CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar *Australian Journal of Agricultural Research*, 2004, **55**, 525–538

Production risk of canola in the semi-arid subtropics of Australia

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Abstract. The area of canola is expanding in the wheat-based farming systems of the summer-dominant rainfall zone of the Australian wheatbelt. Despite this, there is little information on yield and oil content expectations in relation to rainfall, location, and soil type and the reliability of the crop in a region characterised by high climatic variability. In this paper we assess variation in profitability of canola production in locations with different rainfall in the north-eastern wheatbelt by using long-term simulations at 4 locations spanning the climatic range of the region (Gunnedah, Moree, Walgett, Roma) with a validated model (APSIM-Canola). A new semi-mechanistic method for simulating oil content, accounting for temperature and water deficit effects during grain filling, is described and tested. Key agronomic determinants of reliable grain yield and oil content are identified.

Long-term simulations showed strong effects of location, plant-available soil water at sowing (PAW), and in-crop rainfall on grain yield expectations. Yield was negatively related to sowing date, particularly in those situations of high water supply (PAW and in-crop rainfall). Grain yield was positively related to in-crop rainfall up to 300 mm, with water use efficiency in most seasons falling between 6 and 12 kg/ha.mm. Variation in oil content was most strongly affected by sowing date, followed by location, with PAW having a minor effect. Importantly, the price bonus cut-off for oil content of 42% was exceeded in 25, 40, 40, and 55% of seasons for Roma, Walgett, Moree, and Gunnedah, respectively. Negative and falling phases of the SOI in April–May were associated with lower grain yield and oil contents, whereas positive and rising phases with higher grain yield and oil content. This suggests that the choice to sow canola over other alternatives could be a tactical decision that depends upon the seasonal climate outlook.

The approach used in this paper can be applied to the analysis of canola production risk (yield and oil content) and profitability in other prospective environments.

Additional keywords: simulation modelling, oil content, plant-available water, sowing date, profitability.

Introduction

The potential for canola (*Brassicas napus* L.) as a break-crop in the wheat-based farming systems of the summer-dominant rainfall zone of the Australian wheatbelt has long been recognised (Hodgson 1979; Slatter 1989). Significant areas were grown in the early 1990s (Holland *et al*. 2001), but the crop suffered from frost damage, a series of drought years, and the consequences of it being a non-host of abuscular mychorhiza, and the area decreased. Yield and oil content were variable and often disappointing. Problems with crop production were often cited as being due to variable climatic conditions, poorly adapted cultivars, poor establishment and inadequate nutrition. Frost at the early stages of grain-filling devastated a number of commercial crops, leading to the perception that canola was poorly adapted to northern climatic conditions.

The widespread adoption of canola in southern and western Australia in the mid–late 1990s, together with the advent of earlier maturing cultivars and favourable prices, has fuelled resurgence in interest in the crop in the north-eastern wheatbelt. Since 1998 there has been strong growth in the canola area, particularly in north-western New South Wales (Holland *et al*. 2001), accompanied by a notable increase in yield per hectare.

Despite the increasing area of the crop in the north-eastern wheatbelt, there is little information on yield expectations in relation to rainfall, location, and soil type. The north-eastern wheatbelt is characterised by high rainfall variability, high temperature during grain filling, and yield-damaging frosts in spring (Robertson *et al*. 2001). In addition, in contrast to southern and western Australian growing regions, winter crops in the north-eastern wheatbelt have a stronger dependence on stored soil water for growth,

 10.1071/AR03219 0004-9409/04/050525

and the importance of this for the reliability of canola production in the north-eastern wheatbelt is unknown.

Yield and oil content are important for profitability of canola production. Recent advances in the understanding of the environmental determinants of phenological development, growth, and yield formation of current canola cultivars (e.g. Mendham and Salisbury 1995; Robertson *et al.* 2002*b*, 2002*c*) mean that reliable estimates of yield variation can be made with simulation models (Gabrielle *et al.* 1998; Robertson *et al.* 1999; Farre *et al.* 2002) coupled to historical climate data. However, current capabilities to predict environmental effects on oil content are based on more empirical methods. Oil content is affected by temperature (Canvin 1965), water deficit (Mailer and Cornish 1987; Andersen *et al.* 1996; Champolivier and Merrien 1996; Jensen *et al.* 1996; Triboi-Blondel and Renard 1999), and nitrogen supply (Holmes 1980) during grain filling. Various workers have used statistical techniques to relate oil content to temperature (Hocking *et al.* 1997; Walton 1999; Hocking and Stapper 2001), and temperature and rainfall (Si *et al.* 1999; Pritchard *et al.* 2000) conditions during grain filling. However, to date there has been no development of a more mechanistic method to predict oil content of a given cultivar across a wide range of environments and then use this to assess variability in oil content along with variability in yield. In this paper we present a semi-mechanistic method for simulating oil content and use this together with yield simulations to assess variation in profitability of canola production in different rainfall locations of the north-eastern wheatbelt. In addition we assess the utility of using the SOI phase system (Stone and Auliciems 1992; Hammer *et al.* 1996) for seasonal climate forecasting of yield and oil content in canola.

