfall can vary markedly from year to year. For example, at a site with an average annual rainfall of 460 mm, year-to-year rainfall varied from 200 to 800 mm (Asseng *et al.*, 2001a). This leads to the large variation from year to year in the wheat yields observed in Fig. 1.

In subtropical environments, dryland crops can be grown in the warm summer (rainy) season, and also in the cooler dry (post-rainy) season if the water-holding capacity of the soil is sufficient to enable the crop to mature. The high temperatures in the rainy season ensure rapid crop development, but erratic rainfall can lead to water shortage, particularly on shallow or coarse-textured soils. These periods of water shortage can occur at any time during

crop growth. Using long-term weather data (temperature and rainfall), soil water-holding characteristics, and a crop-water stress index (or relative transpiration) it is possible to estimate crop-water use and by cluster analysis to classify similar types of water-deficit scenarios that are likely to occur at a particular location. For example, Wright (1997) did this for one location in Queensland, Australia, and from 85 years of weather data concluded that five different water-shortage scenarios were possible for peanut (groundnut) production in this environment: two with terminal water shortage and three with water shortages at different times during crop growth (Fig. 3).

In temperate regions, dryland farming is less likely to be constrained by water shortage than by other factors such as low radiation, cold temperatures, or frost. In parts of North

America, Eastern Europe, and northern Asia, crop production is restricted to the warmer summer months and the season is constrained by cold soil temperatures in spring and frost in autumn. Where the winters are less severe, crops can be sown during the autumn and are well established when the soil and air temperatures rise in spring, ensuring rapid and earlier growth in the spring compared to a spring-sown crop.

A framework for yield improvement in water-limited environments

Passioura (1977) suggested a framework for the consideration of factors affecting yield in water-limited environments:

$$\text{Yield} = \text{Water use} \times \text{Water-use efficiency} \times \text{Harvest index}$$

where water-use efficiency is the biomass produced per unit evapotranspiration (transpiration plus soil evaporation) and harvest index is the ratio of harvested yield to total above-ground biomass. This relationship applies to both agronomic and genetic factors affecting yield. As rainfall falling at a particular site can be transpired by the crop, transpired by weeds, lost by soil evaporation, deep drainage, runoff, or throughflow (subsurface flow), or stored in the soil for subsequent use by a crop, the yield and rainfall-use efficiency in dryland cropping systems can be improved by decreasing losses of water from the soil and weeds, and maximizing the water use (transpiration) by the crop itself. Taking into account the water losses by the system other than crop transpiration, the above equation then becomes:

$$\text{Yield} = (\text{Rainfall} - \text{Losses from soil and non-crop species}) \times \text{Transpiration efficiency} \times \text{Harvest index}$$

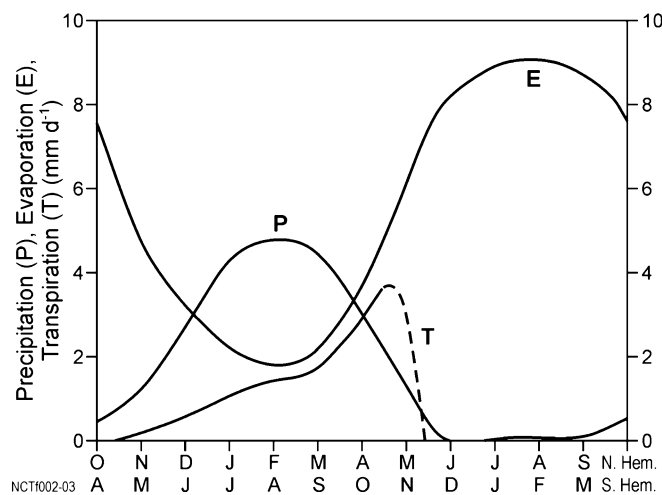


Fig. 2. The mean daily precipitation (P), pan evaporation (E), and annual plant transpiration (T) in a Mediterranean-type climate (adapted from Fischer and Turner, 1978, with permission).

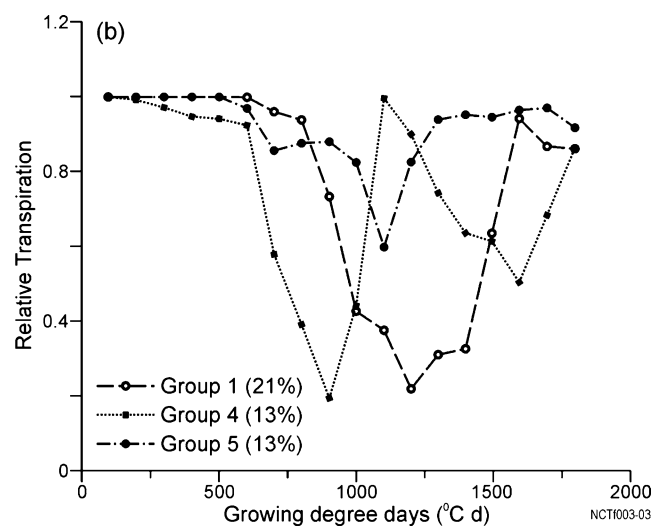
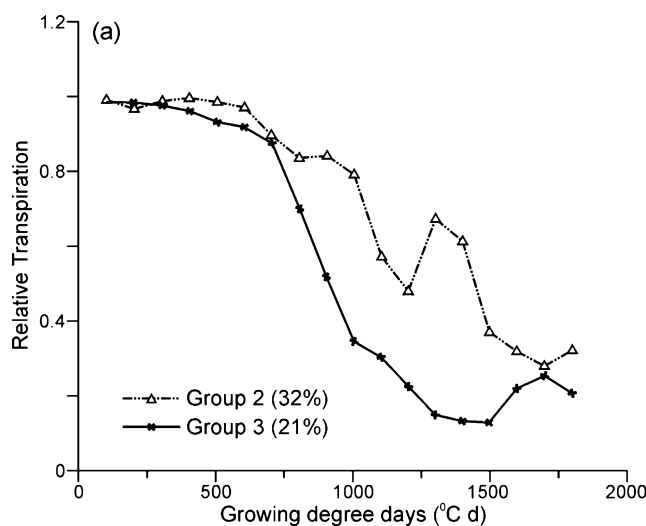


