REVIEW PAPER

Increasing productivity by matching farming system management and genotype in water-limited environments

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Abstract

Improvements in water productivity and yield arise from interactions between varieties (G) and their management (M). Most G×M interactions considered by breeders and physiologists focus on in-crop management (e.g. sowing time, plant density, N management). However, opportunities exist to capture more water and use it more effectively that involve judicious management of prior crops and fallows (e.g. crop sequence, weed control, residue management). The dry-land wheat production system of southern Australia, augmented by simulation studies, is used to demonstrate the relative impacts and interactions of a range of pre-crop and in-crop management decisions on water productivity. A specific case study reveals how a novel genetic trait, long coleoptiles that enable deeper sowing, can interact with different management options to increase the water-limited yield of wheat from 1.6 t ha\(^{-1}\) to 4.5 t ha\(^{-1}\), reflecting the experience of leading growers. Understanding such interactions will be necessary to capture benefits from new varieties within the farming systems of the future.

Key words: APSIM, benchmarking, breeding, crop management, food security, soil management, water-use efficiency.

Introduction

The InterDrought conference series has emphasized that improved production in farmers’ fields in drought-prone environments demands integrated efforts of crop and soil scientists across many disciplines. Retrospective analysis of past productivity trends in such an environment, the dry-land cereal-producing regions of Australia (Fig. 1), illustrate several important points in this regard. First the challenge of limited water is clear as the country deals with the current ‘millennium drought’ and prospects of a warmer, drier future in most cropping regions under climate change (www.csiro.au/ozclim/home.do). The discontinuous yield progress highlights the significant interannual variation in yield driven by seasonal conditions (Potgieter et al., 2002), and the intermittent periods of rapid yield improvement where packages of improved management combined to allow the underlying improvements in genetic yield potential to be realized (Fig. 1).

Fischer (2009) discussed the breeding and agronomy achievements that underpinned these yield gains in Australia and estimated that around half of the 1.1% per annum yield gain arose from improved varieties (G) and genotype-agronomy (G×M) interactions, and 0.6% from improved management (M). As with other drought-prone food production systems worldwide, acceleration of yield improvement to meet the global demand for food will require genetic and management advances to be captured at an unprecedented rate within the future farming environment (E). Much of the management that influences crop production happens before a crop is sown, often by many years, and this pre-crop management is often overlooked in contemporary considerations of G×M interactions.

The aim of this paper is to broaden consideration of the M component in G×M interactions by demonstrating the relative magnitude and interactions of pre-crop and in-crop management within a farming system. These management impacts on production, and the interactions between management and new genetic traits targeting water productivity, are briefly reviewed. The Australian dry-land wheat (Triticum aestivum L. em. Thell.) production system is used to exemplify principles broadly relevant to most...
water-limited environments. A specific case study in southern Australia provides an opportunity to quantify the relative impacts of various pre- and in-crop management interventions and the way in which they interact with a novel genetic trait, long coleoptiles, to influence yield and water-use efficiency (WUE).

Benchmarking performance

Benchmarking crop performance against a biophysically defensible estimate of yield potential underpins improvement of productivity in dry-land environments. In Australia, widespread use of such benchmarks has been a hallmark of the last 30 years in agriculture. The water-limited yield benchmark for wheat (20 kg grain ha\(^{-1}\) mm\(^{-1}\) water transpired) published by French and Schultz (1984), and recently reviewed and updated (Sadras and Angus, 2006; Passioura and Angus, 2010), has provided a valuable framework to assess crop yield against a water-limited potential (Fig. 2). Despite some simplifying assumptions, such as ignoring the significant effects of seasonal rainfall distribution (Oliver et al., 2009) and evaporative demand (Rodriguez et al., 2007), the benchmark is an accessible stimulus for researchers and growers to diagnose and address factors responsible for the frequent failure of crops to achieve water-limited potential due to suboptimal management. More recently, computer-based crop simulation models such as APSIM (Keating et al., 2003) allow more site- and season-specific assessment of crop performance by accounting for seasonal rainfall distribution, evaporative demand, temperature, soil water-holding capacity, and crop management (e.g. sowing time, plant density, nitrogen). These daily time-step models are available to growers through the internet (Carberry et al., 2009; Hochman et al., 2009b) and refine attainable yield targets by separating seasonal factors beyond farmer control (rainfall distribution, high temperature) from management factors that can be improved (Hochman et al., 2009a). Regardless of the benchmark used, the framework underlying the water-limited yield potential concept first proposed by Passioura (1977):

\[
\text{Yield} = W \times \text{TE} \times \text{HI}
\]

where:
- \(W\) (water transpired)
- \(\text{TE}\) (transpiration efficiency for biomass)
- \(\text{HI}\) (harvest index)

remains a useful way to consider proposed management or genetic improvements to water-limited yield, and serves as a ‘reality check’ for proposed improvements in the ‘region of hope’ where crops apparently perform beyond currently known physiological limits (Fig. 2). The options for improving productivity based on the relationship described above are to (i) transpire more of the water made available to the crop; (ii) improve transpiration efficiency for biomass; and (iii) allocate more biomass to grain. There is considerable literature on genetic traits targeted to achieve these goals using conventional and molecular approaches (Richards et al., 2002; Reynolds et al., 2007). Several studies also report how new genetic traits interact with management to influence yield, but most focus on in-crop management such as sowing rate (Hammer et al., 2009), nitrogen management (Asseng and Turner, 2007), or fungicide application (Ransom et al., 2007). Fewer G×M studies consider pre-crop management (e.g. rotation, tillage management), although breeders appreciate these may influence variety performance (Cooper et al., 2001; Richards et al., 2007).

