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Productivity, sustainability, and rainfall-use efficiency in Australian rainfed Mediterranean agricultural systems

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Abstract. Mediterranean environments are characterised by hot, dry summers and cool, wet winters. The native vegetation in Mediterranean-climatic regions is predominantly perennial shrubs and trees intermixed with annual forbs. In south-western Australia, the spread of agriculture has seen the well adapted perennial vegetation replaced by rainfed annual crops and pastures. This has increased waterlogging and secondary salinity, thereby causing loss of productivity in ~10% of the cleared land area. To reduce deep drainage and make the agricultural systems environmentally sustainable requires the re-introduction of perennial vegetation in the form of belts of trees or shrubs, and phase-farming systems with perennials such as lucerne replacing annual pastures between the cropping years. To be economically viable, agricultural productivity needs to increase by at least 3% per annum. Yields of dryland wheat, the predominant crop in the Mediterranean agricultural regions of Australia, have increased at ~1%/year for the century preceding the 1980s and since then by nearly 4%/year. Increases have arisen from both genotypic and agronomic improvements. Genotypic increases have arisen from selection for earliness, early vigour, deep roots, osmotic adjustment, increased transpiration efficiency, improved disease resistance, and an improved harvest index from high ear weight (grain number) at flowering and high assimilate storage and remobilisation. Agronomic increases have arisen from early sowing that has been enabled by minimum tillage, increased fertiliser use, especially nitrogen, weed control, and rotations to improve weed control, minimise disease risk, and increase nitrogen availability. Evidence is presented suggesting that the rapid increase in yield of wheat in the last two decades has likely arisen from the rapid adoption of new technologies. For productivity to be maintained in the face of the increasing requirement to be environmentally sustainable will be a challenge and will require better integration of breeding and agronomy.

Additional keywords: Mediterranean climate, native vegetation, water use, terminal drought, agronomic improvements, genetic improvements.

Introduction

The Mediterranean-climatic regions of the world are characterised by cool wet winters and hot dry summers. The amount and distribution of rainfall, coupled with the high rates of evaporation in summer, result in water being the major limitation to plant productivity. The annual net primary productivity of the Mediterranean-climatic regions has been estimated by Fischer and Turner (1978) to be 2.5–10 t/ha. Despite their semi-arid nature, many of the Mediterranean-climatic regions are highly productive because the native vegetation has been replaced by improved pastures, arable cropping, and horticultural crops (Fischer and Turner 1978). Where water is available, the annual productivity of these agricultural/horticultural systems has been further increased by the use of supplemental irrigation. In this review the physical environment of the Mediterranean-climatic regions of Australia, the features of natural ecosystems, and some of the environmental consequences of clearing the native vegetation for agricultural use will be considered. The emphasis of the review will be on the factors affecting the productivity and sustainability of rainfed (dryland) agricultural systems, particularly in south-western Australia, which has a typical Mediterranean-type climate. The productivity and sustainability of horticultural and irrigated systems in the Mediterranean-climatic regions are outside the scope of the review.

Mediterranean environments

Figure 1 identifies the Mediterranean-climatic region of Australia, sometimes referred to as the temperate seasonally

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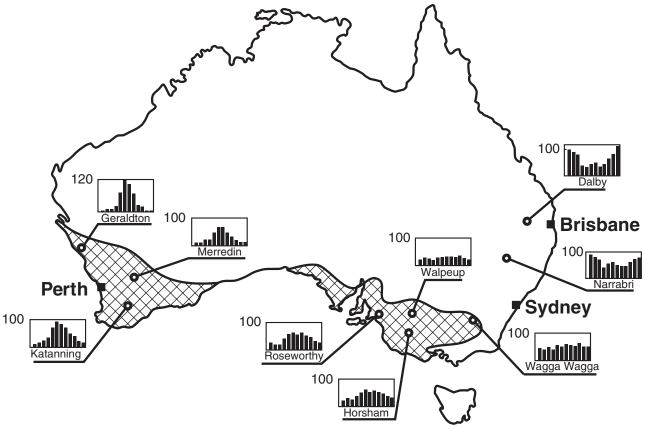

Fig. 1. Map of Australia with the Mediterranean climatic regions highlighted with cross-hatching. The monthly mean rainfall (mm) for selected towns in the cropping region of Australia is also shown.

dry slopes and plains (Williams *et al*. 2002). The rainfall distribution figures for selected locations (also shown in Fig. 1) show the predominance of winter rainfall in the south-west of Australia (Perry 1992). Although in the eastern part of the Mediterranean-climatic region, rainfall is, on average, more evenly spread throughout the year than in the south-west, the high rates of evaporation in the summer cause this area to be classified as having a Mediterranean-type climate. The climate of the region is illustrated in Fig. 2, which shows the daily maximum and minimum temperatures, daily rainfall, and daily pan evaporation for 3 growing seasons at Merredin in the eastern cropping zone of Western Australia, with a long-term average annual rainfall of 310 mm and average growing-season rainfall of 230 mm (Palta *et al*. 2004). Although the growing-season rainfall and length of the growing season varied from year to year, all seasons were characterised by predominantly winter rainfall, rising temperatures, and increasing pan evaporation in spring, leading to terminal drought.

Although rainfall does vary from year to year, a feature of Mediterranean-climatic environments is that, relative to other arid and semi-arid environments, year-to-year variation is smaller (Asseng *et al*. 2001*a*). The standard deviation for annual rainfall in the Mediterranean-climatic region of Western Australia is 23–25% compared with standard deviations of 30–33% in northern New South Wales, Australia, which has a similar annual rainfall, but predominantly summer rainfall (Asseng *et al*. 2001*a*, 2003). The reliability of autumn rainfall results in crop establishment being possible in Mediterranean climates in most years. For example, calculations showed that a sowing opportunity existed for wheat at all locations and on all soil types across the agricultural zone of Western Australia in every year over the past 100 years. These calculations were based on a simple sowing rule that from early May to early June, 25 mm of