Methods

Datasets

In order to examine only the effects of environment on oil content and yield independent of cultivar, data were collated from experiments where the cultivar Monty had been grown. These were experiments where measurements had been made of dates of flowering and maturity, oil content and grain yield, daily rainfall and air temperature, and any additional input data necessary to simulate them with APSIM-Canola (Robertson *et al.* 1999) (e.g. sowing date, plant population, starting soil water, fertiliser nitrogen applied). Experiments used were free of pests, weeds, nutritional constraints, and diseases and had minimal harvest losses.

Datasets totalling of 51 of cv. Monty were used to develop the algorithm for simulating oil content (Table 1). All available datasets were used to derive parameters. We did not use the traditional calibration-validation 2-steps process of model development and testing, but rather utilised all the data in the derivation of the model parameters. This was because we wanted to avoid the in-built correlations between high temperature and water deficit that may have occurred in a smaller dataset. The cultivar Monty was chosen, because until recently, it was a widely adapted conventional cultivar grown throughout Australia. Although the focus of this study was on the variation of oil content and grain yield in the north-eastern wheatbelt, datasets from outside the study area were also collated for model development and testing over a wide range of oil content and grain yield. Of the 51 datasets, 23 were from previous published work in Western Australia on the effect of sowing date and cultivar on oil content and yield (Walton 1999; Walton *et al.* 1999). Farre *et al.* (2002) have already reported on the performance of APSIM-Canola in simulating yields from this dataset, so that test is not repeated here. The remaining 28 datasets were from northern NSW and southern Queensland. The field experiments conducted at Tamworth in 1998, 1999 and 2000, at Roma in 1999, and at Lawes in 2000 are reported in Robertson *et al.* (2004). Otherwise, datasets were collected by the authors and have been previously unpublished.

Datasets covered a wide range of grain yield (390–2977 kg/ha, mean 1514 kg/ha) and oil content (31.5–48.0%, mean 40.8%). Oil content is expressed at 8.5% moisture content, and grain yield is expressed at 0% moisture content.

Model testing for yield

APSIM-Canola was tested for grain yield simulations against the 28 Queensland and northern NSW datasets. In order to simulate the experiments, the APSIM-Canola module was linked with the soil water module SOILWAT2 (Probert *et al.* 1998), the soil nitrogen module SOILN2 (Probert *et al.* 1998), and the surface residue module RESIDUE2 (Probert *et al.* 1998). The genetic coefficients for simulation of the phenological development of Monty are given by Robertson *et al.* (2002*b*). Values for drained upper limit and lower limit were used to define plant-available water capacity for each soil, with soil water samples taken at the sites before sowing being used to initialise the model for the simulation. Weather data (daily minimum and maximum temperature, rainfall, and solar radiation) were recorded as close as possible to the site. Management information (date of sowing, established plant population, dates and amounts of fertiliser application) also provided model inputs. Simulations were run from the date of pre-sowing soil sampling until the observed date of canola physiological maturity.

Review of the effect of environmental factors on oil content in canola

A starting point for the development of the algorithm for prediction of oil content is a brief review of the literature on environmental effects on oil content in canola. The main environmental factors considered here were temperature and water stress. Although there are other factors that will affect oil content (e.g. waterlogging, frost damage) these are not considered here because of a lack of physiological understanding of their effects and because temperature and water stress were judged to be the main environmental factors affecting variation in oil content in Australian canola-growing regions. Although the effect of nitrogen supply on oil content has been well documented (e.g. Holmes 1980), the effects are difficult to develop into model algorithms.

High temperature has been shown to lower oil content and alter composition of fatty acids in canola. Canvin (1965) showed the effect of temperature on oil content in a growth chamber study with constant temperatures of 10, 16, 21, and 26.5°C imposed from pollination to physiological maturity. Corresponding oil content varied from 51.8 to 32.2%. This represented a 1.2% reduction in oil content per rise in temperature of 1°C. Field studies by Walton (1999) in Western Australia gave rates of decline of 0.8–1% per 1°C, in a study with various sowing dates at a range of locations.

In field studies in dryland environments, it is difficult to separate the effects of temperature and drought on oil content, particularly as each is often correlated with delayed sowing. A good example of this is the study of Hocking *et al.* (1997) who, in a comparison of canola, mustard, and linola, found for all 3 species that there was a 2.7% decline in oil content for each 1°C rise in mean temperature during grain filling. This is a considerably stronger response than those mentioned

Table 1. Details of datasets used to develop the model algorithm for oil content, and for testing yield simulations