![Fig. 1. Trends in Australian average annual wheat yields (line) and 10 year moving average (bold) (adapted from Donald, 1965; Angus, 2001, 2009). The approximate timings of selected management (above line) and breeding innovations (below line) are indicated by arrows to demonstrate the synergies between combinations of new management strategies and underlying genetic improvements that have significant and sustained impacts on productivity. The significant falls in yield since 2002 are attributed to the prolonged and widespread millenium drought.](https://academic.oup.com/jxb/article-abstract/61/15/4129/433766)

![Fig. 2. The benchmark of water-limited yield (line) as described by French and Schultz (1984) and updated by Sadras and Angus (2006) relating wheat yield to water use. The upper boundary (22 kg ha\(^{-1}\) mm\(^{-1}\)) represents the current physiological limit for wheat against which paddock or district performance (dots) can be compared for improvement (arrow), while the credibility of proposed genetic or management improvements in the region of hope (Passioura, 2006) can also be evaluated.](https://academic.oup.com/jxb/article-abstract/61/15/4129/433766)
Genotype×management interactions—the in-crop focus

In Australia, advances in water-limited yield were initially made when crop phenology was adapted such that crops sown following autumn rains flowered after the period of significant frost risk, but matured before the onset of summer heat and drought (Woodruff and Tonks, 1983; Richards, 1991). This innovation, pioneered by Farrer at the start of the 20th century (Fig. 1), is vital for crop water economy, and through the continued efforts of physiologists and breeders is now optimal (Passioura, 2002). Growers now have a wide choice of varieties recommended for different sowing times according to the timing of the autumn planting rains, and variety selection is now a management decision (Anderson et al., 1996).

Physiologists, breeders, and agronomists have since focused on potential traits and management strategies to improve water-limited yield within the phenological window defined by sowing opportunity, flowering time, and onset of summer drought (Fig. 3A). These target canopy development to optimize the ratio of pre- and post-anthesis water use, as noted in studies on a number of determinate grain crops (Fischer, 1979; Sadras and Connor, 1991; Richards et al., 2002; Hammer, 2006; Passioura and Angus, 2010). For example, plant density and nitrogen application both accelerate leaf area development and must be managed with the balanced use of available water in mind. Deferring nitrogen inputs can minimize investment risk and maintain the green leaf area during critical periods of grain development (Fig. 3A). Several physiological studies using experiments and simulation have demonstrated the impact of both individual genetic traits and their combinations on yield in different water-limited environments (Condon et al., 2004; Rebetzke et al., 2009). In some cases, management can have impacts similar to new genetic traits. For example, management that accelerates canopy development (sowing density, nitrogen supply) can also be achieved using genotypes with inherently higher rates of leaf area development (Rebetzke and Richards, 1999). Alternatively, adjusting crop row spacing and delaying nitrogen application limits tiller formation and slows canopy development in ways similar to genotypes expressing tiller-inhibitor (tin) genes (Rebetzke et al., 2009).

Despite the possible interactions between some management and genetic interventions, few studies have investigated G×M interactions for novel traits. Recent examples include interactions between increased plant density and rooting depth on yield of new hybrid maize (Zea mays L.) genotypes in the USA (Hammer et al., 2009), and interactions between nitrogen management and early shoot and root vigour on wheat yield on different soils in Mediterranean environments (Asseng and Turner, 2007). Messina et al. (2009) point out that breeders traditionally deal with G×E, and are often less inclined to account for effects of different management (M), while agronomists often take new varieties suited to specific regions and investigate impacts of management. Cooper et al. (2001) showed that G×M represented the largest source of variation in wheat yield and protein content in multilocation breeding trials in northern Australia. They included cropping history (pre-crop management), along with sowing time, nitrogen supply, and irrigation (in-crop management) as each influenced availability of water and nitrogen during the season. Recent studies demonstrating genotypic variation in how cereal root systems adapt to the biology (Watt et al., 2005) and phosphorus status (George et al., 2009) of different tillage systems support continued investigations of broader G×M interactions.

The importance of pre-crop factors

In rain-fed environments the soil profile may not re-fill between crops, so that water use, weed seed banks, disease inoculum, residual nitrogen, and other chemical or biological legacies of previous management can affect the yield of subsequent crops (Fig. 3B). The potential for interactions between pre-crop management (e.g. long-term soil management, prior crops, and fallow management) and in-crop management on water productivity have been discussed previously (Hatfield et al., 2001; Ransom et al., 2007), but they are considered here explicitly to highlight the nature and magnitude of their impact.