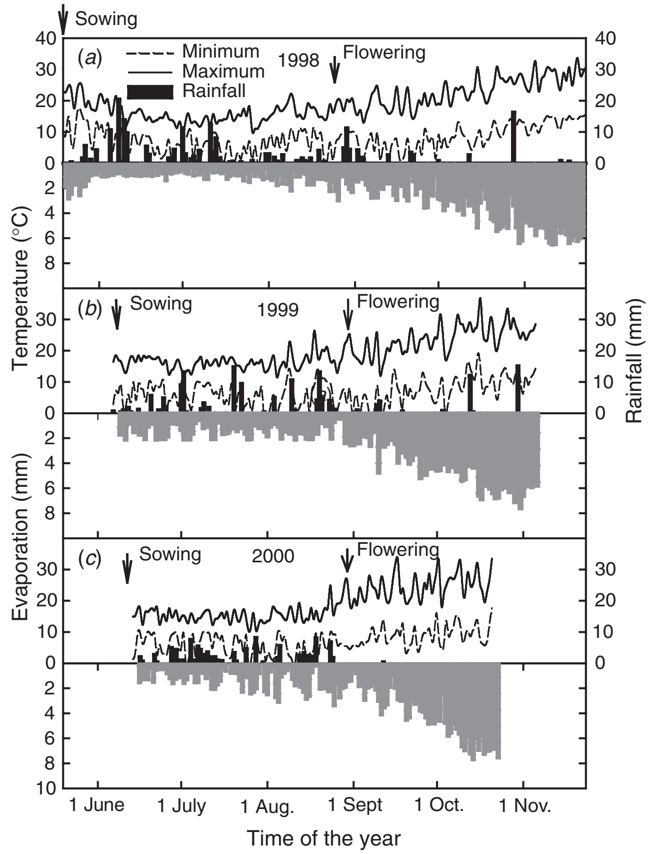

Fig. 2. Maximum (solid line) and minimum (dashed line) air temperatures, daily rainfall (black histogram), and evaporation (shaded histogram) at Merredin, WA, during the growing seasons of (*a*) 1998, (*b*) 1999, and (*c*) 2000. Time of sowing and 50% flowering on the mainstem of narrow-leafed lupin (*Lupinus angustifolius* L.) are shown by vertical arrows. From Palta *et al*. (2004) with permission from **CSIRO Publishing** http://www.publish.csiro.au/ajar.

rainfall was required over the previous 10 days, and from mid-June to the end of July 10 mm was required over the previous 10 days for a sowing opportunity to exist (Asseng *et al*. 2003). In practice the availability of large minimum-disturbance knife-point seeders and zero-tillage systems often provides sowing opportunities on lesser amounts of rainfall than those used in the calculations. By contrast, in southern Queensland with its subtropical environment, there was no opportunity to sow wheat in 10% of years (Turner 2004*a*). Nevertheless, the year-to-year variation is sufficient for crop failures (less than 0.2 t/ha) to occur in Mediterranean-climatic regions. For example, crop failures on fine-textured soils were estimated to occur in 1–2% of years in medium- (320 mm growing-season rainfall) and high- (390 mm) rainfall regions, but in up to 15% of years in a low-rainfall region (230 mm).

The soils in much of southern Australia are ancient, deeply weathered, low in relief, and of inherently low fertility (Perry 1992). Although there are 4 main soil types: (*i*) coarse-textured sands, (*ii*) brown, red, or yellow earths, (*iii*) grey, brown-red, or black clays, and (*iv*) duplex soils (Perry 1992), the texture-contrast duplex soils predominate (Tennant *et al*. 1992). In Western Australia the duplex soils are sandy at the surface with finer textured subsoils. In other Mediterranean-climatic regions the surface soils are fine textured, but still coarser in texture than the subsoils. In Western Australia, duplex soils are found over 60% of the cropping region (Tennant *et al*. 1992), deep sandy soils and deep fine-textured soils occupying the remaining 40% (Turner 1992). Duplex soils in the Mediterranean-climatic region are frequently waterlogged in winter and the surface soil, in which most of the roots are located, dries rapidly in the spring and early summer. The use of machinery and the presence of sheep and cattle in many of the agricultural systems of the Mediterranean region induce the development of hard compacted layers in the sandy surface soils of both duplex soils and the deep sands. This compaction limits root growth and crop yields (Belford *et al*. 1992; Dracup *et al*. 1992; Gregory 1998) unless ameliorated by deep ripping (Jarvis 1982; Perry 1986) or deep ripping accompanied by the application of gypsum (Hamza and Anderson 2002, 2003).

Native vegetation and the consequences of its clearing for agriculture

Historically, the natural vegetation of the Mediterranean-climatic regions was a mixture of evergreen shrubs and trees that were well adapted to the hot dry summers, and annuals that germinated with the first rains of autumn and set seed in spring before the soil moisture in the root zone was depleted (Castri 1981). Many of the perennial trees and shrubs in the Mediterranean-climatic region have morphological adaptations that funnel up to 40% of the water falling on the leaves and branches to the stem and roots in the region near to the tap root (Slatyer 1965). Further, water use by some native species is limited during winter when soil water is plentiful, thus ensuring high rates of growth and photosynthesis longer into the summer (White *et al*. 2000, 2002; Dunin 2002). One of the advantages of the native perennial vegetation of the region is the ability to use late spring and summer rains (White *et al*. 2000), so that the amount of annual rainfall leaking below the root zone as deep drainage rarely exceeded 1 mm in the region now used for crops and pastures. Recently it was shown that perennial species in the Mediterranean-climatic zone not only have deep roots, but also demonstrate hydraulic lift, bringing water from deep in the profile to the surface roots to keep them viable during the dry summer months (Burgess *et al*. 1998, 2000, 2001), and at the break-of-season, when the winter rains commence, remove water from the surface soil down the taproot to deep into the dry soil profile (Burgess *et al*. 1998, 2001) at an average rate of ~1 mm/day for at least 28 days (Burgess *et al*. 2001). Deep roots, hydraulic lift, and the transfer of water down the taproot are all characteristics that assist the native trees to survive the long dry summer.

Despite the importance of perennial vegetation in maintaining a balanced annual water use, the region around the Mediterranean Basin was also the centre of origin of many of the current annual crop species such as wheat, barley, lentil, chickpea, field pea, narrow-leafed lupin (Gladstones and Crosbie 1979; Lev-Yadun *et al*. 2000; Abbo *et al*. 2003), and many of the annual pasture species used today in the Mediterranean-climatic region of southern Australia. In Australia, the replacement of the native perennial vegetation by the annual crops and pastures that had their origin in the Mediterranean region has led to significant sustainability issues, principally secondary salinity and waterlogging lower in the landscape (Peck 1978; Peck and Williamson 1987; Williamson *et al*. 1987). This may be because of southern Australia's proximity to the Southern Ocean, south-westerly winds from which have deposited cyclic salt in the landscape over many millennia. This has resulted in 50–5000 t/ha of salt occurring in the soils beneath south-western Australia (McFarlane and Williamson 2002). In pre-agricultural days, the leakage below the root zone of the native species varied with rainfall, from 0.1 to 1 mm/year as rainfall varied (geographically and seasonally) from 300 to 600 mm/year (Smettam 1998; Turner 2001). This was sufficient to maintain the roots in fresh water and to maintain a fresh flow of water in the rivers. However, under annual crops and pastures, the leakage ranges from 10 to 80 mm/year over the same rainfall range (Smettam 1998; Turner 2001). This has caused the groundwater levels to rise, bringing salt to the surface, so that secondary salinity is now observed in the lower parts of the landscape in ~10% of the cropping region of Western Australia (McFarlane and Williamson 2002) and the rivers contain high levels of salt (Hatton *et al*. 2003). One prediction is that the proportion of land affected by secondary salinity will rise to 30% of the cropping region of Western Australia when hydrological equilibrium is reached (McFarlane and Williamson 2002). The issue has driven policy makers and landowners to try and reverse the trend, or at least to halt the increase (Turner and Ward 2002). Although secondary salinity is a major issue in Western Australia, the problem is not limited to Australia alone. It also occurs for similar reasons in north-eastern Thailand and parts of South Africa (Pannell and Ewing 2006).

