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Water-use efficiency of dryland canola in an equi-seasonal rainfall environment

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Abstract. The French and Shultz approach that relates seasonal rainfall to potential yield in wheat has yet to be applied to dryland canola. Relationships were derived between grain yield of 42 experimental crops (yield range 0.5–5.4 t/ha) free of weeds, pests, diseases, and nutrient deficiencies in southern New South Wales, and various measures of observed (rainfall, available soil water) and simulated (evapotranspiration) seasonal water supply. April to October rainfall and in-crop rainfall were the poorest predictors of yield ($R^2 < 0.5$). By adjusting in-crop rainfall to account for stored soil water at sowing and that remaining at harvest (termed 'seasonal water supply'), 68% of the variance in yield could be explained. Estimates derived using the APSIM-Canola simulation model or simulated totals of evapotranspiration or transpiration explained 73–82% of the variance. The slope of the regression line between yield of the 42 crops, which simulation indicated had all yielded to their water-limited potential, and seasonal water supply (termed here the water-use efficiency for grain production, WUE) was 11 kg/ha.mm above an intercept of 120 mm. WUE varied from 4 to 18 kg/ha.mm and the upper boundary for WUE in those seasons where rainfall distribution facilitated maximum efficiency was 15 kg/ha.mm. Long-term simulations, conducted at locations with mean annual rainfall of 430–660 mm, confirmed the variability of WUE due to rainfall distribution and also that WUE would be expected to decline, on average, by one-third between sowings in early April and early July. This necessitates caution in accepting a single WUE value as an indicator of agronomic constraints to yield. For the purposes of practical application by farmers and advisors, water-limited potential yield can be calculated in the region as a function of seasonal water supply minus 120 mm up to a limit of 450 mm, beyond which potential yield is not limited by water. Available soil water at sowing can be estimated from summer fallow rainfall above a threshold of 80 mm, and water remaining at harvest can be estimated from post-anthesis rainfall above a threshold of 50 mm. This improved method for estimating water-limited potential yield in canola retains the ease of use of the French and Shultz approach, so that other constraints to yield can be more accurately diagnosed in dryland environments by farmers and advisors.

Additional keywords: rainfall, evapotranspiration, soil evaporation, simulation models, APSIM, available soil water, yield, sowing date.

Introduction

The generally low and variable rainfall of the Australian wheatbelt has led to a focus on relationships between rainfall, water use, evapotranspiration, and the degree to which these limit grain yield (French and Schultz 1984; Perry 1987; Cornish and Murray 1989; Angus and van Herwaarden 2001). The best-known attempt in Australia to calculate potential yield from potential water use is that of French and Schultz (1984). They examined the relationship between wheat yield and April–October rainfall as a surrogate for water use in a group of surveyed crops, by drawing a line that defined water-limited yield and enclosed most of the high-yielding crops at different levels of water use. This line is somewhat arbitrary, with some physiological justification, but farmers, advisors, and researchers have used it extensively to estimate potential yield and as an indication of whether a crop yield is limited by the water supply or some other factor. The information helps them decide where improvement in management is needed. Others have adapted the concept to winter grain legumes (Siddique *et al*. 2001), summer grain legumes (Robertson *et al*. 2000) and maize (Robertson *et al*. 2003).

Several authors have pointed out the limitations of the French and Schultz (F&S) approach (e.g. Perry 1987; Cornish and Murray 1989; Connor and Loomis 1991): that it takes no account of the timing of rainfall in relation to crop development, it assumes that runoff and deep drainage losses

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are negligible, it ignores the contribution that stored soil water may make to crop water use, and assumes that all rainfall received during the season contributes to yield. Many of these limitations can be discounted. For example, runoff and deep infiltration are often negligible in the subhumid and semi-arid regions of the temperate environments of the Australian wheatbelt. Also, in Mediterranean climates where summer rainfall is often low, the contribution of stored soil water to crop water use is small. Despite these limitations, the F&S approach remains popular because farmers can readily calculate it without relying on more complex methods such as the use of simulation models.

Although the F&S approach has been applied extensively to wheat in temperate areas of the Australian wheatbelt there are few published attempts at deriving a relationship between potential yield and water supply for canola (*Brassica napus* L.). Hocking *et al*. (1997) plotted yield of canola against water use from a study with different sowing dates over 2 seasons and sites in southern New South Wales. Water use was calculated as rainfall during crop growth plus soil water depletion as measured by soil cores. They proposed that a line with an intercept on the water-use axis of 110 mm and a slope of 12.5 kg/ha.mm represented the water-use efficiency (WUE) frontier. In the semi-arid subtropics, Cocks *et al*. (2001) found that WUE for 15 well-managed crops of cv. Monty measured across 3 seasons varied from 3 to 18 kg/ha.mm. Long-term simulations confirmed this variability and suggested an upper limit of about 13 kg/ha.mm, similar to that found by Hocking *et al*. (1997). Apart from these 2 studies there has been no comprehensive assessment of the relationship between water supply and grain yield of canola, with an attempt to derive a potential yield–water-use relationship similar to that derived for wheat by French and Schultz (1984). The main aim of this paper was to derive relationships between potential yield and water supply using a large dataset of well-managed dryland canola crops from southern NSW, which were kept free of weeds, pests, and diseases. In such field studies it is often difficult and expensive to measure all of the components of the crop–soil water balance. Here we explore the use of a well-validated simulation model to infer components of the water balance on the basis of demonstrating that the model can adequately simulate yield over the wide range of conditions represented in the dataset. Long-term simulations with historical climate data were then used to test the generality of the relationships derived from the experimental sites for a wider range of seasons and locations. In addition to this main aim, we also sought to derive a refinement to the F&S approach by considering the contribution of stored water at sowing towards crop water supply, and by discounting soil water remaining at harvest. Stored water at sowing and rainfall close to crop harvest are both likely in the equi-seasonal environments of southern NSW. To retain the utility of the F&S approach while improving estimates of seasonal water supply for farmers and advisors, simple rules-of-thumb were developed from rainfall data to account for stored water at sowing and water remaining at harvest.

Methods

Relationships were derived between grain yield of 42 crops (Table 1) and various measures of seasonal water supply: April–October rainfall (French and Schultz 1984), rainfall between sowing and crop harvest (hereafter termed in-crop rainfall), in-crop rainfall plus available stored soil water at sowing, in-crop rainfall plus available stored soil water at sowing minus simulated available soil water remaining at harvest (termed here 'seasonal water supply'), in-crop evapotranspiration and transpiration. While measured data for rainfall and available stored soil water at sowing were available for each of the crops, other data (available soil water remaining at harvest, in-crop evapotranspiration, and transpiration) were not and these were estimated using the Agricultural Production Systems Simulator (APSIM) (Keating *et al*. 2002). APSIM has been extensively validated in this region for a range of dryland crops and pastures, their water and nitrogen use, and other components of the water balance such as deep water loss (Asseng and van Herwaarden 2003; Lilley *et al*. 2003; Verburg and Bond 2003). Confidence in using simulation to estimate water-balance components was predicated on an ability to simulate a wide range of crop yields in the dataset, as well as soil water accumulation over the summer fallow (i.e. from the harvest of the previous crop), and in a few cases, available soil water remaining at harvest. The APSIM-Canola module has previously received testing in the semi-arid subtropics of southern Queensland and northern NSW (Robertson and Holland 2004), the Mediterranean environment of Western Australia (Farre *et al*. 2002), and some limited testing in south-eastern Australia (Robertson *et al*. 1999*a*).