Long-term soil management

Soil structural and chemical fertility. The capacity of soil to capture, store, and supply water to crops depends on its long-term management (Hamblin, 1987; Karlen et al., 1994; Hatfield et al., 2001). Retaining surface residues to protect the soil from raindrop impact and erosion (Foley and Silburn, 2002), minimizing excessive cultivation, avoiding compaction by heavy machinery or livestock, and maintaining adequate inputs of soil organic matter are all principles of conservation agriculture that maintain soil structure. In Australia, light textured and hard-setting soils with inherently low organic matter can be particularly susceptible to surface crusting, compaction, and structural decline (Chan and Pratley, 1998). Although numerous reports of reduced run-off and erosion and increased infiltration relate to temporary protective effects of residue cover, long-term changes in soil structure and run-off are often not detected even after 8 years (Packer et al., 1992). Zhang et al. (2007) showed that 24 years of conventionally cultivated soil compared with direct-drill, stubble-retained soil reduced organic carbon from 2.05% to 1.21% and infiltration rate from 85 mm h⁻¹ to 23 mm h⁻¹, although rates as low as 5 mm h⁻¹ have been reported on similar cropping soils in Australia (Chan and Pratley, 1998). Similar reductions (3-fold) in infiltration resulting from tillage and crop sequence were reported in dry areas of the northern Great Plains of the USA (Liebig et al., 2004). Actual benefits to crop yield are very specific to soil and climate, and can be overridden by factors other than water balance (Kirkegaard et al., 1995; Hatfield et al., 2001). Amelioration of compacted or impermeable layers by deep cultivation (Hamza and
application of ameliorants such as gypsum (Chan et al., 2006), or periods of pasture ley to increase subsoil macroporosity (McCallum et al., 2004) can improve water infiltration and storage and crop performance on some soils. Gradual acidification of soil in legume-based cropping systems also requires regular lime additions to avoid damage.
to root systems that reduce water and nutrient uptake (Scott et al., 2007).

Weed management. Integrated pre- and in-crop management is required to maintain weeds below damaging thresholds (Fig. 3). In Australia, this is especially relevant due to herbicide-tolerant and highly adapted weeds for which few herbicide options exist (Preston et al., 1999). The potential yield loss from weeds may exceed losses from disease or insect pests if control is poor, although the efficacy of current control measures is high (Oerke and Dehne, 2004). Managing herbicide-resistant weeds, in particular ryegrass (Lolium rigidum Gaudin) and wild oats (Avenae fatua L.), requires integrated weed management to reduce and maintain weed soil seed banks at low levels (Pannell et al., 2004). Integrated management strategies include pasture leys, crop sequences, rotating herbicide groups, hay-cutting, chaff collection, and strategic tillage and burning. Failure to adopt an integrated strategy can preclude cereal cropping if multiple herbicide-resistant weed populations develop. Impacts of fallow weed control on water-limited yield are discussed further below.

Crop and pasture sequence

In Australia, dry-land crops have been traditionally grown in sequence with phases (2–5 years) of legume-based pastures, which build soil fertility, allow maintenance of an animal enterprise, and reduce whole-farm business risk (Peoples and Baldock, 2001). The sequence of pasture, crop, or fallow preceding cereal crops has a large impact on crop water use and productivity via impacts on water and nitrogen supply, and levels of diseases and weeds (Fig. 3B). Management of annual pastures such as grass removal with selective herbicides, phosphorus and lime application, and insect control can improve legume growth, increase the levels of nitrogen fixed by the pastures (by 100–200 kg ha⁻¹ annually), reduce soil-borne diseases, and increase grain yield of subsequent crops by 30–50% (Peoples et al., 1998; Peoples and Baldock, 2001; Harris et al., 2002). Perennial pastures such as lucerne (Medicago sativa L.) can fix large amounts of nitrogen, but dry the soil profile to a greater extent than annual pastures (by up to 100–200 mm; Angus, 2001). The timing of pasture removal prior to cropping has a large effect on water and nitrogen accumulation in the soil and significant impacts on following crops (Angus et al., 2000; Lilley and Kirkegaard, 2007). The water, nitrogen, and disease legacy of pasture phases can persist for 2–3 years into cropping phases (Harris et al., 2002). During the cropping phase, fallow periods or non-cereal break crops and their management also impact on subsequent wheat crops (Kirkegaard et al., 2008). The major impacts of break crops relate to changes in levels of disease inoculum, water, and nitrogen, although other impacts on weeds and soil structure (discussed above) can also arise. The relative magnitude of these mechanisms varies with break-crop species, soil type, and seasonal conditions, and disease tolerance or resistance levels of the subsequent crop (Kirkegaard et al., 2008, Robertson et al., 2010). Impacts on yield ranging from −51% to +544% have been reported, although mean yield impacts averaged over a wide number of sites and seasons in different countries were 14–33% (Kirkegaard et al., 2008). In water-limited environments, where disease levels and nitrogen requirements are generally low, it is often the amount of residual water remaining after the break crop, and interactions with nitrogen supply, that has the biggest impact on subsequent crops (Cooper et al., 2001; Pala et al., 2007; Kirkegaard et al., 2008).

Pre-crop fallow

In most southern Australian dry-land farming systems, a fallow period of 4–6 months follows the harvest in early summer and precedes planting of the subsequent crop in late autumn (Fischer, 1987) (Fig. 3B). This ‘short’ fallow occurs when mean monthly rainfall is low (20–50 mm) and evaporation rates high (250–300 mm), but a significant portion of rain falls in large, infrequent events. Rainfall in excess of 20–30 mm can infiltrate below the evaporative zone at the soil surface, and be stored for subsequent crop growth. Fallow rainfall stored in the soil can contribute between 6% and 58% of average wheat yield in southern Australia depending on soil type and both pre-crop and in-crop rainfall patterns (JR Hunt and A Whitbread, unpublished).