In Australia, it is now widely recognised that to ameliorate secondary salinity will require the replacement of some of the annual crops and pastures with perennial species. White *et al*. (2002) and Dunin (2002) showed that 16–22% of a catchment replanted with belts of trees would reduce leakage rates to those before clearing in a region with rejuvenated soils, a dissected landscape, and an annual rainfall of 400 mm. The introduction into the rotation of lucerne (Ward *et al*. 2001, 2002; Latta *et al*. 2002) or other perennial species (Pannell and Ewing 2006) that can be grazed increases the options for farmers to reduce deep drainage and maintain diversity in the farming system.

Mediterranean dryland farming systems

Farming systems in the Mediterranean-climatic region of Australia have evolved around rainfed annual crops and annual pastures (Perry 1992; Connor 2004). This is termed the ley farming system (Dunne and Shier 1934). Key features of the system are that temperate cereals, particularly wheat and barley, cool-season pulses (grain legumes), such as narrow-leafed lupin, chickpea, faba bean, and lentil, and canola are sown in autumn with the onset of the rains and cooler temperatures. Flowering occurs in early spring, once the risk of frost has decreased, and grain filling occurs during spring, with harvest in late spring and early summer. One-or-more years of crops are interspersed by one-or-more years of self-regenerating legume-based pastures that provide grazing for stock during the winter and spring (Perry 1992). These pastures set seed in spring and the excess foliage that occurs during spring is either grazed in its dry state or preserved as hay or silage for supplemental feed for animals over the following dry summer period. The principal pasture species are subterranean clover (*Trifolium subterraneum*) and several annual medic (*Medicago*) species. They are characterised by varying degrees of hard-seededness so that only a proportion of the seed softens over the ensuing summer, resulting in some seed being available for germination and emergence several years after being set (Rossiter 1966).

The rapidly rising rate of evaporation and decreasing rainfall in spring results in water deficits occurring during grain filling or seed set in crops and pastures. As water is the major limiting factor in the region, utilisation of as much of the growing-season rainfall as possible is critical for improved yields. French and Schultz (1984*a*) showed that wheat crops in the Mediterranean-climatic region of South Australia could potentially produce 55 kg/ha of biomass or 20 kg/ha of grain per millimetre of water used by the crop. Assuming that there is no stored water in the soil at sowing, this translates into a potential production of 55 kg/ha of biomass and 20 kg/ha of grain per millimetre of growing-season (April–October) rainfall above 110 mm lost through soil evaporation (French and Schultz 1984*b*). However, many crops fail to reach these potentials (French and Schultz 1984*b*; Cornish and Murray 1989), not because of lack of water, but because of late planting, inadequate fertiliser application, inadequate weed control, or yield losses due to pests and diseases. Moreover, Gregory *et al*. (1992) and Zhang *et al*. (2004) showed that in the wetter regions (above 450 mm annual rainfall), loss of rainfall as runoff, throughflow (lateral subsurface flow), and deep drainage reduced yields through the reduced water available to the crop on duplex soils and also through waterlogging. It is incongruous that in a semi-arid environment, rainfall distribution can limit crop and pasture production by excess water (waterlogging) in winter as well as water shortage in spring. Asseng *et al*. (2001*a*), using a modelling approach and over 80 years of weather data, showed that even with high nitrogen inputs potential yields did not reach the values suggested by French and Schultz (1984*b*) in many years because of the uneven rainfall distribution during the growing season.

Pasture production is also limited by rainfall. Bolger and Turner (1999) demonstrated that the potential production by pastures in the Mediterranean-type environment of Western Australia was 30 kg/ha of biomass per millimetre of water use or growing-season rainfall above a loss of 50 mm for soil evaporation. Again, when water use or growing-season rainfall exceeded 400 mm, biomass did not increase with rainfall because of waterlogging and water loss by deep drainage, runoff, or throughflow rather than by soil or pasture evapotranspiration (Bolger and Turner 1999). Furthermore, many pastures did not reach their potential productivity set by rainfall because of inadequate regenerating plant populations, inadequate nutrition, and poor pasture composition, particularly the low proportion of nitrogen-fixing legumes (Thomson *et al*. 1998; Bolger and Turner 1999). There are therefore several agronomic options needed to achieve the potential crop and pasture yields that are set by rainfall or water use (Turner 2004*b*).

Agronomic *v.* genetic improvements in rainfall-use efficiency

In water-limited Mediterranean-type environments the efficient use of water by crops is fundamental. Molden *et al*. (2003) suggested that there is a need to consider crop production in all parts of the world not in terms of production per unit of land but per unit of water, and introduced the concept of water productivity, i.e. ‘more crop per drop’. Water productivity depends on several factors, including crop genetics, water-management practices, agronomic practices, economic policies, and production incentives. It integrates the expertise of crop scientists, breeders, irrigation engineers, planners, and economists. Whereas water productivity is usefully applied in irrigated systems where water throughout the entire chain can be taken into account, in the case of Mediterranean crop and pasture systems where rainfall is the only water input, the term rainfall-use efficiency is preferred (Turner 2004*b*). In rainfed agricultural systems, rainfall-use efficiency can be increased by both agronomic and genetic means.