Datasets

Crops were all grown in southern NSW from 1991 to 2003, under a diverse range of growing conditions (Table 1). Sowing dates spanned the full range encountered in commercial practice from mid April to mid June. Cultivars were a mix of conventional (Hyola, Oscar, Yickadee, Rainbow) and triazine-tolerant (TT) (Pinnacle, Surpass501TT) types. The crops were managed to minimise the incidence of weeds, pests, diseases, lodging, and nutrient limitations. In 40 of the 42 cases, measurements were made of soil water at the start of the growing season by gravimetric soil sampling to 2 m. In 2 exceptions (datasets 11 and 12), crops were high yielding and simulation analysis indicated that they were unlikely to be limited by water, hence unavailability of measured starting soil water was not critical and was estimated by simulation of a bare summer fallow before sowing. In 10 datasets, available soil water was measured within 3 weeks of crop harvest. At most sites, estimates of plant-available water capacity were derived from soil samples taken under appropriate conditions (e.g. under fully wet conditions and following crop senescence under dry conditions) or by direct measurement of soil water potential at −1500 kPa and −30 kPa in the laboratory. Crop measurements at all sites included established plant density, dates of flowering and physiological maturity, and bordered quadrat cuts at maturity for biomass and grain yield.

In datasets 1 and 2 there were contrasting levels of yield potential due to rainfall differences between the 2 seasons. At Cootamundra, datasets spanned the drought year of 1994 as well as higher yielding seasons such as 1993. At Ginninderra and Harden, crops were grown in high-yielding seasons (i.e. early sown, high rainfall, and cool finish). High yields were measured at the Galong and Wallendbeen sites (high rainfall and cool finish). The crops grown at Lockhart, Grenfell, Ardlethan, and Dirnaseer in 2003 spanned a wide range of yields due to variation in in-crop rainfall, sowing date, and soil type. Overall, the datasets covered a wide range of grain yield (499–5440 kg/ha, mean = 2572 kg/ha).

Table 1. Details of datasets used to test the APSIM-Canola model in southern NSW and analyse for water-use efficiency
Nm, data not measured. Starting soil water was that measured within 2 weeks of the date of sowing, whereas finishing soil water was within 3 weeks of harvest

Dataset	Location	Sowing dates	Cultivar	Grain yield (kg/ha)	Apr.–Oct. rainfall (mm)	Soil plant-avail. water capacity (mm)	Starting avail. soil water (mm)	Finishing avail. soil water (mm)	Reference
1	Condobolin (33.07°S,	24 May 1991	Barossa	499	207	137	74	4	Hocking *et al.* (1997)
2	147.23°E)	23 April 1992	Barossa	2055	240	137	116	52	
3	Dirnaseer (34.85°S,	27 May 1991	Barossa	3183	360	216	92	5	Hocking *et al.* (1997)
4	147.57°E)	27 May 1992	Barossa	4212	405	216	85	150	
5		23 May 2003	Surpass501TT	1240	233	212	71	Nm	Kirkegaard and Hamblin (unpubl.)
6		3 June 2003	Surpass501TT	1330	233	212	71	Nm	
7		17 June 2003	Surpass501TT	930	233	212	71	Nm	
8	Cootamundra (34.6°S,	15 June 1993	Hyola42	3520	444	199	35	59	Kirkegaard (unpubl.)
9	148.0°E)	21 June 1994	Oscar	590	175	199	110	24	
10		30 May 1995	Oscar	2890	441	199	185	138	
11	Ginninderra (35.3°S,	15 May 1996	Oscar	4400	540	200	Nm	Nm	Kirkegaard *et al.* (2000)
12	149.1°E)	14 May 1997	Monty	3150	460	200	Nm	Nm	
13	Harden (34.56°S,	26 May 1993	Yickadee	3330	503	273	94	Nm	Kirkegaard *et al.* (2006)
14	148.38°E)	18 May 1999	Pinnacle	4340	494	273	157	103	
15		15 May 2001	Rainbow	4220	311	273	115	5	
16	Galong (34.67°S,	30 April 2001	Rainbow	4340	335	114	46	Nm	Kirkegaard *et al.* (2006)
17	148.63°E)	14 May 2001	Rainbow	3560	335	114	46	Nm	
18		28 May 2001	Rainbow	2710	335	114	46	Nm	
19		29 April 2002	Rainbow	3390	261	173	118	Nm	
20		13 May 2002	Rainbow	2880	261	173	118	Nm	
21		27 May 2002	Rainbow	2240	261	173	118	Nm	
22		1 May 2003	Rainbow	1919	307	132	0	Nm	
23		3 June 2003	Rainbow	1884	307	132	0	Nm	
24		10 June 2003	Rainbow	1951	307	132	0	Nm	
25	Wallendbeen (34.53°S,	30 April 2001	Rainbow	5440	356	319	205	Nm	Kirkegaard *et al.* (2006)
26	148.16°E)	14 May 2001	Rainbow	5240	356	319	205	Nm	
27		29 May 2001	Rainbow	4120	356	319	205	Nm	
28		29 April 2002	Rainbow	2750	261	328	113	17	
29		13 May 2002	Rainbow	2160	261	328	113	Nm	
30		27 May 2002	Rainbow	1730	261	328	113	Nm	
31		1 May 2003	Rainbow	2260	325	197	56	Nm	
32		13 May 2003	Rainbow	1980	325	197	56	Nm	
33		30 May 2003	Rainbow	2070	325	197	56	Nm	
34	Lockhart (34.22°S, 146.72°E)	17 May 2003	Rainbow	2430	283	174	21	Nm	Kirkegaard and Hamblin (unpubl.)
35		26 May 2003	Rainbow	2140	283	174	21	Nm	
36		6 June 2003	Rainbow	1630	283	174	21	Nm	
37	Ardlethan (34.36°S, 146.90°E)	13 June 2003	Rainbow	1006	200	199	12	Nm	Kirkegaard and Hamblin (unpubl.)
38		24 June 2003	Rainbow	796	200	199	12	Nm	
39		3 July 2003	Rainbow	1095	200	199	12	Nm	
40	Grenfell (33.90°S, 148.17°E)	17 April 2003	Surpass501TT	2690	220	150	41	Nm	Kirkegaard and Hamblin (unpubl.)
41		12 May 2003	Surpass501TT	2230	264	150	41	Nm	
42		11 June 2003	Surpass501TT	1500	264	150	41	Nm	

Model testing

In order to simulate the 42 datasets (Table 1), the APSIM-Canola module was linked with the soil water module SOILWAT2 (Probert *et al*. 1997), the soil nitrogen module SOILN2 (Probert *et al*. 1997), and the surface residue module RESIDUE2 (Probert *et al*. 1997).

In some datasets the cultivars used (e.g. Yickadee, Barossa) did not have the genetic coefficients for simulation of phenological development available in APSIM (Robertson *et al*. 2002*b*), so a calibration exercise was used to derive coefficients that simulated observed 50% flowering (anthesis) and maturity dates accurately. This was achieved by adjusting the length of the juvenile phase (Robertson *et al*. 2002*b*) by trial and error so that observed and simulated flowering dates were within 5 days of each other. Soil types were mostly red gradational loams (kandosols) with measured values for plant-available water capacity (PAWC) to 2 m of 115–330 mm. Measured values for drained upper limit and lower limit (Ritchie 1981) were used to define PAWC for each soil, and in most cases soil water and mineral N samples taken at the sites before sowing were used to initialise the model for the simulation. In some cases, where detailed soil data were not available at the site, soil characterisation data compiled by Geeves *et al*. (1995) for similar soils in the region were used. Daily rainfall data were recorded as close as possible to the site and other daily data required for simulation (minimum and maximum temperature and solar radiation) were obtained from the Australian Bureau of Meteorology through the SILO database (http://www.bom.gov.au/silo). Management information (date of sowing, established plant population, dates and amounts of N fertiliser application) was also model input. Simulations were run from the date of pre-sowing soil sampling until the observed date of canola physiological maturity.

In addition to testing APSIM-Canola for grain yield, we also tested its ability to simulate available soil water at the start of the season. In total, 20 observations, taken within 2 weeks of sowing, were available for testing even though Table 1 indicates a measured value for 40 crops. This was because there were multiple sowings per season at a number of sites, and starting soil water was only measured once at the start of the season at these sites. In a smaller number of crops ($n = 10$) available soil water remaining at the end of the season was measured and used to test simulations for late-season water use. For starting soil water a summer fallow was simulated from estimated harvest date of the previous crop to the date of soil water sampling, with an estimate of initial soil water from the previous season based on late-season rainfall, and assuming weed-free conditions and stubble cover over the summer, consistent with tillage practices at the sites. For finishing soil water the simulation was run to the date of sampling, assuming surface canola residues present from the current crop and also no weeds.