Fallow efficiency, the proportion of fallow rain that is stored, is influenced by the management of weeds, crop residues, and soil tilth during the fallow. Weeds transpire water that could otherwise be used by subsequent crops (Fromm and Grieger, 2002; Hunt, 2006). Fromm and Grieger (2002) found weed control increased soil water stored at sowing by 6–21 mm depending on weed density distribution of in-crop rainfall and soil nitrogen status. In a simulation study in southern New South Wales, Lilley and Kirkegaard (2007) estimated that control of summer grass weeds increased subsequent wheat yield by 0.3–0.8 t ha⁻¹ (6–20%) depending on crop reliance on stored water. Hunt et al. (2008a) reported data showing that control of fallow weeds led to an additional 70 mm of soil water available at sowing, increasing subsequent wheat yield by 1.3 t ha⁻¹. Weed control has the biggest impact on grain yield when pre-crop rainfall is high and subsequent in-crop rainfall low. Some summer-growing tap-rooted weed species, in common with lucerne, are capable of drying soil to a greater extent than wheat, and if uncontrolled can leave soil in water deficit for subsequent crops. Summer weeds can also form a ‘green bridge’, hosting root diseases such as root lesion nematodes (Vanstone and Russ, 2001), take-all, and Rhizoctonia (Roget et al., 1987), as well as vectors for viral diseases such as wheat streak mosaic virus (Ellis et al., 2003) which reduce the yield of subsequent crops. In mixed farming systems it is common to graze weeds in summer fallows, but total transpiration is unlikely to be reduced through grazing (Fischer, 1987), and grazed weeds retain their disease host status. Significant mineralization of
organic nitrogen follows rain during the fallow, a major resource for subsequent crops (Angus et al., 1998). Fallow weeds reduce mineral nitrogen by drying the soil and by accumulating nitrogen which is not immediately available for subsequent crop growth. In some instances, nitrogen dynamics alone explain the negative impacts of pre-crop fallow weeds on subsequent crop growth (Osten et al., 2006).

Retaining crop or pasture residues on the soil surface improves fallow efficiency by minimizing the physical impact of raindrops on the surface soil, maintaining structural integrity and infiltration rates, and reducing run-off (Felton et al., 1987). Residues slow the flow of water on the soil surface, allowing more time for infiltration (Freebairn and Boughton, 1981) as well as slowing soil evaporation following rainfall events. If conditions remain dry for an extended period, total evaporation will be unaffected by residues (Felton et al., 1987). As a result, increases in fallow efficiency due to reduced evaporation are minor, and occur only when large amounts of residue are present and rainfall patterns favourable (Schultz, 1972; Felton et al., 1987; Browne and Jones, 2008), or in fallows of >6 months duration (long fallows; Ridge, 1986; Fischer, 1987), particularly on dark, heavy textured soil types prone to evaporation (O’Leary and Connor, 1997). Ward et al. (2009) measured a small increase in evaporation rates from standing wheat stubble compared with bare earth, which they hypothesized was due to intact xylem vessels acting as a hydraulic link between the moist subsoil and atmosphere. However, the difference was not sufficiently large to change the amount of water available at sowing of the subsequent crop. Fischer (1987) reports that 0.2–0.3 mm rain t−1 of horizontal stubble can be intercepted and retained on the soil surface. Residues also reduce fallow efficiency by allowing weeds to establish where they would otherwise not (Moore, 1956), and by reducing fallow herbicide efficacy.

Tillage influences fallow efficiency through numerous mechanisms that depend on site and season relating to weeds, surface residues, soil structure, and micro-relief, which have been extensively described and reviewed (Fischer, 1987; Hatfield et al., 2001), and are not considered in detail here. Tillage can cause an increase or decrease in fallow efficiency depending on specific circumstances, but most authors agree that the greatest and most reliable influence of tillage on fallow efficiency is through weed control (Fischer, 1987).

In search of synergies

Separately, the pre-crop management factors discussed above can influence the water, nitrogen, weeds, and diseases encountered by subsequent crops to give yield impacts of well over 100%. Interactions among these and in-crop management are inevitable, as represented by the overlapping influences shown in Fig. 3B. Synergies between combinations of management strategies have underpinned the periods of rapid yield increases shown in Fig. 1. For example, the widespread introduction of lupin (Lupinus angustifolia L.) and canola (Brassica napus L.) as break crops reduced levels of root disease and grass weeds in wheat crops and, in conjunction with selective herbicides, facilitated earlier sowing using no-till, stubble-retained seeding systems. Disease-free crops were more responsive to applied nitrogen fertilizer, and lime applied to, and paid for by, the responsive, acid-sensitive canola also provided benefits to the wheat in some areas which had previously been insufficient to make it economic. This package of pre- and in-crop management together with favourable rainfall allowed the higher yield potential of semi-dwarf wheat varieties, introduced earlier into Australia (Fig. 1), to be realized. Interactions among novel genotypic traits targeted for improved performance under drought (Condon et al., 2004; Reynolds et al., 2007) and between genotypic traits and management in different environments (Asseng and Turner, 2007; Hammer et al., 2009) have also been investigated, generally using simulation due to the many complex interactions that arise. Asseng and Turner (2007) simulated the relative and combined impacts of five novel wheat traits on yield for different soils and management in Western Australia. Increased rooting depth was predicted to have the biggest impact on sandy soils under low nitrogen application (15% increase) but had little impact when nitrogen application was high, or on clay soils at any nitrogen level. Some traits alone reduced yield under certain conditions, but combined with other traits to increase yield. Faster productivity improvements will come from embracing these G×M interactions. Farming systems simulation provides a tool to investigate the potential impacts of these management and genetic adaptations under current and future climates (Hunt et al., 2008b), and to quantify the likelihood of achieving production gains.