Farmers in the Mediterranean-climatic regions of Australia have to contend with stable or decreasing commodity prices and increasing input costs when considered in actual dollar terms (Fig. 3*a*). Despite this so-called cost-price squeeze, the average rate of return on capital of farmers in the Western Australian cropping region

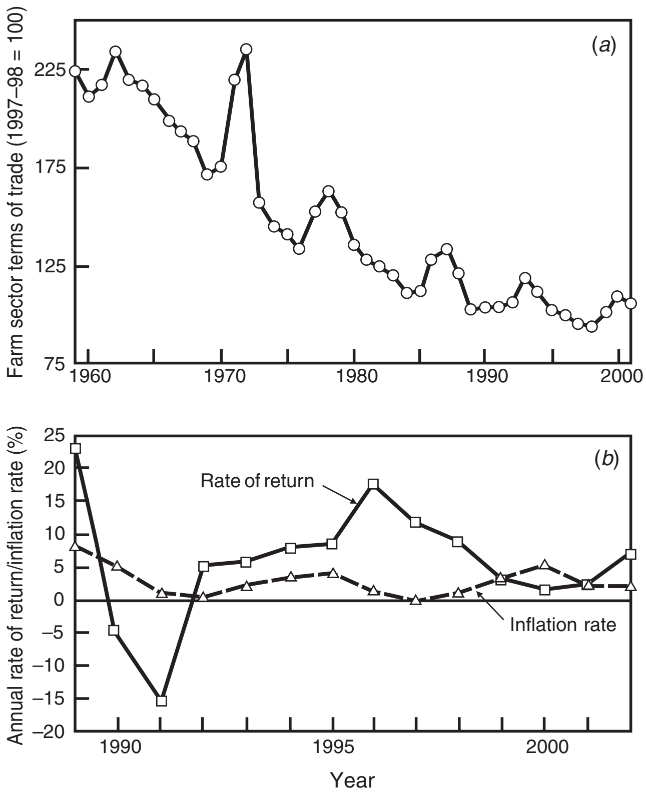

Fig. 3. (*a*) The ratio of prices received for products to prices paid for inputs (farm sector terms of trade) from 1960–61 to 2002–03 with the base year 1997–98 = 100. (*b*) The rate of return on capital (□) for broadacre farms in the central agricultural region of Western Australia and rate of inflation (Δ) from 1989 to 2002. From Kingwell and Pannell (2005) with permission from **CSIRO Publishing** http://www.publish.csiro.au/ajar. The source of the original data is the Australian Bureau of Agricultural and Resource Economics (2003).

has remained reasonably steady at an average of 2% per annum from 1989 to 2000 (Fig. 3*b*). Ha and Chapman (2000) calculated that between 1977–78 and 1998–99 farm productivity in the wheat–sheep belt of Western Australia had risen at a rate of 3.5% per annum. One of the major reasons for this steady increase in productivity has been the increase in yields (Fig. 4). Yields of wheat in Western Australia increased from ∼0.73 t/ha in 1930 to 1.07 t/ha in 1980, an average increase of 7 kg/ha.year or 1%/year. In the 2 decades to 2000 the increase in wheat yields has been 40 kg/ha.year or 3.7%/year (Fig. 4*a*), the same as the rate of farm productivity. In South Australia, another state with a Mediterranean climate, yields have been more variable, but increased at a mean of 11 kg/ha.year or 1.5%/year from 1930 to 1980 and 30 kg/ha.year or 2.3%/year in the period from 1980 to 2000 (Fig. 4*b*). As wheat is not irrigated in either of these states and rainfall has not increased but has decreased over the last 2 decades (Indian Ocean Climate Initiative 2002), the increase in yield represents a significant increase in rainfall-use efficiency. The basis of this increased rainfall-use efficiency is both agronomic and genetic improvements in crop yields. However, in contrast to the observations in Western Australia and South Australia, Stephens (2002) and Connor (2004) observed no increase, and possibly a slowing, in the rate of increase of wheat yields in Victoria over the past 2 decades. This suggests that the changes observed in the Mediterranean-climatic regions of South Australia and Western Australia have not been observed in Victoria, which has only a small area with a Mediterranean-type climate.

An analysis of the gains made by the introduction of new varieties of wheat in Western Australia in the period from the 1884 to 1982 indicated that plant breeding provided

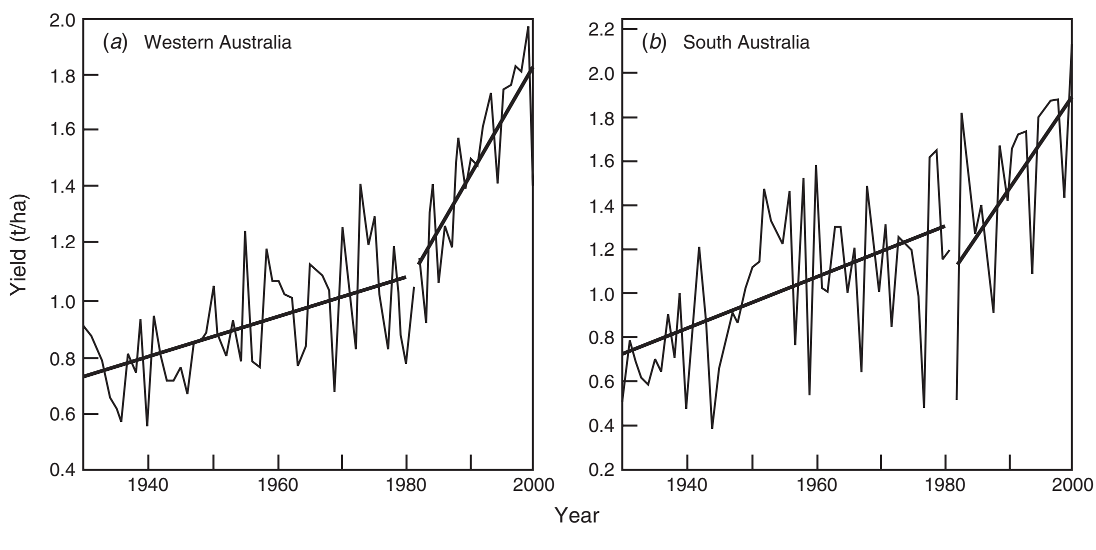

Fig. 4. Changes with time in the yield of rainfed wheat over the past 7 decades in (*a*) Western Australia and (*b*) South Australia. From Stephens (2002), used with permission from the Western Australian Department of Agriculture.

an average increase in yields of 6 kg/ha.year or 1%/year (Perry and D'Antuono 1989). This suggests that the gains before 1980 were largely the result of the breeding and the introduction of new varieties of wheat and that gains from agronomy were minimal. No studies have been conducted comparing the yield increases from new varieties since 1982, but if the rate of increase from improved genetics has remained the same, it suggests that two-thirds of the increases in yield in the 2 decades from 1980 in Western Australia and South Australia have arisen from improved management or agronomy (Fig. 5). This is further analysed by Anderson *et al.* (2005). Earlier analysis by Donald (1965) suggested that use of superphosphate fertilisers, fallowing, the introduction of pasture legumes, mechanisation, and shorter season cultivars during the first 6 decades of the 20th Century were responsible for the reversal of wheat yields that occurred with the depletion of nutrients following the introduction of agriculture in Australia in the mid-19th Century. Longer-term analyses by Angus (2001) and Connor (2004) have suggested that the increase in yields of wheat in southern Australia since 1950 has been associated with the introduction of semi-dwarf varieties of wheat, the introduction of grain legumes and canola into the rotation, the increased use of herbicides to control weeds, and increased use of nitrogen fertiliser. Thus, without another study comparing the yields of recently released cultivars of wheat with those released earlier under similar management, it is not possible to definitively identify the individual benefits of genotype and management on yield. Indeed, it is likely that it is the combined interaction of genotype by environment by management (G × E × M) by farmers that has led to the boost to yields and rainfall-use efficiency in the Mediterranean-type climates of southern Australia (Anderson *et al.* 2005).