Simulated output was compared with observed data with scatter plots between observed and simulated grain yield and available soil water, and goodness-of-fit was quantified with the root mean squared deviation (RMSD) and statistics of the linear regression between observed and simulated data (R^2, slope, intercept).

Relationships between potential yield and water supply

Relationships were derived using linear least-squares regression between grain yield of the 42 crops and various measures of seasonal water supply: April–October rainfall, in-crop rainfall, in-crop rainfall plus available stored soil water at sowing, seasonal water supply (as defined above), in-crop evapotranspiration, and transpiration. Independent variables were a mix of measured and simulated as outlined above.

Scenario analysis

Scenario analyses were run to examine the effects of seasonal variability and location on the relationship between (*1*) potential yield and seasonal water supply, (*2*) summer fallow rainfall and stored soil water at sowing, (*3*) rainfall between anthesis and crop maturity (hereafter termed post-anthesis rainfall) and available soil water at harvest, (*4*) WUE (grain yield divided by seasonal water supply minus 120 mm) and sowing date. Simulations were run at each location (Table 2) to examine inter-annual variation from the 100 seasons between 1904 and 2003, using daily climate data obtained from the Australian Bureau of Meteorology through the SILO database (http://www.bom.gov.au/silo). Locations were chosen to lie on a similar latitude (and hence similar distribution of winter *v.* summer rainfall) along a transect from Narrandera (430 mm annual rainfall) to Yass (660 mm). The canola-growing soils of this region are predominately red gradational acidic loams and hence a common soil type was simulated across the 4 sites with a PAWC of 157 mm to 2 m. At present, canola is not grown commercially on a large scale as far east as Yass, but commences at Galong, 30 km to the west. Nonetheless, simulations were conducted for this location to represent the extreme wet end of the W–E rainfall transect. Such environments are typical of the high-rainfall zone in NSW where grain production may increase in the future.

Sowing time in these dryland systems does not occur on a fixed date every year but depends upon the timing of autumn and early winter rains. In the simulations, sowing time was allowed to vary naturally each year according to a sowing rule. A sowing window was set between 10 April and 1 July. Sowing occurred when at least 15 mm of rainfall had accumulated within 3 days. If the sowing rule was not met within the sowing window then sowing was forced on 2 July, so that a crop was sown in every year of the climate record. Using this rule, a crop was sown in 50% of years by the end of the first week in May across all 4 locations.

Previous crop residues were set at the start of the sowing window to 2000 kg/ha, residue type was assumed as wheat, with a C : N ratio of 70. Both total and mineral N in soil profiles were reset on the day of sowing each year, with 300 kg mineral N/ha in the soil profile so that N supply would not be limiting. Soil water was allowed to carry-over. A cultivar with the phenological characteristics of cv. Oscar, until recently widely grown in south-eastern Australia, was sown at a plant population of 40 plants/m^2. Simulations were run for both

Table 2. Locations used in long-term simulations
Values are the mean for the historical record (1904–2003) used in simulations

Location	Lat. (°S), long. (°E), elevation (m asl)	Ann. rainfall (mm)	Winter rainfall (mm)[A]	Ann. mean temp. (°C)
Narrandera	34.71°, 146.51°, 145 m	428	274 (64%)[B]	16.6
Wagga Wagga	35.16°, 147.46°, 212 m	564	358 (63%)	15.5
Cootamundra	34.63°, 148.04°, 318 m	611	377 (62%)	15.2
Yass	34.83°, 148.91°, 520 m	655	399 (61%)	13.8

[A] Rainfall between April and October.
[B] Values in parentheses are winter rainfall as a percentage of annual.

conventional and TT types, as TT cultivars occupy a significant area of canola production in this region. Conventional and TT cultivars are distinct physiological types (Robertson *et al*. 2002*a*) and hence may be expected to have different relationships between yield and water supply.

Results

Model testing

APSIM-Canola was able to simulate the 42 datasets from southern NSW with a RMSD of 483 kg/ha, which was 21% of the mean observed value. There was no apparent bias and low yields (<1000 kg/ha) were simulated as accurately as high (>5000 kg/ha) yields (Fig. 1). The R^2 value for the linear regression between observed and simulated was 86%. Model performance on this dataset is comparable with previous tests for APSIM-Canola. Farre *et al*. (2002) used a dataset where observed yields ranging from 0.1 to 3.2 t/ha gave simulated yields from 0.4 to 3.0 t/ha and a RMSD of 0.3–0.4 t/ha. A RMSD of 0.5 t/ha was obtained by Robertson *et al*. (1999*a*) when testing the APSIM-Canola model in eastern Australia, and a RMSD of 0.3 t/ha was obtained when testing in southern Queensland and northern NSW (Robertson and Holland 2004).

Examination was applied to a few datasets, labelled with open symbols in Fig. 1, where there was a noticeable discrepancy between observed and simulated yield. For the 2 datasets yielding >5000 kg/ha (datasets 25 and 26, Table 1) it was found that an under-prediction of yield was due to simulated N limitation. In these datasets, measured starting soil N was 382 kg N/ha to 2 m. If starting soil N was raised to 420 kg N/ha then measured and simulated grain yield agreed to within 400 kg/ha, indicating that simulated N deficit was the cause of under-prediction. In such high-yielding crops, simulation of soil N dynamics is crucial to accurate simulation of growth and yield. In datasets 31 and 32, yields were over-predicted by about 1000 kg/ha. A maximum screen temperature of 26°C was recorded on 22 September, which coincided with mid-flowering for these 2 crops, and it was hypothesised that this caused premature cessation of flowering (Morrison and Stewart 2002) and hence limited grain set. Growers noted strong hot winds on those days that may have increased the temperature within crop canopies even further. The measured harvest index in these 2 crops was 22 and 26%, respectively, lower than the expected 30%, and possibly symptomatic of poor grain set. The effect of high temperature on flowering and grain set is currently not captured by APSIM-Canola. Further physiological evidence in the field would be needed to improve the model for this phenomenon.

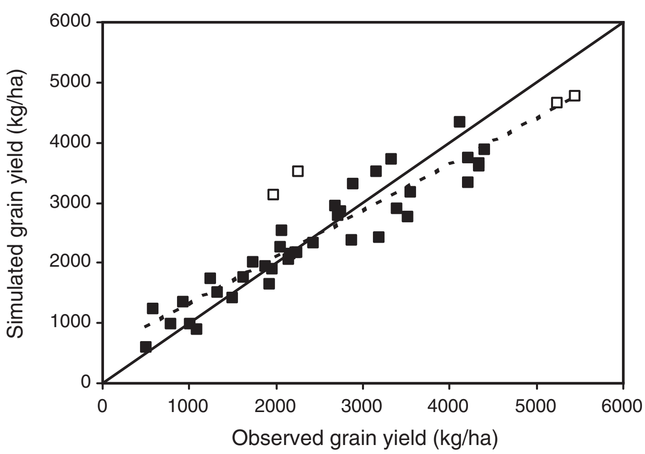

Fig. 1. Simulated *v.* observed grain yield. Fitted regression equation is $y = 0.77x + 561$, $R^2 = 0.86$, $n = 42$. open symbols, where there is a notable discrepancy between observed and simulated yield, are discussed in the text. Also shown is the 1 : 1 solid line of perfect agreement.

Measured starting soil water in the 20 datasets varied from 0 to 205 mm (Fig. 2*a*) as a consequence of variation in pre-season rainfall that ranged from 0 to 461 mm (Fig. 2*b*). Despite a number of assumptions being made about the summer fallow (initial soil water, weed-free, stubble cover), simulated starting soil water agreed well with observed and 89% of variation was explained by the simulation (Fig. 2*a*). Total summer rainfall explained 71% of the variation in starting soil water with a slope of 0.47 and intercept close to zero (Fig. 2*b*), indicating that, on average, 50% of summer rainfall was present as available soil water at the start of the season.