A case study—wheat production in the southern Mallee, Australia

Background

The southern Mallee region of north-western Victoria has a variable climate typical of Australia’s water-limited grain-growing regions (Fig. 4). Growing season rainfall (April to October) varies by a factor of six (Fig. 5a), and over the last century there have been periods marked by series of both above- and below-average rainfall. The last decade has been notably dry (millennium drought) and is unprecedented in the collective experience of contemporary farm managers, although it has historical precedence (Fig. 5a). However, the effects of the millennium drought on crop production have been further exacerbated by increased evaporative demand (Fig. 5b) and extreme temperatures during the critical anthesis period (Fig. 5c, d), a pattern predicted to continue (www.csiro.au/ozclim/home.do).

This sustained change in production climate (E) combined with declining terms of trade has forced Australian farmers to adapt their management in order to remain
profitable. Genetic adaptations cannot be deployed with sufficient speed to maintain productivity in the face of such rapid change, and adaptive management has been the only way for growers to remain profitable. Deployment of new genotypes incorporating targeted traits to improve performance in water-limited environments continues in parallel, and strategies for success are discussed by Rebetzke et al. (2009). Ultimately the most rapid progress in productivity will arise from synergistic combinations of new traits with appropriate management. To exemplify this, a simulation case study based on a commercial farm in southern Australia is presented in which both pre-crop and in-crop management changes made by the farm managers are simulated. Individual and combined impacts of selected pre-crop (long term, crop sequence, and fallow) and in-crop management changes on productivity and WUE are quantified. In addition, interactions with a novel genetic trait (long coleoptiles) thought to have significant potential to synergize with modern management practices to improve productivity are investigated.

Modelling methods

The production model APSIM 7.1 (www.apsim.info, Keating et al., 2003) was parameterized for a commercial farm 25 km south east of the township of Kerang (35°49′46″ S 143°44′2″ E) in the Victorian Mallee (Fig. 4). APSIM has been widely validated for simulating the impacts of a range of crop management and environmental factors on wheat yield in Australia (Carberry et al., 2009). Yield Prophet® (www.yieldprophet.com.au, Hochman et al., 2009b), the commercial web-based form of APSIM, has been used by the Kerang farm managers since 2005. Consequently an existing APSIM soil parameterization existed (Dalgliesh et al., 2009) and simulation of crops at the site formed part of the Yield Prophet® validation reported by Hochman et al. (2009a). Climate data from 1889 to 2009 for Kerang were taken from the patch point data set (Jeffrey et al., 2001). The general farming system and evolution in management is representative of many progressive grain-growing farms in low-rainfall Mediterranean regions of Australia (Kirkegaard et al., 2010). Six continuous 48 year simulation scenarios (1962–2009) were created based on the generalized evolution in pre-crop and in-crop management made by the farm managers during this period (Table 1). All simulations began on 1 January 1962 with soil water set at the crop lower limit of wheat (0 mm of plant-available water).

Scenario descriptions

Scenario 1 (baseline) represents a conventional tillage system typical of regional practice until the late 1980s, and still practised by farm managers unable or unwilling to adapt their system. The effect of autumn stubble burning was captured by the APSIM Surface Organic Matter module by resetting residue from the previous crop to 500 kg ha−1 of stubble on 1 April each year. The same module applied tillage by incorporating 80% of remaining surface residue on 15 April, 1 May, and at sowing. To reflect lower infiltration rates caused by soil structural decline in tilled and trafficked soils (Chan and Pratley, 1998; Hatfield et al., 2001), the Natural Resource Conservation Service (NRCS) curve number (Rallison, 1980) used by the APSIM SoilWat module (CN2Bare) was set at 85. Time of sowing in all simulations was determined by a rainfall rule in which >15 mm rain must fall over a maximum of 3 d during the sowing windows specified in Table 1.

Scenario 2 (Stubble retention) represents the minimum till, retained-stubble farming systems that developed during the 1980s and have been increasingly adopted since in response to increasing concern about soil and wind erosion (Chan and Pratley, 1998) and to improve crop production (D’Emden et al., 2008). All stubble from the previous crop is retained as surface organic matter until sowing, when 40% is incorporated by the sowing operation. The NRCS curve number is set at 60 to reflect the better infiltration rates found in reduced tillage systems (Freebairn and Boughton, 1981). As an example of how this change affects the water balance, following a 92 mm rain event in late spring 1998 run-off decreases from 10 mm in the baseline Scenario 1 to 0 mm in Scenario 2. In both Scenarios 1 and 2, soil water content is reset to the crop lower limit of wheat on 31 March to represent a situation where uncontrolled fallow weeds use all of the water that would otherwise have been stored (Fromm and Grieger, 2002; Hunt et al., 2008a). This is in contrast to Scenarios 3–6 where complete fallow of all stubble from the previous crop was captured by the APSIM Surface Organic Matter module applied tillage by incorporating 80% of remaining surface residue on 15 April, 1 May, and at sowing. To reflect lower infiltration rates caused by soil structural decline in tilled and trafficked soils (Chan and Pratley, 1998; Hatfield et al., 2001), the Natural Resource Conservation Service (NRCS) curve number (Rallison, 1980) used by the APSIM SoilWat module (CN2Bare) was set at 85. Time of sowing in all simulations was determined by a rainfall rule in which >15 mm rain must fall over a maximum of 3 d during the sowing windows specified in Table 1.