Fig. 3. Changes in calculated relative crop transpiration with growing degree days based on long-term (85 years) climatic data from Kingaroy, Australia, for (a) two groups of years showing terminal drought, and (b) three groups of years showing intermittent drought. The percentages in parentheses are the proportion of years in the particular group (from Wright, 1997, with permission from DPI & F Publications).

where transpiration efficiency is the biomass produced per unit of water transpired. Many of the agronomic options for improving the rainfall-use efficiency and yields in dryland cropping systems involve minimizing losses from the soil and weeds and maximizing the proportion of rainfall that is transpired by the crop. Nevertheless, agronomic options for improving the transpiration efficiency and proportion of the crop that is harvested exist and will be discussed briefly.

An alternative framework that has been widely adopted by advisers and producers in southern Australia is that proposed by French and Schultz (1984a, b). From a series of yield and water-use measurements made at a total of 61 sites over a period of 11 years, French and Schultz (1984a) suggested that, in the Mediterranean-type environment of South Australia, the potential grain yield of wheat increased by $20 \text{ kg ha}^{-1} \text{ mm}^{-1}$ of water use (transpiration) above a minimum value of 110 mm, which was assumed to be the amount of water lost by soil evaporation (Fig. 4a). A potential transpiration efficiency of $20 \text{ kg ha}^{-1} \text{ mm}^{-1}$ has been observed to apply in a number of field and glasshouse studies in Australia (Passioura, 1976; Gregory *et al.*, 1992; Zhang *et al.*, 2004). Since water use is strongly correlated with growing-season (April–October in the southern hemisphere) rainfall in this water-limited, winter-rainfall environment, French and Schultz (1984b) used growing-season rainfall to compare the performance of wheat crops in farmers' fields to the potential yield set by rainfall and showed that rarely did actual yields reach potential yields (Fig. 4b). The yield potential of $20 \text{ kg ha}^{-1} \text{ mm}^{-1}$ of growing-season rainfall (i.e. the rainfall-use

efficiency) has provided a useful yardstick for farmers to compare the on-farm performance of their wheat crops. Similar potential-yield yardsticks have been developed for annual pastures (Bolger and Turner, 1999), canola (Hocking *et al.*, 1997), and four cool-season grain legumes (Siddique *et al.*, 2001).

However, the methodology of French and Schultz (1984b) should be used with caution as it assumes that all the growing-season rainfall, except for losses by soil evaporation, which vary with soil type (French and Schultz, 1984a), is used by the crop. This is not always the case as losses by deep drainage, runoff, and throughflow can occur at wetter locations and in wetter years (Bolger and Turner, 1999; Eastham and Gregory, 2000), particularly in coarse-textured soils (Asseng *et al.*, 1998a). Moreover, the methodology assumes that pre-sowing rainfall, that is, rainfall before April in the southern hemisphere, does not contribute to yield. Thus the yardstick provided by French and Schultz (1984b) is primarily for environments where the crops rely on current rainfall and where the growing-season rainfall is less than 500 mm.

An alternative methodology for estimating potential yields and rainfall-use efficiency in water-limited environments is simulation modelling. Asseng *et al.* (1998b) have developed a simulation model, APSIM-wheat, which has been widely validated (Asseng *et al.*, 1998b, 2001b), and predicts potential yields and water use for wheat in a range of environments and soil types, taking into account the weather (rainfall, radiation, and temperature), water and nitrogen movements in the soil, and restrictions arising