Measured finishing (harvest) soil water in 10 datasets varied from 4 to 150 mm (Fig. 2*c*). It was predicted less well than was starting soil water. Although 83% of variation was explained (Fig. 2*c*), the slope of observed *v.* simulated at 0.76 was significantly different from 1.0. Total rainfall from anthesis to harvest (or post-harvest sampling for the 10 measured datasets) explained 77% of the variation in finishing soil water (Fig. 2*d*). The fitted line indicated that above an intercept of 55 mm on the rainfall axis, about 50% of post-anthesis rainfall would be stored as available soil water at, or shortly after, harvest. However, there is considerable scatter in the data around this line due to the effect of timing of rainfall with respect to crop maturity.

The performance of the model on grain yield and available soil water in these dryland experiments gave some confidence that the model could be used to provide estimates of seasonal totals of evapotranspiration and transpiration, and available soil water at sowing and harvest. It also confirmed that crops were grown to their environmental potential, i.e. there were no limitations due to nutrients (other than N), weeds, pests, diseases, waterlogging, lodging, or frost, as was anticipated based on their management.

Relationships between potential yield and water supply

An increasing proportion of the variance in grain yield could be explained as the water supply predictor became

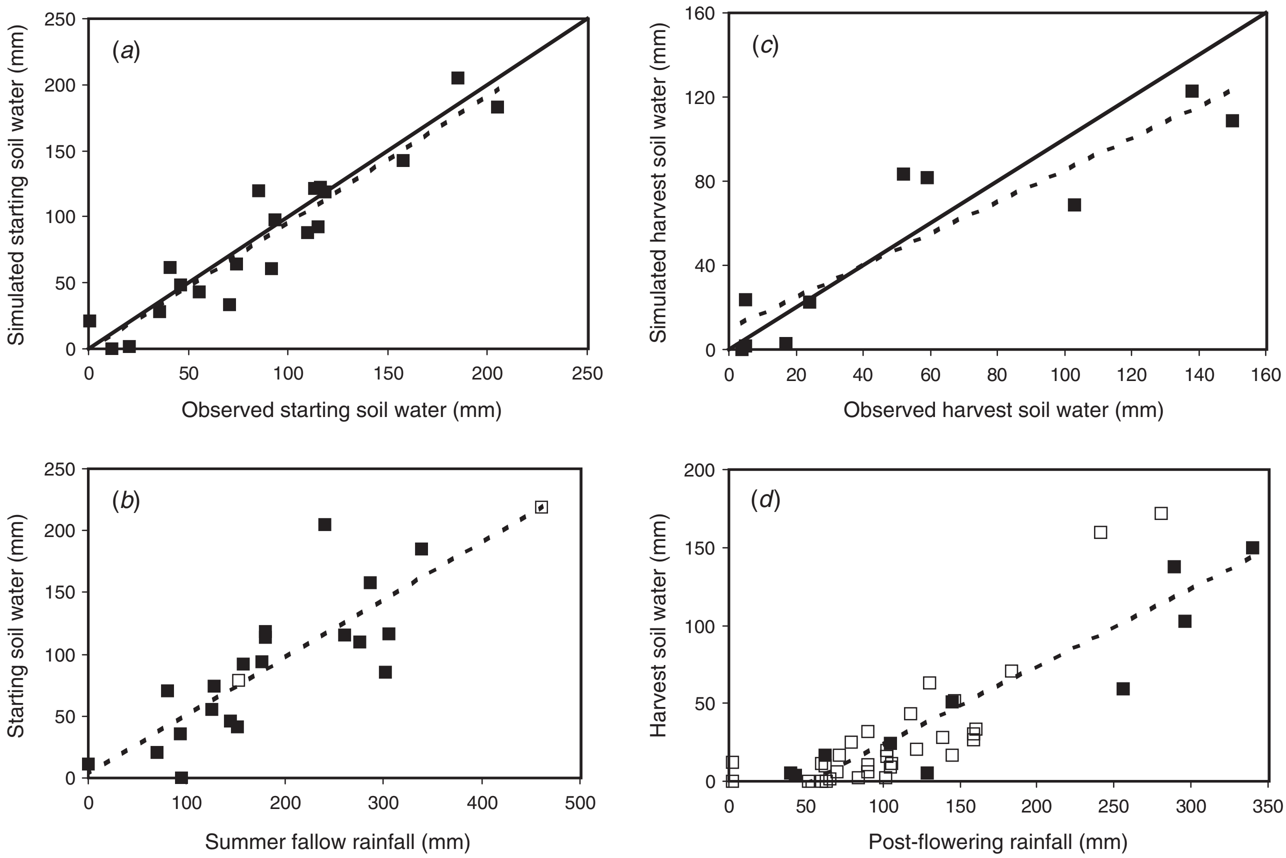

Fig. 2. (*a*) Observed and simulated starting available soil water. Fitted line (- - -) is $y = 0.97x - 2$, $R^2 = 0.89$, $n = 20$. Also shown is the 1 : 1 solid line of perfect agreement. (*b*) Observed (■) and simulated (□) starting available soil water *v.* summer fallow rainfall. Fitted line is $y = 0.47x + 3$, $R^2 = 0.71$, $n = 22$. (*c*) Observed and simulated finishing available soil water. Fitted line (- - -) is $y = 0.76x + 9.4$, $R^2 = 0.83$, $n = 10$. Also shown is the 1 : 1 solid line of perfect agreement. (*d*) Observed (■) and simulated (□) finishing available soil water *v.* post-anthesis rainfall. Fitted line is $y = 0.50x - 27$, $R^2 = 0.77$, $n = 42$.

more accurately defined (Fig. 3): from April to October rainfall (48%), to in-crop rainfall (30%), in-crop rainfall plus available soil water at sowing (56%), in-crop rainfall plus available soil water at sowing minus available soil water at harvest (68%), in-crop evapotranspiration (73%), and transpiration (82%). The largest incremental improvement in predictive power was achieved by accounting for available soil water at sowing (R^2 increasing from 0.30 to 0.56), with a further but smaller improvement by accounting for available soil water remaining at harvest (0.56–0.68). Interestingly, the R^2 value did not improve appreciably when evapotranspiration was used in preference to seasonal water supply; however, the highest predictive power was achieved with transpiration as the independent variable.

Along with an increasing proportion of variance explained with more accurately defined seasonal water supply, there was a trend for the slope (in kg/ha.mm) of the relationship to increase: April–October rainfall (10.2), to in-crop rainfall (7.4), in-crop rainfall plus available soil water at sowing (7.6), seasonal water supply (10.6), in-crop evapotranspiration (13.4), and transpiration (15.1).

The slope (WUE) and intercept of the linear regression between grain yield and seasonal water supply, were 10.6 kg/ha.mm and 117 mm, respectively. Nearly all of the crops could be encompassed by boundary lines that had slopes of 15 and 8 kg/ha.mm above an intercept of 120 mm. Hence, even though all crops were grown to potential (i.e. not limited by weeds, pests, diseases, lodging, frost at flowering, nutrient deficiency other than N) only a few fell on an upper WUE frontier as used by French and Schultz (1984). Although the fitted regression accounted for 68% of the variation in grain yield, individual crops varied in their WUE, defined here as grain yield divided by water supply minus 120 mm. The middle 60% of the 42 datasets had a WUE between 8.5 and 14.5 kg/ha.mm, whereas the bottom 20% varied down to 3.8 kg/ha.mm and the top 20% varied up to 18.3 kg/ha.mm (Table 3). There was a trend for the bottom 20% of crops to be sown later, have lower soil water at sowing, lower grain yield and harvest index, and use less