Scenarios 1, 2, and 3 involve a continuous wheat sequence, reflecting the cereal monoculture that dominated prior to the 1980s, and have re-emerged in response to the
millennium drought as the high risk and drought-sensitive break crops such as canola and lentils (*Lens culinaris* Medik.) were increasingly abandoned (www.abareconomics.com/interactive/agsurf/). Cereals generally use all of the plant-available water in a given season, and no residual water remains for the next crop in the sequence. In Scenario 4 (Crop sequence), a forage field-pea crop (*Pisum sativum* L. var. Morgan) is introduced into the sequence which is cut for hay at early pod-set (October), leaving on average 29% cover. On the commercial farm, introduction of this crop in 2005 provided the managers with a low risk break crop that remained profitable in dry years, and provided residual water for the subsequent wheat crop. Two separate simulations of field-pea/wheat sequence were offset such that for

![Fig. 5.](https://academic.oup.com/jxb/article-abstract/61/15/4129/433766)

Fig. 5. (a) April to October rainfall for Kerang since records began in 1889; (b) April to October potential evapo-transpiration for Kerang since evaporation measurements began in 1970; (c) the number of days per year at Kerang in which maximum temperature exceeds 32 °C during September and October since temperature measurements began in 1962; (d) the number of days per year at Kerang in which minimum air temperature is <2 °C during September and October. Bars represent totals for individual years; the solid black line is a 10 year running mean.
the simulation a wheat crop was grown in every year of the climate record. In reality at the farm scale, this management change would reduce the overall number of wheat crops, and thus total farm wheat production. However, the aim was not to compare the water productivity or profitability of different crop sequences, but to quantify the impact that crop sequence can have on subsequent wheat yield. The disease, weed, and nitrogen benefits of the break crop, although likely, were not simulated, so the sequence impacts relate only to effects on the water balance.

In Scenario 5, an earlier sowing window (starting 25 April), which shifts mean sowing date from 25 June to 24 May, was included to reflect the lowered risk afforded by sowing earlier into the stored soil water preserved by improved infiltration, fallow weed management, stubble retention, and forage peas in the sequence. Earlier commercial sowing times reflect grower response to observations of a stronger than usual relationship between sowing date and grain yield due to the hot, dry springs experienced more consistently during the millennium drought (Fig. 5).

Finally, in Scenario 6, the potential impact of a novel genetic adaption is investigated, namely a wheat cultivar with a long coleoptile (Rebetzke et al., 2007) that could be sown deeply (110 mm) into soil water remaining from the previous field-pea crop and fallow period (Fig. 6). This trait would facilitate sowing on a specific calendar date, as soil water to germinate the crop is usually available at that depth in April, but is too deep for current short-coleoptile wheat varieties sown only after an opening rain. Such a trait controls the timing of crop emergence and phenological development, and provides more opportunities to capture the benefits of timely sowing on a range of soils (Stapper and Fischer, 1990). Deep, moisture-seeking sowing tines allow this with current varieties, but the practice is restricted to black clay soils in the northern grain-cropping region of Australia which have low bulk density and do not set hard following rainfall.

In order to show how pre-crop management and in-crop management can interact to change yield and WUE outcomes, each of the management changes was also simulated individually and compared with the baseline scenario (Scenario 1). In all simulations, soil nitrate in the top three soil layers was maintained above 100 kg ha$^{-1}$ so that nitrogen availability did not limit yield. As APSIM does not model the effects of weeds, pests, diseases, frost, or excessive heat, the yield values reported here are water-limited, attainable yield; that is, yield achievable given skilful use of available technology (Sadras and Angus, 2006) and ignoring constraints placed on realized farm yields by operational considerations and input risk aversion. Thus the sole impact of management on simulated yields is related to water-limited productivity.

For all simulations, a mid-early maturity variety parameterization was selected from the APSIM Wheat module to represent the cultivars grown in the region (e.g. Yitpi and Table 1. The management scenarios simulated for the Mallee case study farm in APSIM 7.1

| Scenario | Management option |
|----------|-------------------|
|          | Tillage system (Long term) | Stubble retention (Long term) | Fallow weed (Fallow) | Crop sequence (Sequence) | Sowing window (in-crop) | Coleoptile length (Genetic) |
| 1. Baseline | Three cultivations prior to sowing and full disturbance at sowing | Burnt in autumn | No control until autumn | Wheat–wheat | 21 May–1 August | Short |
| 2. Stubble retention | Direct drill, min-till | Fully retained | No control until autumn | Wheat–wheat | 21 May–1 August | Short |
| 3. Fallow weed control | Direct drill, min-till | Fully retained | Full control | Wheat–wheat | 21 May–1 August | Short |
| 4. Crop sequence | Direct drill, min-till | Fully retained | Full control | Forage peas–wheat | 21 May–1 August | Short |
| 5. Early sowing | Direct drill, min-till | Fully retained | Full control | Forage peas–wheat | 25 April–July | Short |
| 6. New genotype (long coleoptile) | Direct drill, min-till | Fully retained | Full control | Forage peas–wheat | 20 April | Long |