Location	Season	Sowing date	Oil content (8.5%)	Yield (kg/ha)
Queensland and Northern New South Wales				
Crochantigh	1998	12 May	38.1	1094
Dunkerry South	1998	14 May	43.3	1340
Roma RS	1998	12 May	39.1	1511
Somerset	1998	11 May	40.4	1558
Winnathoola	1998	12 May	43.9	2220
Tamworth[A]	1998	1 May	47.1	1947
		1 June	48.0	1619
		3 Aug.	43.4	1088
		21 Sep.	31.5	647
Kullinjah	1999	14 May	40.8	1200
Dunkerry South	1999	22 June	37.6	1390
Rocky Crossing	1999	18 June	36.3	390
Karee	1999	1 May	41.1	1394
Roma RS[A]	1999	26 May	38.8	845
		12 July	38.0	879
Somerset	1999	17 May	39.4	840
Tamworth[A]	1999	14 Apr.	43.3	2610
		17 May	40.7	2880
		18 June	39.3	1920
		20 Aug.	41.1	1460
Melvyn	2000	11 May	34.9	535
Milroy	2000	12 May	34.5	1333
Lawes[A]	2000	11 May	41.7	2977
		22 June	39.8	2770
Tamworth[A]	2000	19 Apr.	38.1	2366
		18 May	40.5	1856
		19 June	39.7	1486
		19 July	33.3	845
Western Australia[B]				
Mullewa	1997	2 May	47.0	2254
		19 May	44.7	1857
		3 June	42.5	1528
		16 June	39.7	843
Wongan Hills	1997	31 May	41.6	1852
		17 June	40.5	1447
		30 June	42.8	1377
		11 July	40.6	955
Merredin	1997	26 May	43.7	1014
		6 June	41.1	815
		23 June	40.7	448
Newdegate	1997	23 Apr.	44.3	1806
		22 May	41.8	1715
		3 June	38.7	1317
		17 June	38.0	1035
Mullewa	1998	8 May	45.4	2327
		27 May	45.5	2111
		4 June	43.5	1855
		22 June	42.3	1185
Wongan Hills	1998	22 Apr.	44.4	2309
		22 May	43.4	2378
		19 June	40.0	1458
		10 July	38.8	1088

[A]Described in full by Robertson *et al*. (2004).
[B]Data of Walton (1999) and Walton *et al*. (1999).

above (1–1.2% per 1°C) and could have been related to the terminal drought experienced in this experiment. In another study (Hocking and Stapper 2001), oil content also fell by 1.7% per 1°C rise in grain-filling temperature in a sowing date study in NSW.

In dry environments a positive correlation has been found between post-anthesis rainfall and oil content (Si *et al*. 1999; Walton 1999; Pritchard *et al*. 2000), although some workers failed to find significant relationships (Robertson *et al*. 2004). Detailed physiological studies have shown that water stress after flowering reduces oil content. Jensen *et al*. (1996) found that oil content was 43.2% in well-watered plants and 39.9% in droughted plants. Mailer and Cornish (1987) found that oil content fell from 36.9 to 31.4% under water stress. Triboi-Blondel and Renard (1999), in a large-pot experiment, also showed that high temperature and water stress after anthesis reduced oil content. In the low temperature treatment (18/10°C day/night), water stress reduced yield by two-thirds, individual seed weight by three-quarters, and oil content from 48.5 to 42.5%. Under high temperature (26/18°C) the respective oil contents were 43 and 40%. Champolivier and Merrien (1996) also found a strong reduction of oil content with water stress after anthesis.

Simulation of oil content

The algorithm for predicting oil content was developed using the full 51 datasets listed in Table 1. Based on the review of literature it was decided to derive an algorithm that related mean air temperature during grain filling to a 'baseline' oil content, unaffected by water deficit, and then discount this baseline for the negative effect of water deficit between flowering and maturity. Previous attempts at relating post-anthesis drought to oil content (Si *et al*. 1999; Pritchard *et al*. 2000) have used rainfall. However, because the degree of water deficit experienced by the crop will depend not only upon rainfall, but also evaporative demand, soil plant-available water, and crop leaf area, it was decided to use an index of the balance of supply and demand for soil water. This index was the simulated daily soil water deficit factor from APSIM-Canola, averaged over the simulated flowering to maturity period, and is an integrated measure of photosynthesis water stress experienced by the crop. The soil water deficit factor (SWDEF) varies from 1 (no stress) to 0 (complete water stress). Robertson *et al*. (2002*a*) gave details on the calculation of the soil water deficit factor in APSIM. As detailed measurements of soil water content or plant water stress were not available for any of the datasets, confidence in the ability of the model to simulate a realistic pattern of SWDEF through grain filling was gained indirectly by demonstrating reasonable agreement between observed and simulated grain yield.

APSIM-Canola was run for each of the 51 datasets (Table 1) and the daily mean air temperature and simulated soil water deficit factor between flowering and maturity was collated and the mean daily value for the period calculated. The optimisation routine 'SOLVER' in MS-Excel was then used to minimise the root mean squared deviation between observed and simulated oil content by varying the parameters in the following equations:

$$O = O_{\max} \quad \text{where } T_{\text{mean}} < A$$

$$O = O_{\max} + [B^{*}(T_{\text{mean}} - A)] - [C^{*}(1 - \text{SWDEF}\hat{\ }2)]$$

$$\text{where } T_{\text{mean}} \geq A$$

where O is the oil content, $O_{\max}$ is the maximum possible oil content that can be attained, A is the threshold temperature below which $O_{\max}$ is attained, B is the slope term relating grain-filling mean temperature (T_{mean}) to reductions in O, and C is the maximum negative effect on oil content when the mean grain-filling soil water deficit (SWDEF) = 0. The algorithm is summarised diagrammatically in Fig. 1.