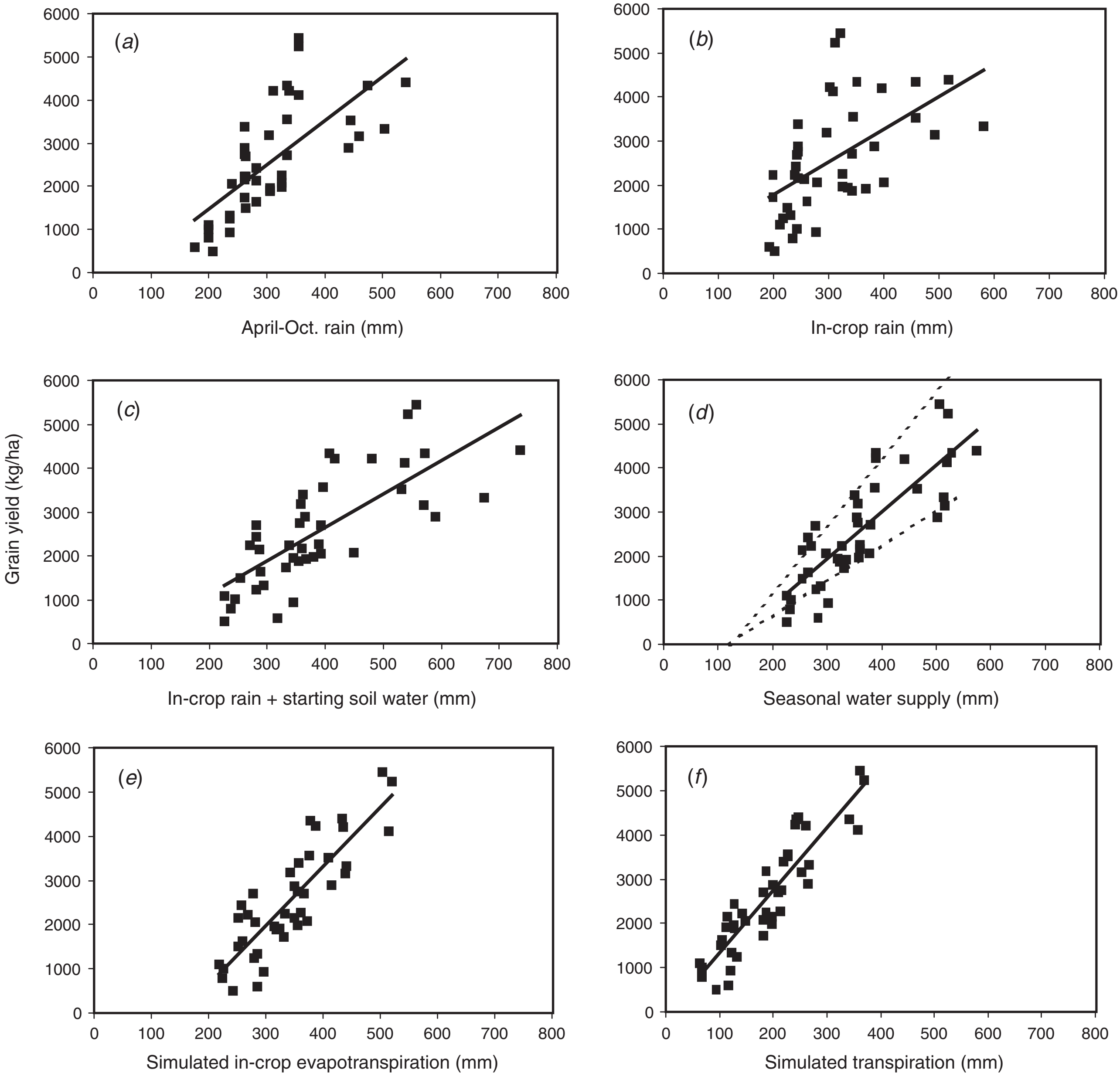

Fig. 3. Regression relationships (all $n = 42$) between: (*a*) grain yield *v.* April–October rainfall, $y = 10.2x - 577$, $R^2 = 0.48$; (*b*) grain yield *v.* in-crop (sowing to harvest) rainfall, $y = 7.45x + 288$, $R^2 = 0.30$; (*c*) grain yield *v.* in-crop rainfall plus starting available soil water, $y = 7.60x - 383$, $R^2 = 0.56$; (*d*) grain yield *v.* seasonal water supply [in-crop rainfall plus starting available soil water minus finishing available soil water], $y = 10.6x - 1243$, $R^2 = 0.68$. Boundary lines are given above an intercept of 120 mm, with slopes of 15 (upper) and 8 (lower) kg/ha.mm; (*e*) grain yield *v.* simulated evapotranspiration from sowing to harvest, $y = 13.4x - 2031$, $R^2 = 0.73$; (*f*) grain yield *v.* simulated transpiration, $y = 15.1x - 96$, $R^2 = 0.82$.

ET as transpiration compared with the middle 60% of crops, which in turn were lower than the top 20%.

Estimating stored soil water at sowing

The utility of definitions of seasonal water supply, which account for available soil water at the start of the season, relies on simple means to estimate this from rainfall records. Analysis data for the 40 crops, where measurements of starting soil water were available, indicated that summer rainfall might provide a ready means to estimate available soil water at sowing. The 40 datasets used were from only a small number of seasons, sowing dates, and soil

Table 3. Mean attributes for lowest 20%, highest 20% and middle 60% of water use efficiency (WUE) values for the 42 datasets listed in Table 1

Transpiration as a % of total seasonal evapotranspiration and available soil water at harvest was simulated. All other variables were observed. WUE was calculated as grain yield divided by water supply minus 120 mm

WUE (min–max) (kg/ha.mm)	Sowing date	Yield (kg/ha)	Harvest index (%)	April-Oct. rainfall (mm)	Available soil water (mm)		Water supply (% pre-flowering) (mm)	Transpiration (% season ET)
					Sowing	Harvest		
7.0 (3.8–8.4)	1 June	1483	27.3	280	65	37	331 (58)	43
10.4 (8.5–14.5)	24 May	2488	29.4	317	90	34	372 (55)	51
16.2 (15.3–18.3)	7 May	3569	29.9	296	95	23	357 (53)	58

types. Hence, we used long-term simulations with 100 years of climate data conducted at 4 locations along a rainfall transect in southern NSW to develop a more comprehensive relationship between summer fallow rainfall and soil water at sowing.

Median values for stored soil water at sowing varied from 40 mm at Narrandera to 100 mm at Yass (Table 4), emphasising the significance of this component of the water balance in an equi-seasonal rainfall environment. Taking the two extremes of locations on the rainfall transect, there was a high degree of scatter in the relationship between rainfall occurring from the harvest of the previous crop to the sowing of the next, and available soil water at sowing (Fig. 4). Trend lines fitted by eye to the 100 simulated seasons give a storage efficiency of 0.4 and 0.6 mm/mm at Narrandera and Yass, respectively, above a threshold of approximately 80 mm. At Yass there was evidence of an asymptote to soil water storage set by the PAWC above about 400 mm of fallow rainfall. The efficiency of fallow storage is greater at Yass than Narrandera because of summer rain falling in larger events that are less prone to soil evaporation. Yass is also a cooler environment (Table 2), which would contribute to slower evaporative loss.