Fig. 6. A comparison of coleoptile length in current semi-dwarf wheat varieties (right: 3 cm) and a long-coleoptile breeding line (left: 15 cm) developed by CSIRO Canberra. Long-coleoptile lines can successfully emerge when sown at depths of 15 cm into stored soil water. Photo courtesy of Dr Greg Rebetzke, CSIRO Canberra.
Correll). Frost risk will increase for these maturity types under earlier sowing scenarios (Scenarios 5 and 6) and, although the increased risk can be predicted by the model, the impact on yield is not explicitly simulated. This interaction between simulated attainable yield and frost risk for early-sown scenarios is discussed in more detail below. All crops were sown at a density of 150 plants m$^{-2}$ and 0.21 m row spacing. Water use is defined here as the sum of evaporation, transpiration, drainage, and run-off from sowing to harvest. WUE is final grain yield divided by water use. All grain yields are reported at 0% moisture.

Simulation results

The impact of management changes on mean simulated yield and WUE over both the 48 year and 10 year period are considerable and cumulative within the scenarios simulated (Tables 2, 3). However, the relative magnitude of the benefits arising from the different pre-crop categories discussed above (long term, sequence, and pre-crop fallow) varies, and synergies are evident, both within the pre-crop management and with the in-crop management and novel genetic trait considered.

The simulated change in farming system from the baseline scenario to direct drill and stubble retention (Scenario 2) increased water storage and yield by a modest amount over the historic (48 year) simulation and, perhaps surprisingly, by a slightly smaller margin proportionally during the millennium drought (10 year) period (Tables 2, 3). The change in the susceptibility of soil to run-off due to improved structure (simulated by the decreased NRCS curve number) and increased surface organic matter reduced the proportion of run-off and evaporation relative to total water use, but without fallow weed control there was no increase in water storage by 1 May (Table 2). However, by improving the in-crop water balance, this management change improved yields in all years of the simulation, increasing the mean, median, and lowest yield achieved (Fig. 7), albeit by a relatively small margin.

The small impact on yield, which did not improve in drier years, is consistent with the results of long-term experiments throughout southern Australia where tillage and stubble treatments were imposed under otherwise identical management, including sowing dates (Kirkegaard et al., 1995). This emphasizes that responses to reduced tillage and stubble retention alone may be small, or even negative, where biological constraints such as weeds, stubble, or soil-borne diseases, not accounted for in this simulation, arise. In contrast, the largest increase to water available on 1 May, yield, and WUE (Table 2) was achieved by improved weed management during the pre-crop fallow period (Scenario 3). This significantly increased water use, and also improved WUE by increasing the average harvest index (data not shown) as more water was available during the critical period (Sadras and Connor, 1991; Kirkegaard et al., 2007). During the millennium drought period this management change provided a similar absolute yield increase, and thus a much greater proportional yield increase (doubling), to that in the 48 year period. This is because the water stored during the summer fallow during the millennium drought represents a much greater proportion of the total water available to the crop, and because conditions during the critical period in spring were hot and dry in those years (Fig. 5). A somewhat lower absolute yield increase arose when fallow weed management was introduced alone (Table 3) because the soil cover and superior infiltration rates offered by reduced tillage and stubble retention are needed to maximize fallow efficiency. Scenario 3 generated similar minimum yield, higher maximum yield, no negative yield responses, and an increase in median yield of 1000 kg ha$^{-1}$ (Fig. 7). The introduction of forage peas into the rotation (Scenario 4) also increased water supply carried over to the wheat crop (Table 2) and effectively acted in the same manner as fallow weed management to improve yield, but to a slightly smaller extent. However, when added alone, the impact of the forage peas was diminished (by 76% in absolute terms) because the water used by weeds allowed to grow in the subsequent fallow, and water lost from bare, cultivated soil, reduced the residual water left by the peas that would be otherwise conserved. The proportional impact of the forage peas added alone was similar in the historical and millennium drought periods (10% and 11%) but in combination provided a trebling of the proportional increase during the millennium drought period (from 41% to 122%). This was presumably due to the deeper storage of the preserved water and its availability during the dry spring

### Table 2. Mean simulated yield and water-use efficiency from the different scenarios for all years (1962–2009) and the millennium drought period (2000–2009)

| Scenario | Management lever | All years | 2000–2009 |
|----------|-----------------|-----------|-----------|
|          | Mean plant available water on 1 May (mm) | Mean grain yield (kg ha$^{-1}$) | Mean WUE (kg ha$^{-1}$ mm$^{-1}$) | Mean plant available water on 1 May (mm) | Mean grain yield (kg ha$^{-1}$) | Mean WUE (kg ha$^{-1}$ mm$^{-1}$) |
| 1 Baseline | 9 | 1574 | 6.0 | 5 | 416 | 2.4 |
| 2 Stubble retention | 10 | 1811 | 6.8 | 5 | 468 | 2.7 |
| 3 Fallow weed control | 51 | 2767 | 9.6 | 38 | 1403 | 6.2 |
| 4 Crop sequence | 91 | 3414 | 11.1 | 64 | 1910 | 8.1 |
| 5 Early sowing | 94 | 3977 | 12.9 | 66 | 2234 | 9.5 |
| 6 New genotype | 103 | 4539 | 15.2 | 74 | 3078 | 12.6 |
than to either treatment imposed alone (Ransom et al., 2007), and relate primarily to improved water supply. This provides the most obvious example of the impacts of synergies which can arise between management strategies. The impacts of the pea break crops on both reducing disease levels and increasing nitrogen availability are further benefits, albeit generally lower in dry environments, which have been widely reported (Kirkegaard et al., 2008) but are not accounted for in this simulation. At the farm scale, overall wheat production may be reduced as the proportion of pea forage crops in the sequence is increased. Ultimately the optimum proportion of break crops to maximize productivity and profitability is influenced by relative economics, the realized wheat yield increase (as simulated here), as well as operational advantages and risk reduction that they provide (Robertson et al. 2010).