Scenario analysis

Scenario analyses were run to examine the effects of seasonal variability, location, and plant-available soil water at sowing, on grain yield and oil content. Oil content was simulated using the algorithm developed earlier. Four locations were simulated for the climate record 1900–2002: Gunnedah (30.99 S, 150.25 E), Moree (29.48 S, 149.84 E), and Walgett (30.04 S, 148.12 E) in New South Wales and Roma (26.55 S, 148.78 E) in Queensland. Gunnedah and Roma represent the southern- and northern-most extent of canola production in the summer-dominant rainfall zone of the Australian wheatbelt. Moree is centrally located and close to the majority of commercial canola currently being grown in northern NSW. Walgett is on a similar latitude to Moree, but is in a drier rainfall zone and represents a more marginal environment for canola production. Simulations were run at each location so as to examine inter-annual variation in yield and oil content. Soil type was a deep cracking clay loam with 200 mm plant-available water in the root-zone of 180 cm, typical of the northern wheatbelt of eastern Australia. The soil water profile was initialised (reset) each year on the date of sowing so that either 50, 100, or 200 mm of plant-available soil water was present in the profile. Different levels of soil water at sowing were designed to represent the varying degrees of fallow water storage that can occur in the dryland farming systems of the north-eastern wheatbelt. Previous crop residues were also set at this time 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 150 kg mineral N/ha in the soil profile in each simulation, designed to ensure that N did not limit yields in wet seasons. As 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, sowing time was allowed to vary naturally each year according to a sowing rule. A sowing window was set between 1 May (DOY 121) and 31 July (DOY 212). Sowing occurred when at least 20 mm of rainfall had accumulated within 10 days. If the sowing rule was not met within the sowing window then sowing was forced on 1 August, so that a crop was sown in every year of the climate record. Cultivar Monty, an early–medium maturity type, typical of that grown by farmers in the north-eastern wheatbelt, was sown to establish 40 plants/m^2.

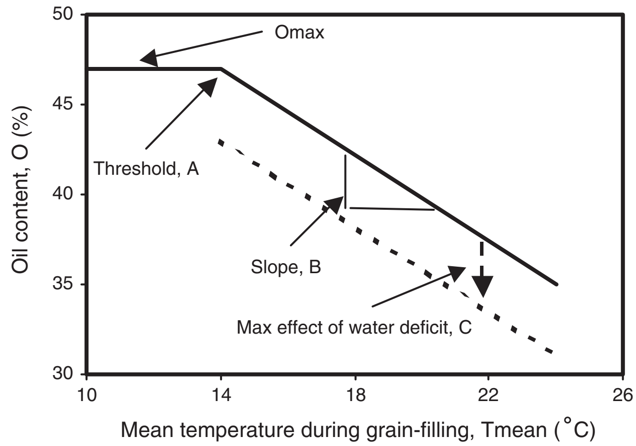

Fig. 1. Schematic diagram of the model algorithm used to predict oil content in relation to mean grain-filling temperature and soil water deficit. O is the oil content, $O_{\max}$ is the maximum possible oil content that can be attained, A is the threshold temperature below which $O_{\max}$ is attained, B is the slope term relating mean temperature during grain filling (T_{mean}) to reductions in O, and C is the maximum negative effect on oil content when the mean soil water deficit during grain filling (SWDEF) = 0. The dashed line represents the maximum reduction of oil content by water deficit as a function of temperature.

Model output for grain yield and oil content was analysed in various ways. Correlations were examined between grain yield, oil content, in-crop rainfall, sowing date, and mean temperature and water deficit factors during grain filling. Distributions of yield and oil content were summarised as cumulative probability distributions. Yield and oil content were also summarised for groups of seasons that had a similar phase of the Southern Oscillation Index (SOI) (Stone and Auliciems 1992) in April–May. The April–May phase was chosen as this has been shown previously for other winter crops as giving the strongest levels of discrimination between different season types (Hammer *et al*. 1996). The effect on gross margin of variation in grain price and the bonus/penalty system for oil content in the canola payment system were also examined. Currently, the canola payment system for oil content reduces the price received by 1.5% for each 1% oil content below 42%, and increases the price received by 1.5% for each 1% oil content above 42%.

Results and discussion

Testing of APSIM-canola for grain yield

APSIM-Canola was able to simulate the 28 datasets from northern NSW and southern Queensland with a RMSD of 327 kg/ha, which was 22% of the mean observed value (Fig. 2). There was no apparent bias, with low yields (<1000 kg/ha) being simulated as well as high (>2500 kg/ha) yields. The R^2 value for the linear regression between observed and simulated was 82%. 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) when testing the APSIM-Canola model in eastern Australia.

The performance of the model on yield testing in these dryland experiments gave some confidence that the soil water deficit factor was being simulated reasonably well and hence could be used in the derivation of the algorithm for oil content.