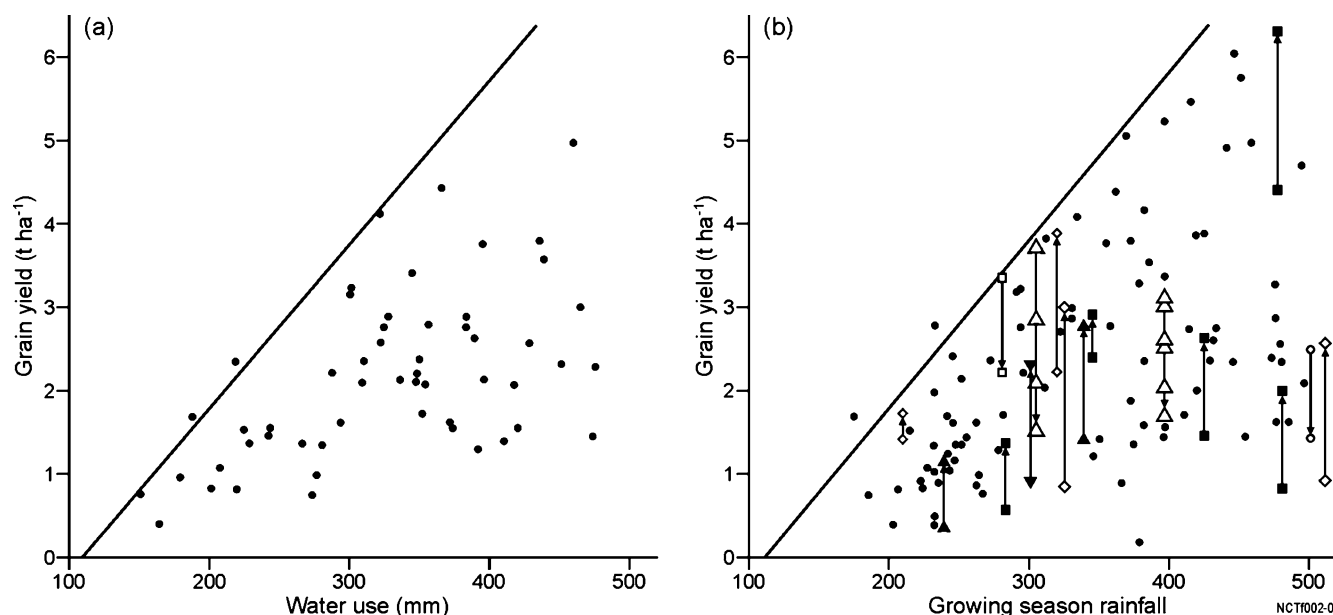


Fig. 4. The relationship between the yield of wheat and (a) water use, and (b) growing-season (April–October in the southern hemisphere) rainfall for experimental sites and farmers' fields in South Australia. The sloping line gives the potential yield from water transpired, after allowing for a loss of 110 mm for soil evaporation, and the vertical lines give the responses to nitrogen (solid squares), phosphorus (inverted solid triangles), control of root nematodes (closed triangles), multiple factors (open diamonds), time of sowing (open triangles), weeds (open squares), and waterlogging (open circles) (adapted from French and Schultz, 1984a, b, with permission from CSIRO Publishing).

from waterlogging in the rooting zone. A comparison of the yields predicted by the APSIM-wheat model and by French and Schultz (1984b) showed that the latter's yield potential was useful for the environment in which it was developed, but that factors such as soil type and rainfall distribution during the growing season play major roles in determining the yield potential and rainfall-use efficiency of wheat in any one year (Fig. 5). In particular, deep drainage and soil evaporation varied markedly depending on rainfall distribution

and soil type (Asseng *et al.*, 2001b). For example, using 80 years of weather data, Asseng *et al.* (2001b) showed that water in the soil at sowing and rainfall distribution through the growing season had major influences on predicted potential yield and rainfall-use efficiency in semi-arid Mediterranean-type environments.

French and Schultz (1984a) showed that water use before anthesis determined the number of grains set in wheat and hence had a major influence on final grain yield