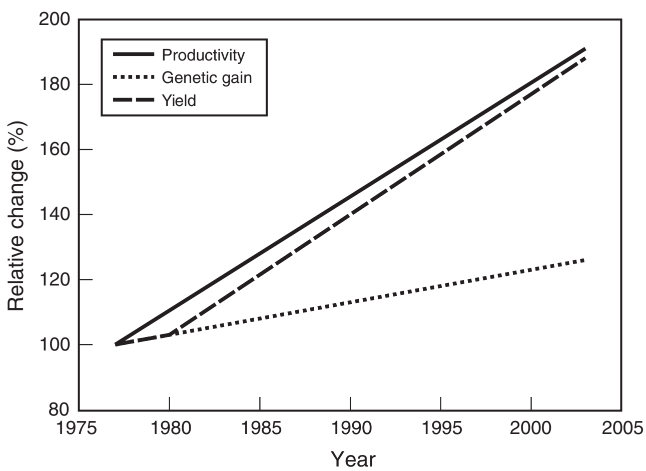

Fig. 5. Changes with time from 1977 to 2003 in farm productivity (solid line), yield of wheat (dashed line), and yields of wheat derived from use of new genotypes (dotted line). The base year 1977 = 100.

Agronomic factors influencing the yield and rainfall-use efficiency of agricultural systems

There is a range of agronomic or management opportunities for increasing the yield and rainfall use efficiency of crops and pastures in water-limited environments. These include time of planting, tillage, weed and pest control, fertilisation and liming, and rotation and fallowing (Table 1). Several of these factors interact or complement each other. For example, the introduction of minimum tillage and herbicides to control weeds has made it possible to plant earlier, and rotations can be used for weed and pest control as well as increasing the nutritional status of the soil.

Time of planting, tillage, and weed control

Time of planting has had a major effect on the productivity of agricultural systems in the Mediterranean agricultural region of Australia. Numerous studies have shown that delaying planting decreases yields in almost all crops (e.g. French and Schultz 1984*b*; Anderson *et al.* 1995; Siddique *et al.* 1998; Riffkin *et al.* 2003). A simulation analysis using 40 years of weather data showed that yields of lupine (*Lupines angustifolius* L.) in south-western Australia decreased by 0.9%/day (19 kg/day) on average for each day's delay in planting after 15 April in the low-rainfall region (230 mm growing-season rainfall), but in a high-rainfall region (390 mm growing-season rainfall), delaying planting to the end of May had no effect on simulated yields (Fig. 6). Delaying seeding by 21 days after the first sowing opportunity reduced yields of lupins by 17% and 34%, on average, in the high- and low-rainfall regions, respectively (Fig. 6, Farré *et al.* 2004). Earlier planting increases the effective duration of the growing season by better matching growth to the seasonal distribution of rainfall, reducing soil evaporation and increasing the transpiration efficiency of the crop by maximising growth when vapour pressure deficits are low in winter (Gregory and Eastham 1996; Richards *et al.* 2002; Turner 2004*b*). However, early planting is not beneficial if it exposes crops to increased disease risk, frost risk, or terminal drought. Gregory and Eastham (1996) found that early planting of wheat at a duplex soil site in south-western Australia increased yields only in 1 of the 3 years of study due to the increased biomass in the early planted crop increasing

Table 1. Agronomic and genetic options for increasing yields and water productivity in water-limited environments

Agronomic options	Genetic options
Time of planting	Phenological adaptation
Tillage	Early vigour
Rotation	Deep roots
Nutritional management	Osmotic adjustment
Weed control	Transpiration efficiency
Fallowing	Assimilate redistribution

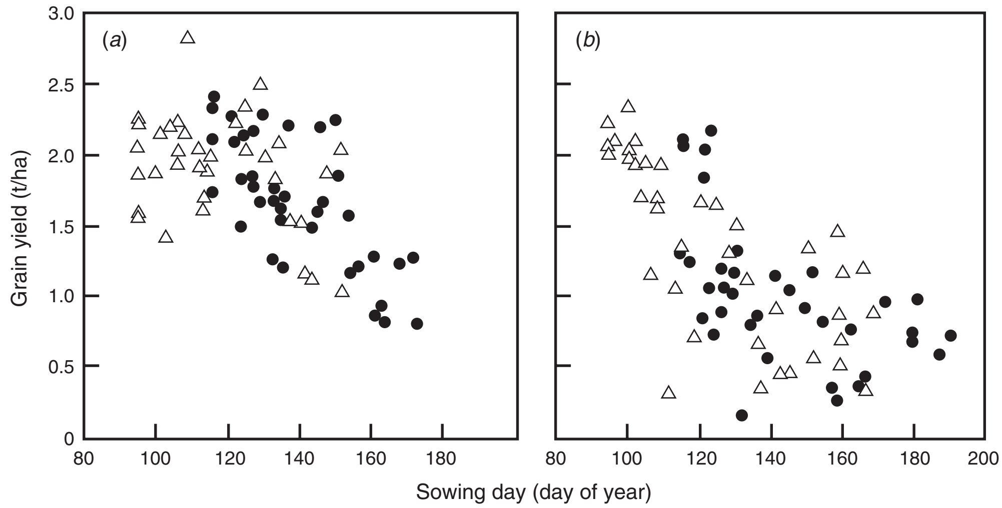

Fig. 6. Simulated narrow-leafed lupin (*Lupinus angustifolius* L.) yields for various sowing dates on a deep sandy soil for sowing at the first opportunity (△) and sowing 21 days later (●) in (*a*) a high-rainfall zone (390 mm growing-season rainfall) and (*b*) a low-rainfall zone (230 mm rainfall) of Western Australia. From Farré *et al*. (2004) with permission from **CSIRO Publishing** http://www.publish.csiro.au/ajar.

disease incidence and increasing the severity of terminal drought. Likewise, delayed planting is advocated to avoid increased disease incidence in early sown crops of field pea (Bretag *et al*. 1995) and chickpea (Abbo *et al*. 2003) for which there is little inherent disease resistance.