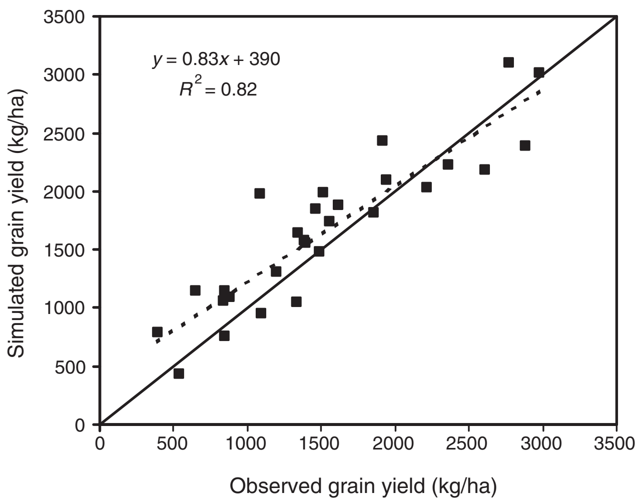

Fig. 2. Observed *v*. simulated grain yield for canola. The solid line is the line of 1:1 agreement and the dashed line is the fitted linear regression between observed and simulated ($y = 0.83x - 390$, $n = 28$, $R^2 = 0.82$).

Prediction of oil content

Across the 51 datasets there was a noticeable negative trend between mean temperature during grain filling and oil content (Fig. 3*a*). There was not a clear correlation between the grain-filling water deficit and oil content (Fig. 3*b*). This meant that there was not a strong association between temperature and the degree of water deficit between flowering and maturity (Fig. 3*c*) so that the model that was developed from this dataset did not have in-built correlations between temperature and water stress often found in dryland environments and with variable sowing date. Although there was a trend for the higher yielding crops to also have high oil content, the correlation was not strong (Fig. 3*d*). The results from these correlation analyses show that temperature, soil water deficit during grain filling, and grain yield alone are not strong predictors of oil content and that a combined approach could result in a better predictive ability.

The first step in the development of the algorithm was to assess if temperature alone could explain the observed variation in oil content without needing to invoke water deficit effects. A model without a water deficit effect gave a RMSD of 2.28%. The slope of the observed *v.* fitted linear regression was 0.52, indicating a bias in the model, with oil content under-predicted at high values and over-predicted at low values (Fig. 4*a*).

The algorithm developed that combined a negative effect of temperature on ‘baseline’ oil content with an additional negative effect of water deficit explained a similar amount of the variation in the observed data as the temperature-only model, with a RMSD of 2.61% (Fig. 4*b*). Mean (n = 51) observed oil content was 40.8% *v.* 41.3% for the fitted. The algorithm seemed to capture the extremes of oil content, with observed and fitted minimum values being 31.7 and 32.7% and observed and fitted maximum values being 48.0 and 47.0%, respectively. The slope of the observed *v.* fitted linear regression was 0.68, indicating less bias than in the temperature-only model. There were 3 outliers in the plot of observed *v.* fitted oil content, where observed and fitted deviated by >5 oil percentage units (see square symbols in Fig. 4*b*). These points were all from northern NSW or Queensland in the 2000 season (Milroy 2000, Tamworth RS April and July 2000). The reasons for such large deviations were difficult to explain on the basis of temperature and water deficit conditions experienced in the experiments. If these 3 outliers were removed from the analysis then the slope of the observed *v.* fitted linear regression improved from 0.67 to 0.81, the RMSD from 2.61 to 2.10%, and the R^2 for observed *v.* fitted from 50 to 63% (Fig. 4*c*). As it was difficult to justify the removal of these 3 outliers on the basis of, e.g. error in the observations, it was decided to derive the final model with the