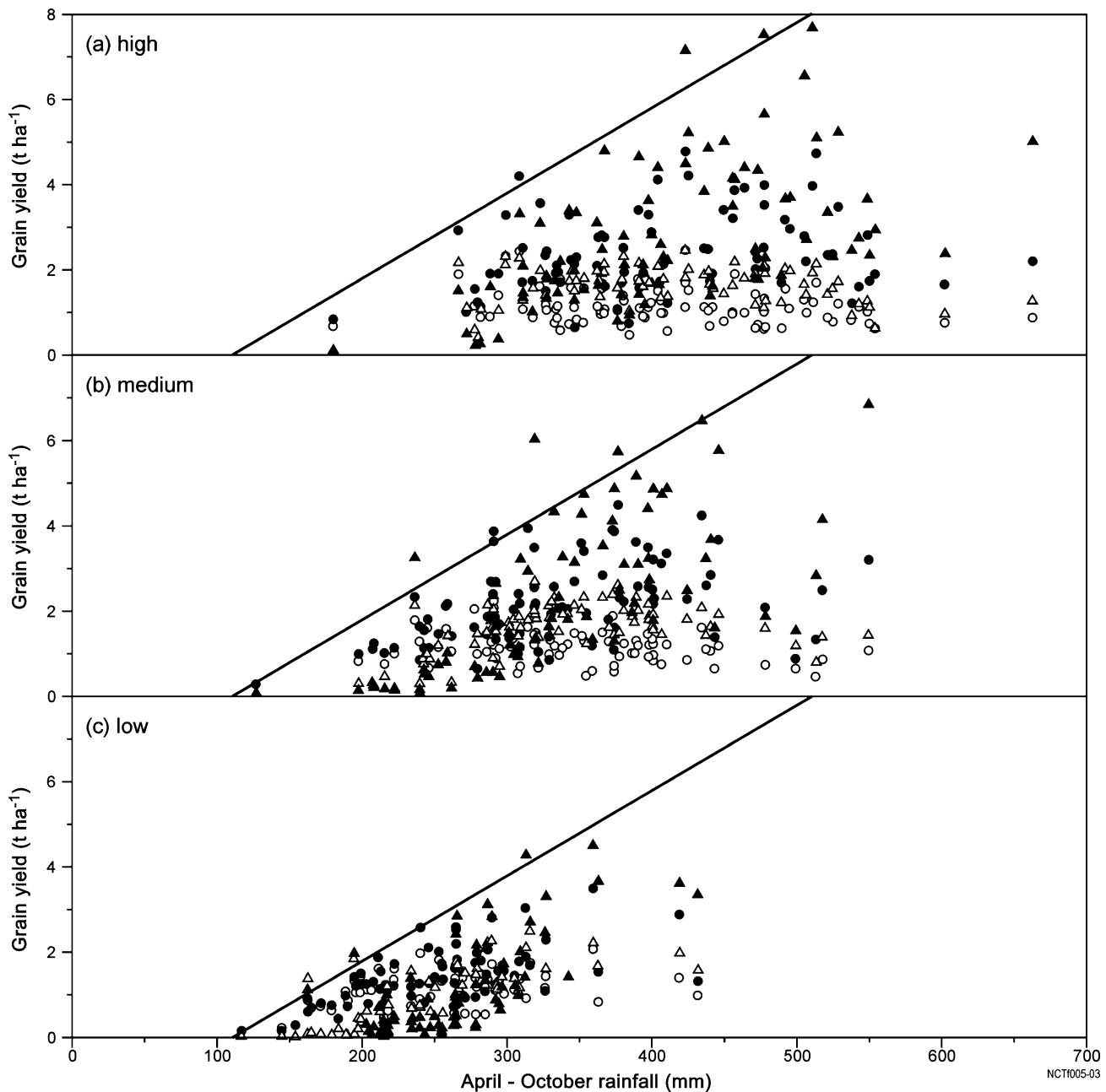


Fig. 5. Relationship between simulated wheat yields and growing-season (April to October in the southern hemisphere) rainfall for a sandy (open circles, closed circles) and a clay (open triangles, closed triangles) soil in the (a) high (mean annual rainfall = 460 mm), (b) medium (390 mm), and (c) low (310 mm) rainfall zones with zero (open circles, open triangles) and 150 (closed circles, closed triangles) kg N ha⁻¹. The sloping line gives the potential yield line from Fig. 4 (from Asseng *et al.*, 2001b, with kind permission of Springer Science and Business Media).

in Mediterranean-type environments. This contrasts with studies where high water use prior to anthesis in wheat resulted in 'haying off' of spikelets and poor yields (van Herwaarden *et al.*, 1998) and conclusions that water use after anthesis was an important determinant of yield. Turner (1997), using data for barley from Syria (Shepherd *et al.*, 1987), showed that, while there was an increase in yield at sites and in seasons with greater water availability after anthesis, factors that affected early growth and water use before anthesis could vary yields at maturity by more than 2-fold (Fig. 6). The analysis by Asseng *et al.* (2001b) showed a similar general increase in potential yield with water use after anthesis, but the scatter was very large when predicted yields were simulated over 80 years of weather data (Asseng and Turner, 2003). Simulation modelling can be a powerful tool for predicting potential yields for a range of environments and soil types, and for analysing historical weather data to determine the risks associated with any one management option or combination of options (Asseng *et al.*, 2001b).

Agronomic options for improving water use by the crop

One of the major ways to increase the water use of the crop itself is by increasing the depth of rooting. In many dryland environments, crops do not use all the water available in the soil profile because of restrictions to root growth. These restrictions may be physical, chemical, or biological. Agronomic practices that reduce the physical impedance to root growth can benefit yields of dryland crops in water-limited environments. Deep ripping to about 30 cm has been shown to increase yields and hence rainfall-use efficiency on deep sandy soils (Jarvis, 1982; Delroy and

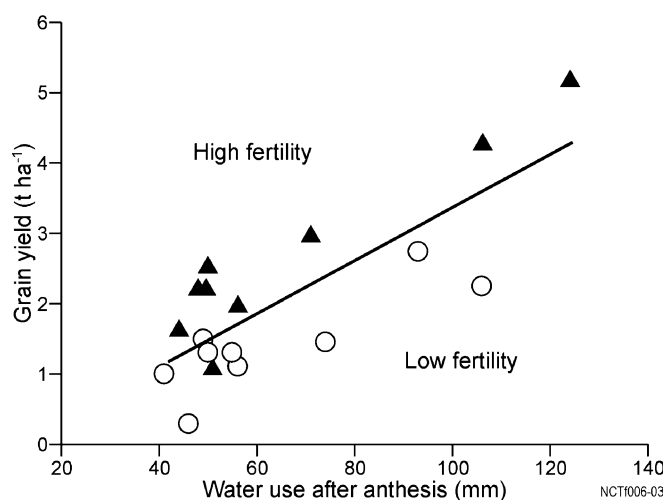


Fig. 6. The relationship between grain yield and water use between anthesis and maturity for unfertilized (open circles) and fertilized (closed triangles) barley. The line gives the mean regression (from Turner, 1997, reproduced with permission from Elsevier).