Earlier planting has been made possible by the widespread use of herbicides in place of cultivation to control weeds. The use of herbicides in association with minimum tillage techniques has enabled growers to seed on, or even before, the early break-of-season rains and on lower rainfall amounts. Early sowing ensures that crop growth and transpiration are much more closely matched to incoming rainfall than planting later in the season. Weeds compete with the crop for water and nitrogen (Palta and Peltzer 2001), thereby reducing yield and nitrogen uptake by the crop. Grass weeds and their residues also act as a carrier from one crop to the next for cereal diseases such as 'take-all' (*Gaeumannomyces graminis*), thus removal of grasses with herbicides in the previous crop or pasture is used to increase yield and rainfall-use efficiency (MacLeod *et al*. 1993).

Deep tillage to ~0.3 m to break up the compacted layer that develops in the soils of the region has been very effective in increasing yields in the deep sandy soils and has been widely practiced (Jarvis 1982; Perry 1986). More recently, deep ripping in association with the application of gypsum at depth to flocculate the clay subsoil has been shown to be effective in increasing yields of cereals on the fine-textured and duplex soils (Hamza and Anderson 2002, 2003).

Nutritional management

Nitrogen and phosphorus nutrition have both been shown to increase yields and rainfall-use efficiency in water-limited Mediterranean farming systems (French and Schultz 1984*b*; Shepherd *et al*. 1987; Anderson *et al*. 2005). Asseng *et al*. (2001*a*) simulated the potential yields of wheat in south-western Australia using almost 90 years of weather data and showed that increasing the nitrogen input increased yields, but had little effect on total evapotranspiration by the crop. The benefits to yield from the increased nitrogen arose from an increased water use by plant transpiration and decreased losses by soil evaporation (Asseng *et al*. 2001*a*), as was observed for increased fertiliser use in field studies with barley in Syria in which up to 120 kg/ha of nitrogen and phosphorus was applied (Gregory *et al*. 1984; Shepherd *et al*. 1987). In such field studies, the increased fertiliser application increased the biomass at anthesis and the number of ears per unit area (Gregory *et al*. 1984; Shepherd *et al*. 1987; Palta *et al*. 1994). Rather than decreasing water use in the post-anthesis period and inducing 'haying-off' (van Herwaarden *et al*. 1998), the increased fertiliser increased water use by up to 18% (Shepherd *et al*. 1987), presumably by more prolific and deeper roots, and increased yields. This increase in yield was shown to be more than 2-fold higher than the increase in total water use from an application of 150 kg N/ha in the simulation study by Asseng *et al*. (2001*a*).

Rotations

Rotations have been widely used to provide nutritional benefits to a subsequent crop. Legume-based pastures or grain legumes provide nitrogen to subsequent crops (Rowland *et al*. 1988, 1994; Perry 1992; Angus *et al*. 2001; Fillery 2001). Figure 7, taken from a long-term study in Western Australia in which the levels of soil nitrogen were followed from

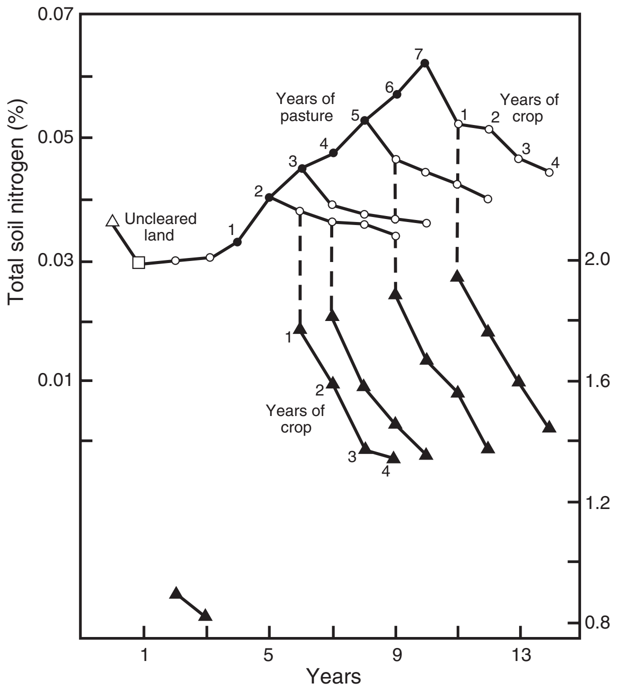

Fig. 7. Changes with time in soil nitrogen (Δ, □, ○, ●) and wheat grain yield (▲) in a long-term rotation experiment from before the land was cleared (Δ), to a fallow year (□), then cropped (○) and put into pasture (●) in the Mediterranean-climatic zone of south-western Australia. From Perry (1992), reprinted from 'Field Crop Ecosystems' (Ed. CJ Pearson) pp. 451–483, with permission from Elsevier, The Netherlands.

before the land was cleared, through a subsequent fallow year and 2 years of cropping before being put into pasture, shows that a subterranean clover-based pasture increased the total soil nitrogen by ~64 kg/ha.year (Perry 1992). Sowing wheat into these pastures caused a rapid decrease in soil nitrogen by mineralisation in the first year, with a slower decrease in subsequent years. The longer the pasture phase the higher the subsequent yields of wheat, but the decrease in soil nitrogen content with continuous cropping induced decreasing wheat yields (Fig. 7). The amount of nitrogen available to the subsequent cereal or oilseed crop depends on the proportion of legume in the pasture, the length of time in pasture, and the amount of nitrogen removed in the grain in the case of the grain legumes (Perry 1992; Evans *et al.* 2001; Peoples and Baldock 2001). Moreover, the nutritional benefit of the nitrogen from a previous legume may not simply be from the amount of nitrogen supplied, as similar amounts supplied in chemical form do not necessarily give the same yield benefit, but the distribution of the nitrogen availability during the season as the organic matter is broken down in the soil. Additionally, the benefit of a legume in the rotation may also arise from the disease-break afforded by rotation. Broad-leafed crops and legume pastures in the rotation are used to control grass weeds and prevent the carry-over of a disease such as 'take-all' to subsequent cereal crops, which reduces yield and water productivity (MacLeod *et al.* 1993). *Brassica* crops such as canola and Indian mustard have been shown to produce isothiocyanates and other breakdown products of glucosinolates from their residues, which reduces the incidence of 'take-all' and other soil-borne pathogens (Kirkegaard and Sarwar 1999; Angus *et al.* 2001), thereby increasing yields and water productivity of subsequent crops in the rotation. Conversely, cereals and legumes are used in the rotation to reduce the development of high levels of the disease black-leg (*Leptosphaeria maculans*), which reduces yield and rainfall-use efficiency of canola.