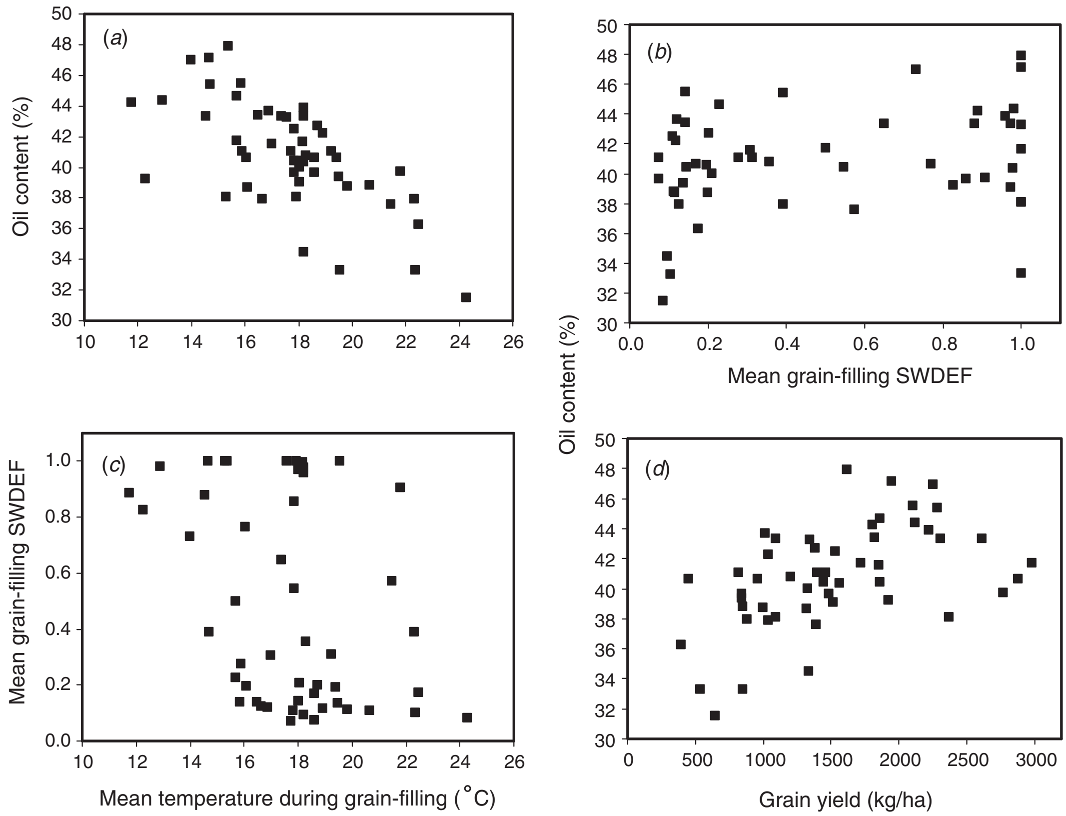

Fig. 3. Associations between key variables and oil content for the 51 datasets used to develop the oil prediction algorithm: (*a*) oil content *v*. mean air temperature during grain filling, (*b*) oil content *v*. mean soil water deficit factor during grain filling, (*c*) mean air temperature during grain filling *v*. mean soil water deficit factor during grain filling, and (*d*) grain yield *v*. oil content.

3 outliers included in the dataset. The fitted model parameters were: 47% for $O_{\max}$, the maximum possible oil content; 14°C for A, the threshold temperature above which increases in temperature cause reductions in oil content; 1.21% per 1°C for B, the slope relating oil content reduction to temperature; and 1.91% for C, the maximum reduction in oil content due to water deficit.

The fitted slope relating mean grain-filling temperature to oil content (1.21% per 1°C) was remarkably similar to the value of 1.2% per 1°C that was derived by Canvin (1965) in a growth chamber study where water deficit was absent and only temperature treatments of 10, 16, 21, and 26.5°C from pollination to physiological maturity were imposed. We were able to generate a similar range of temperature in this collated field dataset of 12–24°C. Similar slope values have been derived in dryland field environments by Walton (1999) and Robertson *et al*. (2004). However, as these environments had variable levels of water deficit, it is difficult to make direct comparisons with studies where only temperature varied.

The model parameter that represents the maximum effect that severe water deficit can have on oil content was 1.91%. This value is smaller than experimental observations of the difference in oil content between well watered and droughted plants (Mailer and Cornish 1987; Jensen *et al*. 1996; Triboi-Blondel and Renard 1999). Some of these studies were conducted in pots and may have imposed water stress at a faster rate than is commonly encountered in the field and did not allow time for physiological adjustment (Ritchie 1973). It is unlikely that our model under-estimated the effect of water deficit by confounding high levels of water stress with high temperature, as the two effects were not correlated (Fig. 3*c*). Another possible explanation of the smaller than expected effect of water deficit is that SWDEF is averaged over the whole grain-filling period and it may be that earlier stresses are more important than later stresses.

In order for this algorithm to be of use in canola agronomy it must be able to be adapted for different cultivars. Walton (1999) has shown that, when oil content is plotted against mean temperature during grain filling, there are still cultivar differences in oil content at equivalent mean grain-filling temperatures. Interestingly, in the study of Walton (1999) the rate of decline in oil content per 1°C was similar across cultivars, but the intercept value was different. Apart from intrinsic differences in cultivars for oil content, there will also be indirect effects of maturity type (phenology) that will influence the degree of water stress experienced in