Bowden, 1986; Asseng *et al.*, 2002; Asseng and Turner, 2003). Other physical soil constraints such as compacted subsoils can be alleviated by the application of gypsum to flocculate the soil particles, and to increase water penetration and root growth (Hamza and Anderson, 2002, 2003). Chemical constraints are not as easily remedied, but soil acidity at depth that constrains root growth can be ameliorated by liming, particularly with deep placement of lime. However, soil alkalinity that restricts the growth of lupin roots (Atwell, 1991; Tang *et al.*, 1992), soil sodicity, and boron toxicity are more difficult to ameliorate agronomically and may need to rely on the use of different species or tolerant genotypes (Tang *et al.*, 1993). Finally, root diseases and nematodes can constrain root growth and are most easily controlled by rotations to reduce the disease- and nematode-incidence and by cultivation techniques that minimize fungal activity (Roget *et al.*, 1996).

It should be noted that deeper roots are not always beneficial. In environments in which the seasonal rainfall and soil characteristics are such that the depth of soil wetting is restricted, deeper rooting will be of no benefit. A simulation analysis by Asseng *et al.* (2002) showed that deeper roots gave the greatest benefit on sandy soils, particularly in the high-rainfall zones where nitrogen can leach below the root zone, and had smaller or even negative effects on yields for wheat growing on clay soils with limited wetting to depth (Smith and Harris, 1981). The analysis also demonstrated the role of nitrogen application in overcoming restrictions to rooting depth, particularly in sandy soils (Asseng *et al.*, 2001b).

Rotations also provide an opportunity to increase water use by a crop. Roots of some species have the potential to penetrate deeper into the soil than others (Hamblin and Hamblin, 1985), and this may provide 'biopores' for a subsequent crop. It has been suggested that both narrow-leaved lupin (*Lupinus angustifolius*) and canola/oilseed rape (*Brassica napus*) develop 'biopores' in the soil that allow easier root penetration by the water and roots of a subsequent crop (Angus *et al.*, 1991; Cresswell and Kirkegaard, 1995). However, results have been equivocal. Nevertheless, there is considerable evidence that lucerne (*Medicago sativa*) has roots that penetrate deep into the soil over 2–3 years and allow deeper water penetration and deeper root penetration by a subsequent crop (Ward *et al.*, 2002).

However, the major impact of agronomic management on rainfall-use efficiency has not arisen from increasing total water use by the crop in evapotranspiration, but from increasing water use by the crop itself in transpiration at the expense of water loss by weeds or from the soil by soil evaporation, deep drainage, surface runoff, or lateral throughflow. This increase in water use by the crop at the expense of other losses generally results in significantly increased yields, with only a 5–10% increase in total evapotranspiration (Asseng *et al.*, 2001c).

Agronomic options for decreasing losses from the soil and weeds

Figure 2 shows that transpiration (T) by annual crops in Mediterranean-type climates is offset or delayed in relation to incoming rainfall. Earlier planting to more closely match incoming rainfall and reduce soil evaporation will increase yield and rainfall-use efficiency (French and Schultz, 1984a; Anderson *et al.*, 1995; Siddique *et al.*, 1998; Asseng *et al.*, 2001c; Riffkin *et al.*, 2003). Eastham *et al.* (1999) and Eastham and Gregory (2000) showed that earlier planting of wheat and lupin crops in a Mediterranean-type environment did not affect the total evapotranspiration, but reduced soil evaporation, particularly early in the season before the leaf area of the later-sown crop reached full ground cover. In some cases, this resulted in higher yields and water-use efficiency (and rainfall-use efficiency) of the early-sown crops (Gregory and Eastham, 1996). With the use of herbicides to control weeds, farmers in some parts of southern Australia are sowing into dry soil (dry seeding) so that the seeds emerge on the opening rains of the season and thereby gain several days' more growth than would be the case if they waited to sow until after the rain. However, early planting is not always an advantage (Eastham and Gregory, 2000). If appropriate cultivars are not available, early planting increases the risk of damage by frost during flowering and there is a greater vulnerability to terminal drought due to increased biomass and water use by anthesis, thereby reducing yields (Anderson *et al.*, 1995, 1996; Riffkin *et al.*, 2003). Indeed, Gregory and Eastham (1996) found that early planting of wheat only gave yield benefits in 1 out of 3 years because of increased disease incidence and earlier water deficits in the early-planted, high-biomass wheat in the other 2 years. Likewise, early planting of field peas is not recommended in southern Australia as this raises the risk of increased disease incidence and lower yields (Bretag *et al.*, 1995) from black spot (*Mycosphaerella pinodes* and *Ascochyta pisi*), a disease for which resistance is not currently available in field peas. Indeed, in west Asia chickpea crops are generally not sown in autumn, but in late winter or early spring in order to avoid the endemic *Ascochyta* blight for which there is currently little disease resistance (Abbo *et al.*, 2003), but

this is at the cost of yield and rainfall-use efficiency (Keatinge and Cooper, 1983; Singh *et al.*, 1997).