Fallowing

Fallowing, the practice of leaving land without a crop or pasture for a season (Perry 1992), has traditionally been used to increase the soil water and nitrogen available to a subsequent crop. Whereas chemical fallowing to control weeds that grow in the hot and usually dry summer season is still widely practiced in rainfed Mediterranean farming systems in Australia, fallowing for more than the summer period has largely been abandoned. The reason for this is that fallowing efficiency is generally low (Perry 1992). Stewart and Robinson (1997) have pointed out that only ~12–20% of the precipitation in the fallow period was retained by the time of sowing the following year. Likewise, O'Leary and Connor (1997) reported that the highest fallow efficiencies on clay soils with retained stubbles in southern Australia were 40% and fell away markedly if stubbles were not retained, weeds were allowed to grow in the fallow, or the soils were sandy and had low water-holding capacity. Traditionally, fallows were maintained by tillage that not only increased soil evaporation, but also made the soils much more vulnerable to wind and water erosion. Indeed, best practice retains stubble over the summer and autumn to minimise wind and water erosion and to assist in building up soil organic matter. With retained stubbles, evapotranspiration over the summer in the south-west of Australia has been shown to be negligible (Zhang *et al.* 2005).

Genetic factors influencing the yield and rainfall-use efficiency of agricultural systems

Table 1 lists the range of genetic factors that influence yields and rainfall-use efficiency in Mediterranean water-limited agricultural systems.

Early flowering

Early planting to more closely match growth to rainfall and maximise growth when vapour pressure deficits are low was shown above to be important in increasing yields and rainfall-use efficiency of crops in the Mediterranean-climatic regions of Australia. Higher yields and rainfall-use efficiency have also been achieved by breeding for earliness. For example, Siddique *et al*. (1989) showed that yields had improved in modern wheat cultivars compared with historical cultivars through the breeding and selection for earlier flowering and earlier maturity by better matching growth to rainfall distribution (Turner 2004*a*). Palta *et al*. (2004) grew rainfed lupins for 3 years at a low-rainfall site where rainfall varied among the years (see Fig. 2), and showed that the cultivars with the highest yields flowered and podded 6–10 days earlier than the low-yielding cultivars. Likewise, Berger *et al*. (2004) grew 72 genotypes of chickpea (*Cicer arietinum* L.) at 5 sites across Australia over 2 years and showed that the highest yielding group of genotypes across all sites/years was the one that flowered and podded early. In chickpea, early flowering does not necessarily result in early podding because cool temperatures prevent fertilisation and pod development (Clarke and Siddique 2004), but early phenology characterised high productivity at sites suffering terminal drought even with delayed podding (Berger *et al*. 2004).

Early vigour

On sandy soils in Mediterranean-climatic regions of Australia, vigorous early growth has been shown to increase yields of wheat (Fig. 8*a*), not because of earliness to flower, but due to greater plant biomass at anthesis, greater ear biomass at anthesis (Fig. 8*b*), deeper rooting, and greater seasonal water use (Turner and Nicolas 1998). Early dry matter production at the 5- to 6-leaf stage was linked to increased leaf area and this in turn was associated with reduced water loss by soil evaporation and increased water use as transpiration (Turner and Nicolas 1998).

A simulation exercise of the influence of the early vigour trait showed that it was only expressed if there was sufficient nitrogen available in the soil, particularly at sites with higher rainfall, and that the trait could result in reduced yields on heavy-textured soils where early water use associated with early vigour and high leaf area can result in water scarcity for post-anthesis growth (Asseng *et al*. 2003). However, on sandy soils, yield increases of 10–15% were predicted as a result of early vigour in the low- (230 mm growing-season rainfall), medium- (320 mm) and high- (390 mm) rainfall regions of the Mediterranean-climatic zone of south-western Australia (Asseng *et al*. 2003).

Deep roots

Although in some regions or seasons, rainfall may be insufficient to penetrate below 1 m (Smith and Harris 1981), the utilisation of all the seasonal rainfall frequently does not occur because it penetrates below the depth of rooting, particularly on sandy soils with high hydraulic conductivity. As mentioned above, genotypes with good early vigour also have deeper roots and reach more water in the soil profile. Breeding for deep roots for crops for Mediterranean-type environments has been extremely limited due to the difficulties of screening for this trait. Saxena *et al*. (1994) and Krishnamurthy *et al*. (1996) used a sand culture technique to screen for differences in early root growth of seedlings and then grew the plants to maturity in the field to select for more vigorous root growth in chickpea. Asseng *et al*. (2002) used a simulation model to show that a deep root trait (faster root penetration to depth) increased wheat yields by up to 20% in a deep sandy soil in the Mediterranean-climatic zone, particularly in the high to medium rainfall (320–390 mm growing-season rainfall) regions. However, the yield boost was only 10% in the same soils in the low-rainfall (230 mm growing-season rainfall) region and there were even smaller benefits on heavy-textured soils. The simulation at a series of levels of nitrogen input showed that the benefits of deeper roots decreased with increasing levels of nitrogen, suggesting that the benefit of faster and deeper roots arose from their ability to capture nitrogen that had moved down

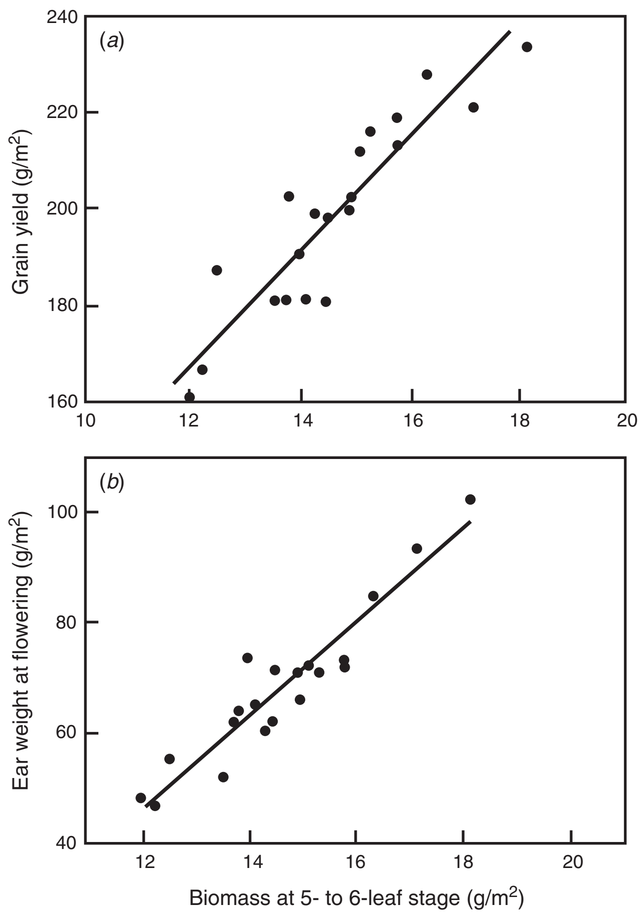

Fig. 8. Relationship between (*a*) grain yield and plant biomass at the 5- to 6-leaf stage, and (*b*) ear weight at flowering and biomass at the 5- to 6-leaf stage in 20 wheat genotypes grown under rainfed conditions in the field at Bruce Rock, Western Australia. From Turner and Nicolas (1998), used with permission.

the soil profile, as shown in the field by Delroy and Bowden (1986), rather than their ability to capture more water at the end of the season.