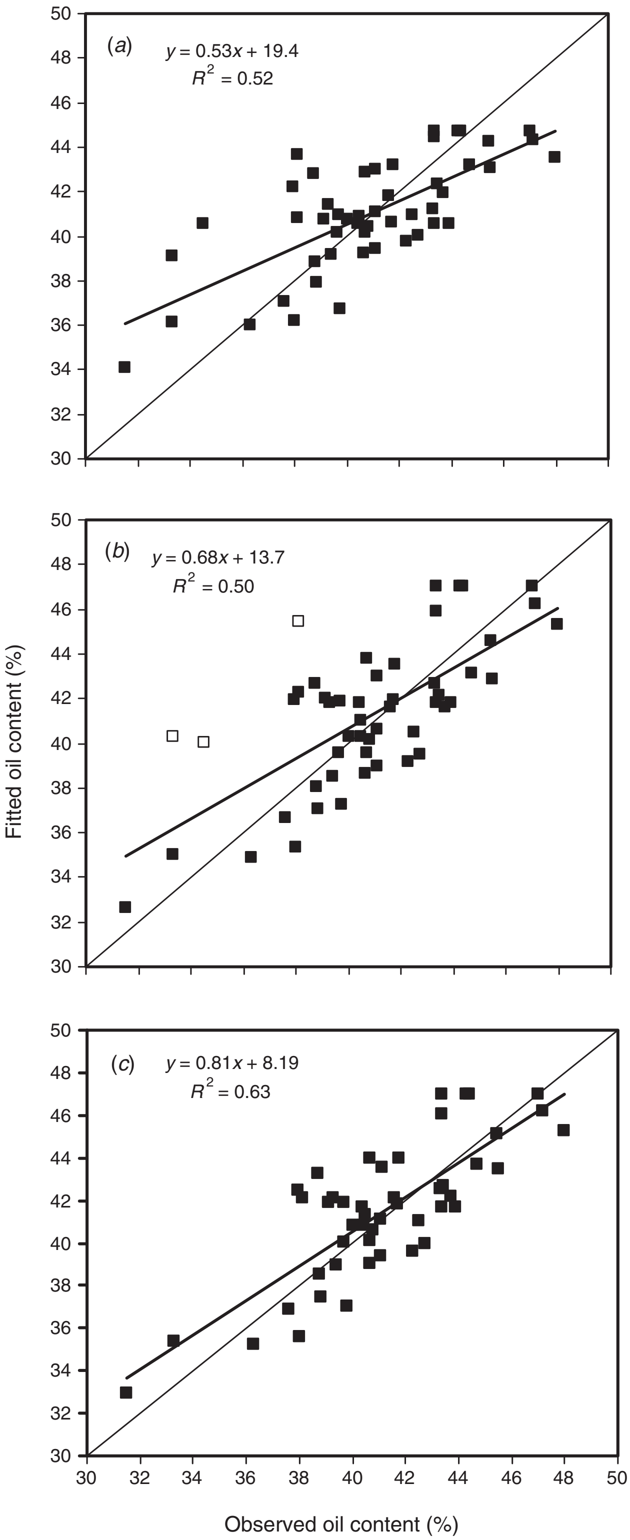

Fig. 4. Observed *v.* fitted oil content for model algorithms: (*a*) with a temperature only effect, (*b*) with temperature and water deficit effects, (*c*) as in (*b*) but with 3 outliers (□) removed. Shown is the 1 : 1 line of perfect agreement and the linear regression between observed and fitted oil content.

terminal drought environments. The effects of other cultivar attributes, such as triazine tolerance (TT), would also have to be considered. Robertson *et al*. (2002*c*) showed that, in a comparison of cultivars near-isogenic for the triazine tolerance trait, grain oil content in the TT cultivar could also be related linearly to that in the non-TT cultivar. The absolute difference in oil content tended to be larger at lower oil contents. At oil contents of around 45% in the non-TT cultivar, oil content in the TT cultivar was only about 2 oil percentage points less, whereas at oil contents less than 40% in the non-TT the difference was 4–5%.

Variation in grain yield due to location, season, and starting soil water

Simulated variation in grain yield for the 4 locations and 3 levels of plant-available soil water at sowing is summarised in Fig. 5 as cumulative distribution functions (CDF). Overall the results demonstrate the large variability in yield generated by climate variability in the region. Maximum yields simulated were 2.5–3.0 t/ha, independent of starting soil water and location. Minimum yields varied from 0.17 t/ha at Walgett, with 50 mm starting soil water, to 1.3 t/ha at Gunnedah, with 200 mm starting soil water. The results underscore the importance of starting soil water in determining the overall level of production. For instance, the median yield at Moree went from 1.1 to 2.5 t/ha as starting soil water increased from 50 to 200 mm. Gunnedah was the most productive location, with a median yield for the 100-mm soil water level of 2.1 t/ha. The next most productive was Moree (1.7 t/ha) and Roma and Walgett (1.4 t/ha). There were no zero yields simulated in any situation. This was partly due to the fact that sowing was forced to occur in every season, where in reality, in very dry years, sowing would not occur due to lack of rainfall. The range of yields simulated narrowed with higher starting soil water. For instance, at Moree, with 50 mm starting soil water, yield was 0.1–2.7 t/ha, 0.5–2.7 t/ha with 100 mm, and 1.2–2.8 t/ha with 200 mm. Similar trends were evident at other locations.

Within a location and level of starting soil water, grain yield was only weakly to moderately correlated with sowing date (Table 2), with R^2 values less than 0.6 in all cases. The correlation tended to be stronger at higher levels of starting soil water, probably because of the declining influence of in-crop rainfall on yield and the stronger influence of shorter crop duration with later sowing that would limit yield potential. Robertson *et al*. (2004) analysed the response of grain yield of canola and Indian mustard to sowing date in the north-eastern wheatbelt. The rate of decline in yield per days delay in sowing date varied from no decline in a very dry situation to 18 kg/ha.day in a high yielding situation, with a median value across a range of sowing date experiments of about 8 kg/ha.day. These values are similar to the range of values reported here (Table 2) of 1–12 kg/ha.day, as well