Table 4. Summary statistics for long-term (1904–2003) conventional (non-triazine-tolerant) canola for simulated sowing date, grain yield, starting available soil water, finishing available soil water, and in-crop rainfall for 4 locations in southern New South Wales

Location	Sowing date	Grain yield (kg/ha)	Starting soil water (mm)	Finishing soil water (mm)	In-crop rainfall (mm)
		Narrandera			
10th percentile	13 Apr.	358	14	0	130
Median	7 May	1935	40	3	248
90th percentile	22 June	3485	98	26	352
		Wagga Wagga			
10th percentile	10 Apr.	1649	22	2	202
Median	29 Apr.	3516	74	14	329
90th percentile	7 June	4212	157	75	475
		Cootamundra			
10th percentile	9 Apr.	1307	27	2	196
Median	25 Apr.	3565	88	16	361
90th percentile	11 June	4357	165	90	516
		Yass			
10th percentile	10 Apr.	2042	34	4	251
Median	26 Apr.	3876	101	21	377
90th percentile	25 May	4372	169	109	565

Estimating stored soil water at harvest

In the 42 datasets there was some scatter in the relationship between simulated soil water at harvest and post-anthesis rainfall, although some trends were evident (Fig. 2*d*). The simulated and observed soil water at harvest was negligible (<10 mm) in those situations of less than about 50 mm of post-anthesis rainfall. In a similar manner to starting soil water, long-term simulations with 100 years of climate data conducted at 4 locations along a rainfall transect in southern NSW enabled an assessment of the robustness of the relationship developed on the 42 datasets between post-anthesis rainfall and soil water at harvest. Median values for available soil water remaining at harvest varied from 3 mm at Narrandera to 21 mm at Yass (Table 4), showing that this component of the water balance is not as significant as stored soil water at sowing. A similar degree of scatter was evident in the relationship between post-anthesis rainfall and simulated available soil water at harvest (Fig. 5). Consistent with the 42 datasets (Fig. 2*d*) there was a suggestion that the simulated soil water at harvest was negligible (<10 mm) in those situations of <50 mm of post-anthesis rainfall. Where post-anthesis rainfall was >50 mm, in most seasons at Narrandera, 20–50% of the rainfall >50 mm was remaining at harvest. At the wetter and cooler location of Yass, storage efficiency of rainfall >50 mm was more often between 50 and 100%. These efficiency values compare with a fitted slope in Fig. 2*d* of 0.50.

Seasonal water supply and potential yield

Long-term simulations with 100 years of climate data conducted at 4 locations along a rainfall transect in southern NSW were used to assess the robustness of the relationship

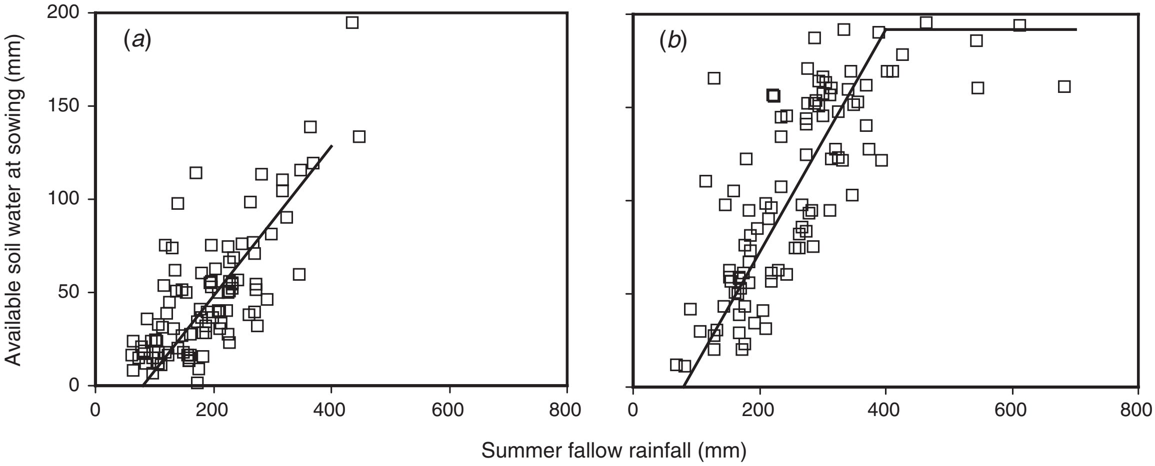

Fig. 4. Long-term (1904–2003) simulated relationship between available soil water at sowing and summer fallow rainfall for (*a*) Narrandera, and (*b*) Yass. Each point is one of 100 simulated seasons. Trend lines fitted to the data by eye have a slope of 0.4 and 0.6 mm/mm at Narrandera and Yass, respectively, between values of fallow rainfall of 80 and 400 mm.

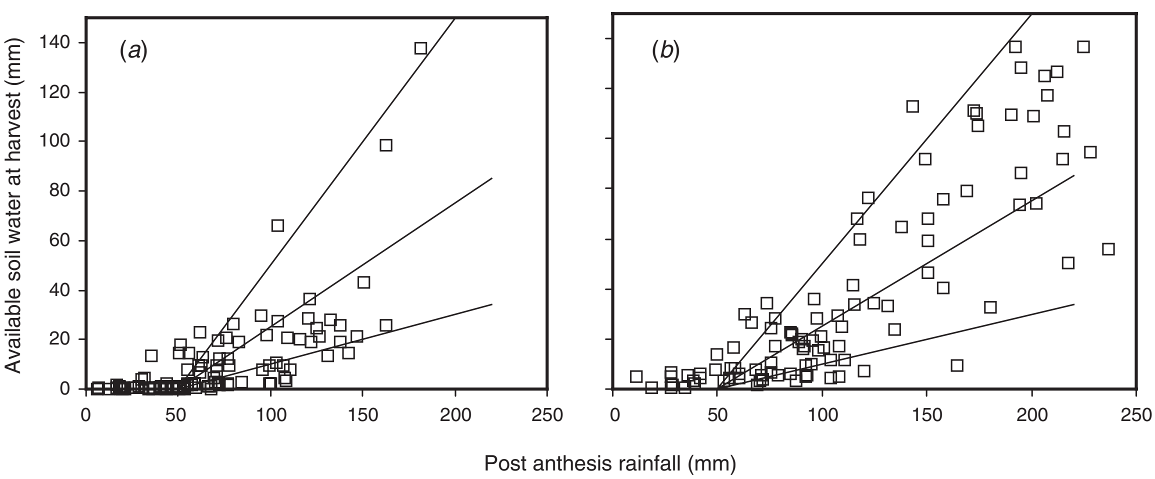

Fig. 5. Long-term (1904–2003) simulated relationship between available soil water at harvest and post-anthesis rainfall for (*a*) Narrandera, and (*b*) Yass. Each point is one of 100 simulated seasons. Envelope lines plotted have slopes of 0.2, 0.5, and 1 mm/mm above a value of 50 mm post-anthesis rainfall.

between seasonal water supply and potential yield. Yield was positively correlated with seasonal water supply up to around 450 mm, beyond which a similar yield was attained for a wide range of water supplies for conventional and TT varieties (Fig. 6). At Narrandera, the driest location, only one simulated crop experienced more than 450 mm so that crops were always potentially water-limited. In contrast, at Yass, around 30% of seasons were >450 mm and hence not apparently water-limited. Corresponding figures for Wagga Wagga and Cootamundra were 20 and 25%, respectively.

For conventional cultivars in the water-limited range of seasons (*c.* <450 mm) nearly all of the points could be bounded by lines with slopes of 9 and 15 kg/ha.mm above an intercept of 120 mm, with a median value of 12 kg/ha.mm (Fig. 6). For triazine-tolerant cultivars the asymptote yield achieved at >450 mm was lower than that for the conventional cultivar due to lower inherent yield potential (data not shown). In the water-limited range of seasons (*c.* <450 mm), nearly all the points could be bounded by lines with slopes of 8 and 14 kg/ha.mm above an intercept of 150 mm, with a median value of 11 kg/ha.mm (data not shown).

Effect of sowing date

The 42 measured datasets indicated a trend for lower WUE (defined as grain yield divided by seasonal water supply minus 120 mm) for later sown *v.* early sown crops (Table 3).