Sowing early (Scenario 5) increased yield significantly in both the historic and millennium drought period (Table 3), independently of stored water at 1 May (Table 2) due to more efficient in-crop water use. However, sowing wheat early or ‘dry’ immediately before or after the autumn rains is an adaptation only made possible by the exceptional weed control provided by the forage pea break crop, good fallow management, and, often, the action of surface stubble retaining early autumn rain at the surface. The managers of the case study farm were alerted to the potential value of early sowing when Yield Prophet® simulations indicated a greater penalty existed for delayed sowing when water was available (i.e. after pea forage) than when it was not. Unlike the previous three management changes, sowing early can have a ‘downside’ in that it lowered the highest yields achieved in the simulations, and in eight seasons reduced yield compared with the baseline scenario (Fig. 7). This happened in years with cool, wet springs in which early-sown crops matured too early to take advantage of these ideal grain-filling conditions compared with later sown crops. However, this spring rainfall was preserved during the fallow period and reflected in a small increase in stored water on 1 May (Table 2). Sowing early also increased the simulated incidence of frost (defined as a minimum temperature <2 °C) during the critical flowering period from 4% to 17% of years for wheat varieties with early-mid maturity. The experience of the farm managers has been that the risk of frost in some years has been more than offset by increased yield potential and avoidance of heat stress in most years. However, this simulation does highlight that increased incidence of frost damage is likely to moderate the yield levels predicted for these early-sown simulations and that frost-tolerant wheat would be a valuable genetic trait for this farming system.

The genotypic adaptation of a long coleoptile provided an opportunity for a fixed, early sowing date and generated further benefits in combination with the other management improvements discussed (Scenario 6). It generated particularly large yield advantages (more than double) in the millennium drought years than in all years (Table 3) for the same reasons discussed above for earlier sowing. However, this adaptation generated a yield decrease when added individually, because unless this trait is used to optimize flowering time by sowing deeply in the presence of stored water from the pea crop, good fallow management, and improved soil and stubble management, there was a yield penalty due to delayed emergence from a sowing depth of 110 mm (Table 3). This demonstrates how fruitless development and deployment of such traits can be if...
consideration is not given to how they should be managed in specific environments. Some yield penalties compared with Scenario 5 (in 13 seasons) may also have occurred in years where late rains could not be captured by these earlier maturing crops (Fig. 7). However, in combination with the other management options in Scenario 6, yield variability and hence business risk was considerably reduced along with the higher mean (Table 2) and median yields (Fig. 7). Some moderation of the predicted overall yield increase would need to be made as the frost risk associated with the earlier sowing for these varieties increased from 17% in Scenario 5 to 35% in Scenario 6.

When added individually to the baseline scenario, all of the management changes gave an increase in productivity that was less than when they were added in combination (Table 3). This illustrates the point that management effects, pre-crop, in-crop, and new genetic traits, can synergize to provide greater productivity gains.

**Future challenge**

The case study provided here illustrates the importance of understanding pre-crop management impacts within G×M interactions yet is relatively simplistic in the context of all of the management interactions possible (Fig. 3) and the many genetic traits under investigation (as discussed within the InterDrought conference). Table 4 provides a summary of selected management and genotypic traits that have been investigated specifically to improve productivity in water-limited environments, organized by the time at which the effects of each are most apparent during the cropping cycle. Those considered in the case study, selected to emphasize the interactions between some pre-crop and in-crop management options and a single novel genetic trait, represent a very small subset of the potential management and genetic options available (Table 4). Yet depending on how they were combined, various options could either reduce mean yield from the baseline of 1574 kg ha⁻¹ to 1420 kg ha⁻¹ (where long coleoptile was adopted alone), or increase yield to 4539 kg ha⁻¹ (all management and genotypic improvements combined in Scenario 6) (Table 3). The magnitude of yield response to some of the genetic traits listed in Table 4 has been simulated, and in some cases measured, and the potential for separate or substitutive effects, and synergistic or antagonistic interactions, reported (Condon *et al.*, 2004; Manschadi *et al.*, 2006; Asseng and Turner, 2007; Reynolds *et al.*, 2007; Semenov *et al.*, 2009). Genotypic traits alone or in combination are often reported to generate potential yield benefits of 5–30%, and in some studies important interactions with soil type and nitrogen management also dramatically influenced the outcome (Asseng and Turner, 2007). Despite the many assumptions made by necessity in this and other simulation studies, they reflect the reviewed experimental evidence and the experience of progressive farmers who have modified their management according to some of the scenarios considered. In the search for accelerated productivity improvements to meet future global food demands, research and development approaches will need to better understand and embrace these broader G×M interactions in ways that are less retrospective or serendipitous, through closer interactions between agronomists and breeders.

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