Fertilizer use can also have a very marked effect on crop yield and rainfall-use efficiency. Nitrogen nutrition and phosphorus nutrition have both been shown to increase the early growth of cereals in water-limited Mediterranean environments (French and Schultz, 1984b; Shepherd *et al.*, 1987; Asseng *et al.*, 2001b). Asseng *et al.* (2001b) showed that nitrogen fertilizer input increased the water use by the crops and reduced soil evaporation so that total evapotranspiration was little changed, thereby increasing yields and rainfall-use efficiency (Table 1). Similar effects on the balance of crop transpiration and soil evaporation were observed by Gregory *et al.* (1984) and Shepherd *et al.* (1987) with fertilizer use on barley in Syria. While fertilizer increases biomass and water use prior to anthesis, the additional ears produced by the increased fertilizer result in greater sinks for assimilates and higher yields even with lower amounts of water available in the post-anthesis period. As mentioned previously, Turner (1997) showed that while yields increased with increases in water available after anthesis, there was at least a 2-fold increase in yield at high fertilizer rates at any one level of water use, and that the increased yield occurred with little or no increase in water use; that is, the fertilizer increased rainfall-use efficiency (Fig. 6). Rotations are also important means of increasing fertility. Use of legume-rich pastures or grain legume crops provides nitrogen to a subsequent cereal or oilseed crop (Rowland *et al.*, 1988, 1994; Fillery, 2001; Angus *et al.*, 2001). The quantity of nitrogen supplied depends both on the proportion of legume in the pasture (Peoples and Baldock, 2001) and the amount of nitrogen removed in the seed of the legume crop (Evans *et al.*, 2001). However, high nitrogen levels can reduce yields through 'haying off' due to excess water use in the pre-anthesis period, leaving insufficient water for post-anthesis grain filling (van Herwaarden *et al.*, 1998). Fischer (1981) suggests that in dryland environments there is an optimum biomass at anthesis, depending on available water, to maximize grain yield. While this appears to be true for heavy-textured soils, on sandy soils high nitrogen levels do not induce lower yields (Halse *et al.*, 1969; Turner, 1987; Asseng *et al.*, 2001b).

High plant density increases crop-water use and reduces soil evaporation in Mediterranean-type environments, but

Table 1. Simulated yield, evapotranspiration, soil evaporation, crop transpiration, and transpiration efficiency for a wheat crop in Western Australia

The crop was growing on two soil types and given two levels of nitrogen fertilizer at a medium-rainfall (390 mm annual rainfall, 322 mm growing-season rainfall) site (adapted from Asseng *et al.*, 2001b, with kind permission of Springer Science and Business Media).

Soil type	Nitrogen treatment (kg N ha ⁻¹)	Grain yield (kg ha ⁻¹)	Evapotranspiration (mm)	Soil evaporation (mm)	Crop transpiration (mm)	Transpiration efficiency (kg ha ⁻¹ mm ⁻¹)
Sand	0	1170	214	168	46	25
	150	2090	229	138	90	23
Clay	0	1630	269	188	81	20
	150	1820	286	138	148	12

the compensation provided by growth of tillers in cereals and branching in pulses results in a broad range of planting densities producing similar yields (Anderson and Sawkins, 1997; Johnston *et al.*, 2002; Seymour *et al.*, 2002; Regan *et al.*, 2003) and hence similar rainfall-use efficiencies. Low planting density and uneven planting can result in low yields and a greater proportion of small seeds (pinched grain) that are discarded at harvest (Turner *et al.*, 1994), resulting in poorer rainfall-use efficiency. However, where crops are grown on stored soil moisture, low planting densities are frequently used to provide a greater source of water per plant and hence increased yields per plant and per hectare. Gregory (1989) reported studies with pearl millet in Niamey, Niger, grown at three row widths but with the same within-row density. The studies showed that at the low planting densities (wider row spacing) the crop continued to extract water longer into the dry period and had greater dry matter accumulation and root growth than the plants at the high planting density. Moreover, there was evidence that at low planting densities the year-to-year variation in yield was less where rainfall was erratic (Gregory, 1989). This contrasts with Mediterranean-type environments in which high seedling rates have been shown to incur no greater risk than low seeding rates (O'Connell *et al.*, 2003). Thus, planting density depends on rainfall distribution, with low densities being detrimental in Mediterranean-type environments, but low densities being preferred where the crop relies on stored soil moisture, particularly in areas with little or no rainfall during the growing season and little soil evaporation from the dry soil surface. It also depends on the degree of risk that a farmer is prepared to take to gain advantage of the above-average years.

Competition for water by weeds and the impact of weed growth on yields is well recognized (French and Schultz, 1984b). Likewise root diseases, insect damage, and root nematodes all reduce yields and rainfall-use efficiency (French and Schultz, 1984b). To reduce the influence of these factors, herbicides, fungicides, insecticides, and nematocides can be used. However, in low-yield, water-limited environments, rotations and agronomic management practices in the previous crop are often utilized. For example, 'take-all' (*Gaeumannomyces graminis*) can be carried over in the residues of the previous crop, but also by grass weeds in the previous crop. Removal of these weeds in the previous crop or pasture will reduce the incidence of the disease in the cereal crop. Likewise, broad-leaved weeds can be removed in a previous cereal crop more easily than with selective herbicides in a pulse crop. *Brassica* crops such as canola and Indian mustard have been shown to produce isothiocyanates and other breakdown products of glucosinolates from their residues, leading to biofumigation of the soil that reduces the incidence of 'take-all' and other soil-borne pathogens, weeds, insects, and nematodes in the subsequent crop (Kirkegaard and Sarwar, 1999; Angus *et al.*, 2001). Thus

the better use of rotations in providing nitrogen (Rowland *et al.*, 1988, 1994; Fillery, 2001; Angus *et al.*, 2001) and a disease/weed break for the subsequent crop is an important agronomic management tool for influencing dryland crop yields and rainfall-use efficiency.