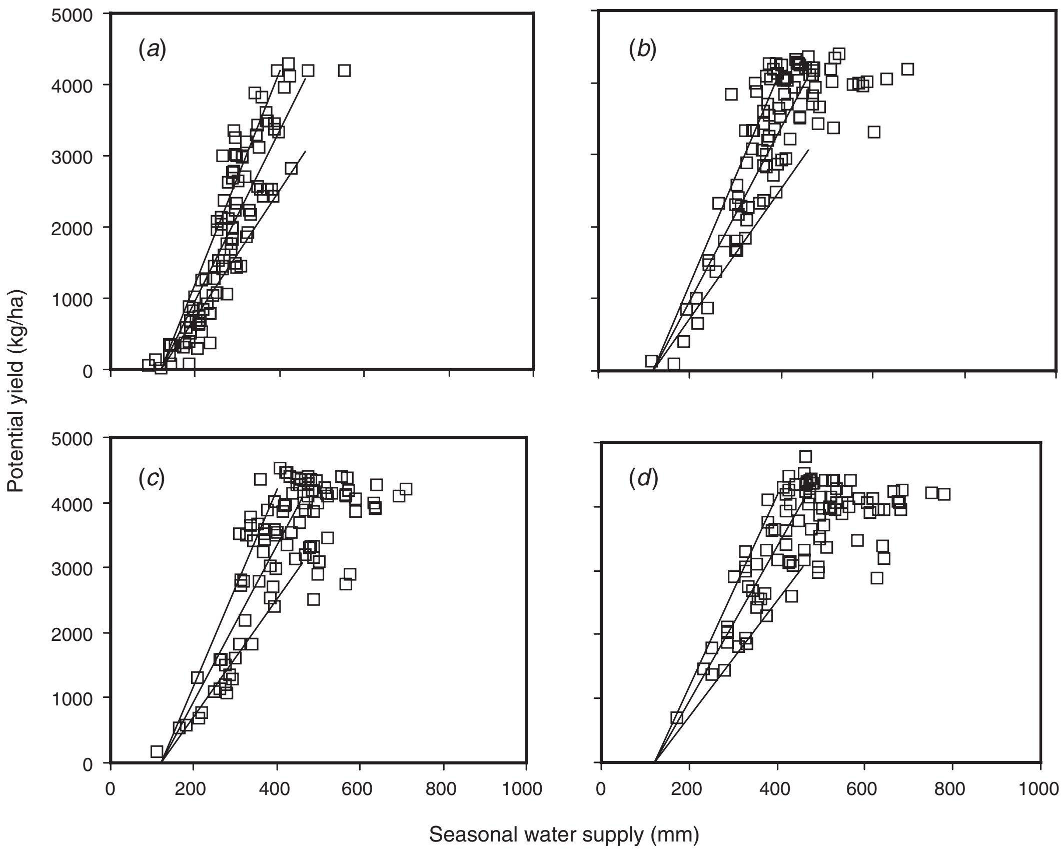

Fig. 6. Long-term (1904–2003) simulated relationship for conventional (non-triazine-tolerant) canola between grain yield and in-crop rainfall plus starting available soil water minus finishing available soil water for (*a*) Narrandera, (*b*) Wagga Wagga, (*c*) Cootamundra, and (*d*) Yass. Each point is one of 100 simulated seasons. Envelope lines are plotted for slopes of 9, 12, and 15 kg/ha.mm above an intercept of 120 mm.

Long-term simulation for Narrandera, the most water-limited location, indicated that computed WUE varied widely for a given sowing date. However, there was a trend for later sown crops to have lower water-use efficiency than earlier sown crops (Fig. 7). WUE declined by an average of one-third between sowings in early April to early July.

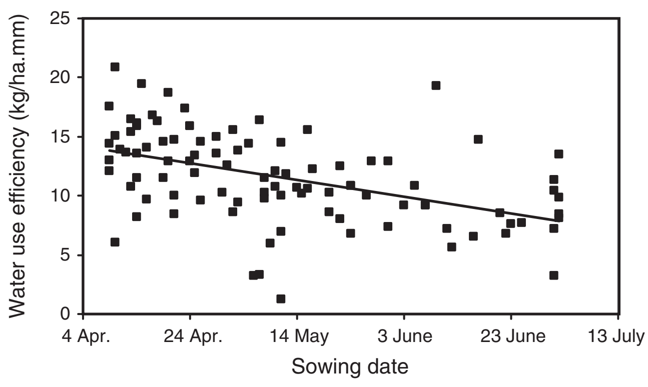

Fig. 7. Variation in simulated water-use efficiency (grain yield divided by seasonal water supply minus 120 mm) as a function of sowing date for Narrandera. Fitted trend line is $y = -0.07x + 21, R^2 = 0.22, n = 100$.

Discussion

Relationships between potential yield and seasonal water supply

The best water supply predictors of yield were able to explain 70–80% of the variance. Seasonal water supply, a value that would be relatively easy to compute, gave similar predictive power to those that would require the computation of a daily water balance with a simulation model (evapotranspiration or transpiration). A large improvement in predictive power beyond that used in F&S was gained by accounting for available soil water at sowing (Fig. 3) and long-term simulation analyses emphasised the significance of this component of the water balance in this region

(Table 4). There was less to be gained by accounting for unused water remaining at harvest (Fig. 3), which represented only a fifth of that for available soil water at sowing (Table 4). The poorer prediction of yield by in-crop rainfall compared with April–October rainfall is expected because the latter definition implicitly accounts for any rainfall shortly before sowing and also discounts rainfall close to windrowing, which occurs in the month of November in this environment. The increase in the slope as the water supply predictor became more accurately defined results from the increase in the fraction of seasonal water supply that is transpiration and hence more directly related to biomass production.

The slopes of the regressions shown in Fig. 3 are *not* equivalent to the boundary line fitted by French and Schultz (1984) to their data and hence do not represent 'potential yield' as defined by them. A line fitted to the upper envelope of points in Fig. 3*d*, to give an upper WUE frontier, has a slope of 15 kg/ha.mm and represents crop response to those seasonal conditions where water is used the most efficiently due to its timing in relation to crop demand and minimal unproductive losses of water (deep drainage, runoff, and soil evaporation). Importantly, crops that fall below this line were *not* limited by poor management or biotic constraints but rather could not make the most efficient use of the water available due to less favourable timing of rainfall and an increase in the unproductive loss of water. It is erroneous to assume that crops falling below the upper WUE frontier are poorly managed because all of the crops in this study were managed to water-limited potential, and there was good correspondence between observed and simulated yield. An upper limit to the WUE frontier of 15 kg/ha.mm is not unexpected given a maximum value for wheat of 25 kg/ha.mm (Angus and van Herwaarden 2001) and the common rule of thumb used by farmers, consultants, and scientists in southern NSW that canola yields 60% that of wheat (Robertson *et al*. 1999*b*).

The slope of the line between yield and seasonal water supply (WUE) was 11 kg/ha.mm for the relationship fitted to the 42 datasets (Fig. 3*d*). Long-term simulations implied a median line of 12 and 11 kg/ha.mm across locations for conventional and TT cultivars, respectively. The difference between the cultivar types is consistent with their known differences in radiation-use efficiency and transpiration efficiency of biomass production (Robertson *et al*. 2003; Matus *et al*. 1995). Values of 11–12 kg/ha.mm are similar to the 12.5 kg/ha.mm derived by Hocking *et al*. (1997) for canola from wheat data on a biochemical basis. Upper limits to these relationships, encapsulated by an upper envelope, suggest that values of 14–15 kg/ha.mm are appropriate where water is used the most efficiently due to its timing in relation to crop demand and minimal unproductive losses of water. Conversely, it is unreasonable to expect canola crops to have efficiencies greater than 8–9 kg/ha.mm above the intercept in seasons where water is used less efficiently due to poorer timing of rainfall and to increases in unproductive water loss.

We also have presented evidence from both the measured (Table 2) and simulated (Fig. 7) datasets that the WUE would be expected to decline with delayed sowing. A less efficient relationship between water supply and growth for later sowing is consistent with the concept that vapour pressure deficit rises with later sowing and hence more water is transpired for a given amount of biomass produced. Moreover, later sowings would be expected to have more occurrences of terminal water deficit and hence lower harvest index. This effect would add to that of vapour pressure deficit and result in a lower conversion of water supply to grain yield.