Osmotic adjustment

The accumulation of solutes in the leaves as water deficits develop is termed osmotic adjustment (Turner and Jones 1980) or osmoregulation (Morgan 1984). In wheat, osmotic adjustment has been demonstrated to be under the control of a single or major gene and has been shown to increase yields in water-limited environments, by increasing water uptake from deeper in the soil profile (Morgan and Condon 1986; Morgan *et al*. 1986). This has led to the development of a pollen selection technique (Morgan 1999) and the release of a wheat cultivar 'Mulgara' with high osmotic adjustment for water-limited environments (Richards 2006). The yield advantage of lines with the high osmotic adjustment gene can be double that in lines lacking the gene in severely stressing environments (Morgan 2000; Richards 2006). Not all crops grown in Mediterranean-type environments have osmotic adjustment. For example narrow-leafed lupin does not adjust osmotically (Turner *et al*. 1987; Palta and Plaut 1999). Chickpea has been shown to osmotically adjust to water deficits in some genotypes, but not in others (Morgan *et al*. 1991; Leport *et al*. 1999), but whether this provides a yield benefit under water-limited environments is disputed (Leport *et al*. 1999). As with other physiological traits, selection in breeding populations is difficult, but not impossible (Turner 2004*c*), suggesting that the development of molecular markers for selection of osmotic adjustment would be beneficial.

Transpiration efficiency

Genotypic differences in transpiration efficiency have been demonstrated in several crop species grown in the Mediterranean-climatic region of Australia. Moreover, it is a trait that has been shown to increase yields by up to 40% in wheat grown at low-rainfall sites (Condon *et al*. 2002; Richards *et al*. 2002; Richards 2006), leading to the release in Australia of two cultivars, 'Drysdale' and 'Rees', with high transpiration efficiency (Richards 2006). However, genotypes with high transpiration efficiency usually grow more slowly, due to reductions in stomatal conductance, at the vegetative growth stage, conserving soil water for the period after flowering. This is beneficial where wheat is grown on stored soil moisture in summer-rainfall regions, but does not confer an advantage in Mediterranean-climatic regions and on sandy soils where early vigour has been shown to benefit yields (Turner and Nicolas 1998). Studies reported by Condon *et al*. (2002) show that the high transpiration efficiency trait was not detrimental to yield on fine-textured soils in the Mediterranean-climatic region and a simulation analysis suggests that it may benefit yields in the region even on sandy soils if sufficient nitrogen is supplied (Asseng *et al*. 2002), but this needs to be verified by use of the newly released cultivars on the sandy soils of the region.

Assimilate redistribution

The storage of assimilates in vegetative parts of the plants for remobilisation to the grain during grain filling has been recognised as an important trait to enable continued grain filling when current assimilation is reduced due to terminal drought (Palta *et al*. 1994; Palta and Fillery 1995). Genetic variation in assimilate storage and remobilisation has been shown in wheat and chickpea (Nicolas and Turner 1993; Davies *et al*. 2000) and has been shown to maintain grain size in wheat subjected to reduced photosynthesis after flowering (Nicolas and Turner 1993). Blum *et al*. (1983*a*, 1983*b*) developed a technique of spraying the leaves of plants with a desiccant 10–14 days after flowering and comparing the grain size with those of unsprayed plants to screen for differences in assimilate storage and transfer to the grain. Nicolas and Turner (1993) modified the technique to use a rapid senescing agent, a technique that has been used to screen for assimilate storage and remobilisation for wheat for dry environments (Blum 1988) and for heat tolerance (Hossain *et al*. 1990). A simulation analysis suggested that assimilate storage and remobilisation could increase yields of wheat by 12% at moderate levels of water shortage, but had little benefit when soil water was plentiful and current assimilation was not reduced, and also when severe water shortage reduced assimilate storage and grain number (Asseng and van Herwaarden 2003).

Conclusions

In many Mediterranean-climatic regions of the world a good supply of water for irrigation is used to ensure high crop yields and to enable crops and high-value perennial species such as olives, grape vines, and fruit trees to be grown during the summer when radiation levels are high and humidities are low. In the Mediterranean regions of Australia, water for irrigation is limited and crops and pastures rely solely on rainfall. This paper has shown that farmers in the region have learned how to use the limited rainfall to produce annual crops and pastures with high rainfall-use efficiency. This high rainfall-use efficiency is based on the production of cultivars adapted to the water-limited environments and the adoption of agronomic practices that maximise water use by the crop and minimise losses by soil evaporation, runoff, deep drainage, and water use by weeds. Analysis of the rapid increase in yields over the last 2 decades in Western Australia and South Australia suggests that the adoption of agronomic practices to overcome constraints has been the primary reason for the increased yields of wheat. Longer-term analyses of yield trends in wheat (e.g. Donald 1965; Perry 1992; Angus 2001; Connor 2004) suggest that rapid increases in yield are usually followed by a decrease in the rate of increase until another technology is available and adopted. This indicates that agronomic practice and genetic improvement need to develop concurrently if yield increases are to be sustained. Thus, the search for genotypes with continued and improved disease resistance and a higher genetic potential in water-limited environments and the development of agronomic packages that maximise water use by the crop need to continue.

Although the productivity of annual crops, particularly cereals, and pastures has increased in recent years, this has increased water use to only a very limited extent (Bolger and Turner 1999; Asseng *et al*. 2001*b*) so that deep drainage of water under annual crops and pastures is significantly higher than under the perennial native vegetation cleared for the production of the annual crops and pastures. This leakage of water below the root zone has led to waterlogging and secondary salinity, particularly in the lower parts of the landscape. The reintroduction of short-term perennial species, such as lucerne, and longer-term species such as trees in parts of the landscape is aiding in the fight against waterlogging and secondary salinity (Turner and Ward 2002). However, the development of environmentally sustainable and profitable farming systems is an urgent complement to the need to continue to increase the rainfall-use efficiency of annual crops and pastures in the Mediterranean-climatic regions of southern Australia.

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