The use of minimum tillage or conservation tillage, whereby residues from the previous crop are left on the surface, weeds are controlled by herbicides rather than tillage, and the seed is sown with minimum disturbance of the soil surface by the use of narrow tines, has led to reduced losses of water by soil evaporation and increased yields (Unger, 1978; Stewart and Robinson, 1997; Cornish and Pratley, 1991). Further, minimum tillage systems allow earlier planting as delays resulting from using tillage to remove weeds are reduced. However, recent studies suggest that the greater retention of incoming rainfall through minimum tillage may increase water losses through deep drainage that are detrimental in a landscape in which secondary salinity can develop (Sadler and Turner, 1994), and reduce rainfall-use efficiency.

Finally, fallowing land to conserve moisture has been widely practised as a means of improving yields in water-limited environments (Stewart and Robinson, 1997) and was given credit by Donald (1965) for the increase in wheat yields in Australia in the first half of the last century. However, Stewart and Robinson (1997) have pointed out that only 12–20% of the precipitation in the fallow period is retained in the soil at seeding. O'Leary and Connor (1997a) showed that the amount of water stored in the soil and available to a subsequent crop varied with season, soil type, and management of the fallow land. At sites with about 250 mm of annual rainfall, the amount of water available at the time of sowing the subsequent crop varied from –100 to +100 mm over 4 years, with greater soil water available in the heavier clay soil, when stubble from the previous crop was retained, and when the soil was not tilled. On the clay soil, the greater the soil water in the profile at seeding the greater the water use and the higher the yield (O'Leary and Connor, 1997b). However, benefits from fallowing land were minimal on the sandy soil, whether or not the stubble was retained or the soil tilled (O'Leary and Connor, 1997a, b). Moreover, tillage during the fallow period can reduce the soil organic matter, leading to a decline in soil structure (Stewart and Robinson, 1997). Indeed crop intensification, by growing a crop instead of fallowing land, while reducing yields per crop can improve overall crop yields and markedly increase rainfall-use efficiency (Jones and Popham, 1997; Farahani *et al.*, 1998a, b).

Agronomic options for improving transpiration efficiency

Until the 1980s it was considered that there was no genetic variation within a species for differences in transpiration efficiency (Tanner and Sinclair, 1983; Fischer, 1981), a view

that was dispelled by the development of the isotopic-carbon discrimination technique to measure transpiration efficiency (Hall *et al.*, 1994). However, it has long been recognized that species that were subsequently shown to have the C_4 pathway of photosynthesis had higher transpiration efficiencies than those with the C_3 pathway of photosynthesis (Briggs and Shantz, 1912; Fischer and Turner, 1978). While C_4 species tend to have a higher temperature optimum and grow in the warmer periods of the year with high vapour-pressure deficits, the selection of genotypes with the ability to grow in cooler temperatures has allowed them to be grown in temperate regions, where their higher transpiration efficiency can result in higher yields than C_3 species on the same amount of rainfall. Thus, choice of species can be used to improve yields with similar water use, that is, to increase the rainfall-use efficiency. For example, Jones and Popham (1997) showed that growing sorghum rather than wheat more than doubled the grain yield and increased precipitation-(snowfall as well as rainfall) use efficiency in the western plains of the United States of America.

While low levels of nitrogen in the leaf reduce photosynthesis more than transpiration, resulting in low transpiration efficiency, the major agronomic way of increasing transpiration efficiency is to maximize the growth of crops during periods of low vapour-pressure deficits (Fig. 7). Thus in Mediterranean-type climates autumn sowing rather than spring sowing has a major influence on transpiration efficiency as a greater proportion of the autumn-sown crop's life occurs during the period of low vapour-pressure deficits in winter (Fischer, 1981; Singh *et al.*, 1997; Richards *et al.*, 2002).

Agronomic options for improving the harvest index

Grain yield as a proportion of the total biomass yield, that is, the harvest index, varies with water use both before and after the establishment of the floral and seed structures (Fischer, 1981) and thus can be influenced by management decisions taken throughout the life cycle of the crop. In subtropical semi-arid environments where crops are grown on stored soil moisture, agronomic treatments such as increased fertilizer use and deep ripping that increase biomass production and water use prior to flowering can reduce the harvest index, as insufficient water is available after anthesis and the number of pods, spikelets, and seeds is reduced either through low numbers produced or pod or seed abortion. In Mediterranean-type semi-arid environments, treatments that increase early growth increase the harvest index as the head weight at anthesis is often strongly correlated with the final grain yield (Turner and Nicolas, 1998). This is particularly true on deep sandy soils, but too-vigorous early growth of crops growing on heavy clay soils can lead to a lower harvest index as the water available after anthesis is too little to fill the grains (Fischer,