The intercept of the line between yield and seasonal water supply, commonly interpreted as soil evaporation (Cornish and Murray 1989; Angus and van Herwaarden 2001), is more reasonably interpreted as the threshold water supply that needs to be exceeded in order for any yield to be produced. Indeed, the relationships between yield and simulated evapotranspiration (Fig. 3*e*) and transpiration (Fig. 3*f*) differ in slope (13.4 *v.* 15.1 kg/ha.mm) as well as intercept (152 *v.* 6 mm). Simulated soil evaporation from sowing to harvest across the 42 crops varied from 97 to 212 mm, with a mean of 157 mm. For the relationship in Fig. 3*d*, the fitted intercept of 117 mm is slightly greater than the 110 mm derived by French and Schultz (1984) and used by Hocking *et al*. (1997). We have fitted different intercepts for conventional (120 mm) and TT (150 mm) cultivars (Fig. 6, data not shown for TTs), although it is difficult to be definitive in the absence of many simulated points close to the water supply-axis. There are justifiable physiological grounds for expecting TT cultivars to have a higher intercept due to lower early vigour, slower canopy development, and hence more soil evaporation losses (Lythgoe *et al*. 2001; Robertson *et al*. 2002*a*)

The utility of a F&S type of approach to estimate potential yield is seen in those environments where water is limiting. In the 42 observed datasets, seasonal water supply did not exceed 400 mm and hence yield in these well-managed crops was linearly related to seasonal water supply. Long-term simulations showed that in a significant proportion of seasons, and more so at the wetter locations, yield was not limited by water when seasonal water supply exceeded *c*. 450 mm. In these situations the F&S approach is inappropriate because factors other than water (e.g. solar radiation, nutrients, waterlogging) are limiting and a significant proportion of rainfall is lost through deep drainage. In a comparison of district average wheat yields in southern NSW with a calculated water-limited potential yield, both Cornish and Murray (1989) and Angus and van Herwaarden (2001) showed that district yields were close to predicted potential in dry years, but reached a plateau regardless of rainfall when water use exceeded 300 mm. This suggests that low rainfall does not directly limit wheat yield in many years in southern NSW and that an analysis of the reasons for low yield on farms could lead to substantial increases in yield for many farmers. A similar analysis has been initiated for canola as there are concerns that canola is not yielding to its potential in this environment (Kirkegaard *et al*. 2006).

Aside from the effect of sowing date, we attempted to identify additional easy-to-measure attributes of weather or crop management that would explain the discrepancy between the upper bound of 15 kg/ha.mm and WUE of individual crops. If such factors were readily identifiable it would enable more precise benchmarking of WUE of individual crops and avoid the mistake of attributing non-potential yield to a crop when it fell below the 15 kg/ha.mm upper bound. Several variables were examined in the 42-crop dataset and the long-term simulations with a focus on summary measures of wasteful use of rainfall: rainfall totals in individual months, simulated seasonal totals of runoff and deep water loss, the ratio of rainfall before to after anthesis (as a measure of terminal drought and low harvest index), and number of rainfall events before flowering (as a surrogate of soil evaporation before canopy closure). No one factor explained variation in WUE with R^2 values all less than 30%. The variable with strongest explanatory power was simulated seasonal soil evaporation, which varied 2-fold in the 42-crop dataset. Soil evaporation is going to be a consequence of the interactions between sowing date, the number and size of rainfall events before canopy closure and crop size, and there are no readily available rules of thumb to derive it. Future research should focus on farmer-friendly methods for estimating seasonal totals of soil evaporation. Until then, it is apparent that for the purposes of precise benchmarking, the seasonal water supply predictor for yield will remain inferior to the use of a daily time step simulation model ($R^2 = 0.68$ *v.* 0.86 in the 42-crop dataset). Simulation models are able to account for daily dynamics of soil water supply in relation to crop demand, as well as runoff, deep water loss, and variable soil evaporation losses. Where input data are available for such models, and the question warrants a detailed approach, simulation is a powerful approach for estimating potential yield and diagnosing possible constraints.

Estimating stored soil water at sowing and harvest

In the equi-seasonal rainfall environments studied here, rainfall during the summer fallow can contribute significantly to storage of available soil water at sowing, whereas rainfall near harvest may not be used by crops (Fig. 2*b*, Table 4). Failing to account for both effects will result in a poorer ability to predict yield when using totals of seasonal rainfall, and as a result, yield limitations may be incorrectly ascribed to poor management when inefficient water use is the primary cause. The use of a modified F&S approach to estimate canola yield from seasonal water supply (in-crop rainfall and soil water depletion between sowing and harvest) relies upon a ready means to estimate the available soil water at sowing and that remaining at harvest from rainfall records.

The measurements (Fig. 2) and long-term simulations (Fig. 4) highlighted that starting soil water in this environment can vary from an empty to a full profile, depending upon the timing and amount of summer rainfall. For a given total of fallow rainfall there was a wide range of storage efficiencies. This highlights the need for deep soil monitoring of soil water if an accurate estimate of this is needed. Nonetheless, trend lines fitted to the long-term simulated data indicate that a rule of thumb could be used to estimate stored soil water based on a total fallow rainfall (Fig. 4). Above a threshold value of 80 mm between 40 and 60% of rainfall, depending upon location, was stored at sowing time. The measured data (Fig. 2*b*) did not indicate an intercept value; however, as they were based on a limited number of seasons, the long-term simulations are likely to give a more reliable estimate of an intercept value. It must also be emphasised that both the measured data and simulations concerned situations where summer water storage would be maximised due to stubble cover and the absence of weeds. When the management of the summer fallow does not meet these assumptions then storage of available soil water will be less than that reported here.

Analysis of simulated soil water at harvest for the 42 datasets suggested that it could be predicted reasonably reliably from total post-anthesis rainfall (Figs 2*d* and 5). Although long-term simulations and the measured datasets confirmed that negligible water would be stored if post-anthesis rainfall was less than *c*. 50 mm, considerable scatter existed in the relationship between soil water and rainfall for totals >50 mm. There was a tendency for wetter sites (e.g. Yass) to store rainfall more efficiently than drier sites (e.g. Narrandera) in seasons with rainfall totals >50 mm. This could be used as a starting point for developing a rule of thumb.

Summarising these simplified rules of thumb, an improved prediction of grain yield of canola in relation to seasonal water supply is as follows:

$$\text{WUE} = \text{yield/seasonal water supply [SWS]}$$

(expected median 11 kg/ha.mm; range 8–14, depending on timing of rainfall and sowing date. WUE can be reduced by 10% for each month's delay in sowing between early April and early July), where:

$$\text{SWS} = [\text{in-crop rain}] + [\text{soil water at sowing}] \\ -[\text{soil water at harvest}] - [120]$$

where in-crop rain <450 mm, and soil water at sowing = (fallow rainfall − 80) × 0.5, where 0.5 can vary from 0.4 to 0.6 depending on timing and amount of rainfall (this assumes a weed-free fallow with stubble cover); and soil water at harvest = [Post flowering rainfall − 50] × 0.5, where 0.5 can vary from 0.5 to 1.0 at wetter locations and 0.2 to 0.5 at drier locations.

Conclusions

Using experimental plot yields and simulation we have derived a more comprehensive basis for a water-use efficiency framework for dryland canola. The approach appears to be robust across a range of rainfall locations for southern NSW and awaits further extrapolation to Mediterranean and summer-dominant rainfall environments in the Australian wheatbelt. In the equi-seasonal rainfall environment of southern NSW it is important to account for stored soil water at sowing when computing seasonal water supply, and to a lesser extent soil water remaining at harvest.

For the purposes of practical application by farmers and advisors, water-limited potential yield can be calculated as a function of seasonal water supply minus 120 mm up to a limit of 450 mm, beyond which potential yield is not limited by water. Seasonal water supply can be computed as in-crop rainfall plus available soil water at sowing minus soil water at harvest. Available soil water at sowing can be estimated from summer fallow rainfall above a threshold of 80 mm, whereas water remaining at harvest can be estimated from post-anthesis rainfall above a threshold of 50 mm. More precise definitions of potential yield, while retaining their ease of use, will allow further diagnosis of yield constraints by farmers and advisors in dryland environments. The encouraging performance of APSIM-Canola in simulating both high- and low-yielding crops means that simulation can be applied with confidence to diagnosis of yield constraints and other applications of crop management where this approach is warranted.

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