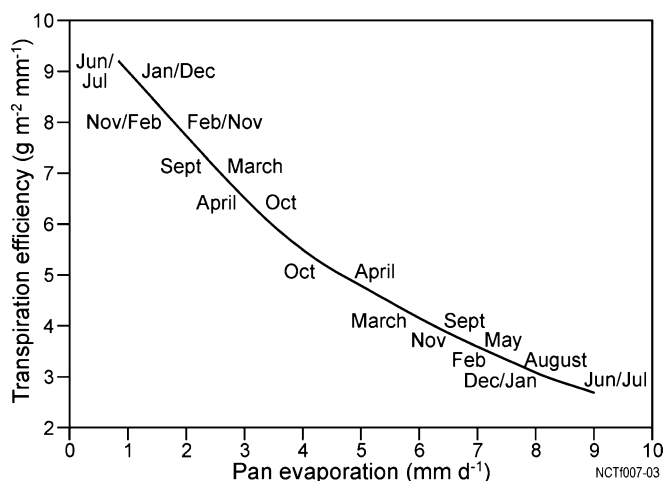


Fig. 7. The relationship between transpiration efficiency of wheat and pan evaporation for various months in the southern hemisphere (left of the line) and the northern hemisphere (right of the line) (adapted from Fischer, 1981, and Richards *et al.*, 2002, with permission).

1981; van Herwaarden *et al.*, 1998; Asseng *et al.*, 2001b, 2003). In some Mediterranean-type environments in southern Australia excess water in winter can lead to waterlogging and a low harvest index (Gregory *et al.*, 1992; Gregory, 1998), and management options to alleviate waterlogging, such as drainage or early planting, can increase the yield and harvest index of crops (Zhang *et al.*, 2004). By contrast, water shortage during vegetative growth has been shown to stimulate reproductive development in indeterminate crops such as lupin and cotton, and to increase the harvest index of the crop (French and Turner, 1991). Indeed, intermittent shortage of water on deep, sandy, coarse-textured soils may account for the success of lupin production in Western Australia (French and Turner, 1991) and the large variation in the harvest index from season to season.

Conclusions

Donald (1965) reviewed decadal wheat yields in Australia from 1860 to 1960 and showed that until the turn of the twentieth century yields decreased as nutrients were exhausted. The introduction of the practice of leaving land fallow to conserve soil moisture, the use of shorter-season, better-adapted cultivars, and the use of superphosphate fertilizer and rotations, including legumes, for the supply of nitrogen produced a steady increase in wheat yields between 1900 and 1950. Angus (2001) and Angus *et al.* (2001) have extended Donald's (1965) findings to the year 2000 and suggest that from 1950 to 1980 wheat yields increased as a result of better rotations and more timely sowing because of mechanization, and increased again in the 1980s and 1990s as a result of the introduction of herbicides and break crops such as lupins, other pulses, and canola into the rotation (Fig. 8). The introduction of

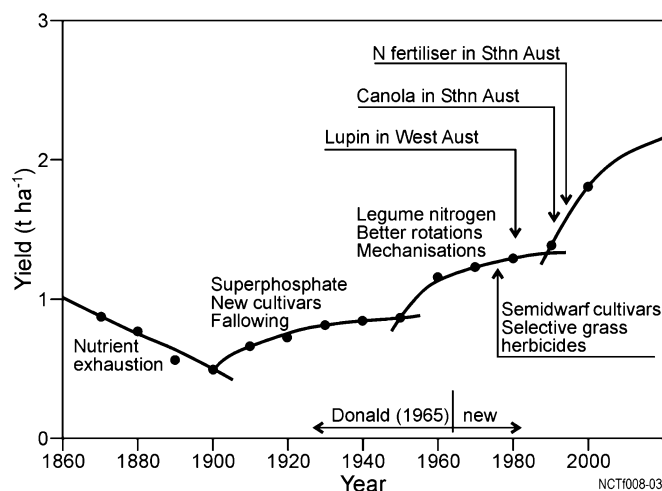


Fig. 8. Changes with time in decadal wheat yields from 1860 to 2000 with explanations for the trends (from Angus, 2001, with permission from CSIRO Publishing).

semi-dwarf varieties in the 1970s also had a role in increasing yields and enabled agronomic management, such as increased fertilizer use, to benefit yields too. Similar conclusions on the role of agronomic changes have been drawn from studies of the Broadbalk experiment at the Rothamsted Experiment Station (Rasmussen *et al.*, 1998; Mifflin, 2000). These increases in yield have occurred as rainfall has remained unchanged, resulting in significant improvements in rainfall-use efficiency. While the early analysis suggested that until 1980 the increase in rainfall-use efficiency could be attributed half to new cultivars and half to increased agronomic practices (Turner, 1997), the surge in yields and rainfall-use-efficiency in the past two decades is considered to be one-third attributable to new cultivars and two-thirds attributable to agronomic management (Angus *et al.*, 2001; Stephens, 2002). Indeed, the combination of agronomists working with breeders to develop appropriate agronomic packages for new cultivars and the ability of modern cultivars to respond to increased agronomic inputs is probably the reason for the recent surge in rainfall-use efficiency in wheat crops in Australia. It is clear that it is not just one factor that has led to the higher rainfall-use efficiency, but rather the combination of appropriate fertilizer use, improved weed/disease/pest control, timely planting, and the increased adoption of a range of rotations. This is the basis of the 'Green Revolution in Rainfed Environments'.

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