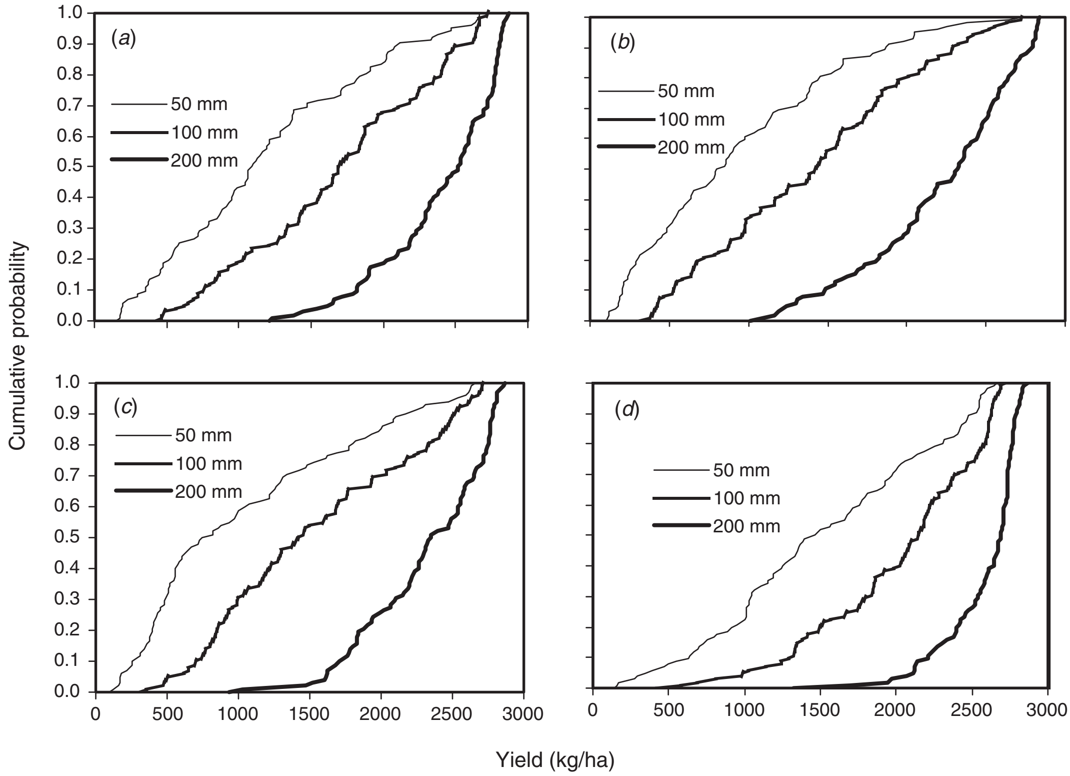

Fig. 5. Cumulative distribution functions of simulated grain yield for (*a*) Moree, (*b*) Roma, (*c*) Walgett, and (*d*) Gunnedah locations showing curves for 3 levels of plant-available soil water at sowing. Each curve is composed of 103 simulated seasons.

as a wider dataset from dryland and irrigated environments around Australia (Robertson *et al*. 1999; Farre *et al*. 2002). The rate of decline was smaller in more marginal situations (e.g. at Roma, or with lower starting soil water) as also found experimentally by Robertson *et al*. (2004).

Yield was positively correlated with in-crop rainfall (Fig. 6). The scatter of points that forms the relationship can be defined by upper and lower envelopes, the slopes of which represent the bounds of water use efficiency as defined by French and Schultz (1984). In all 4 locations, most of the points fell between envelopes defining water use efficiencies of 12 and 6 kg/ha.mm. Variability in simulated water use efficiency will be due to the timing of rainfall in relation to crop development. The value of

Table 2. Associations between simulated oil content and sowing date, oil content and grain yield, and grain yield and sowing date for Gunnedah, Moree, Walgett, and Roma at 50, 100, or 200 mm of starting plant-available soil water

Correlations are for the simulated historical climate record 1900–2002

Location	Soil water (mm)	Grain yield *v.* sowing date R^2	Slope	Intercept	Oil content *v.* sowing date R^2	Slope	Intercept	Oil content *v.* grain yield R^2	Slope	Intercept
Gunnedah	50	0.21 n.s.	–11.8	3279	0.81**	–0.097	56.4	0.38 n.s.	0.003	37.9
	100	0.35 n.s.	–11.7	3769	0.81**	–0.101	57.1	0.55*	0.004	33.7
	200	0.60*	–7.5	3698	0.82**	–0.097	57.2	0.71*	0.009	18.8
Moree	50	0.12 n.s.	–8.0	2385	0.78**	–0.118	57.5	0.33 n.s.	0.003	35.9
	100	0.21 n.s.	–10.0	3183	0.78**	–0.121	58.0	0.47*	0.004	32.7
	200	0.44*	–9.1	3746	0.79**	–0.126	59.3	0.66*	0.008	20.3
Walgett	50	0.14 n.s.	–9.0	2395	0.83**	–0.120	57.2	0.30 n.s.	0.003	35.9
	100	0.21 n.s.	–10.1	3072	0.83**	–0.124	57.8	0.43 n.s.	0.004	32.9
	200	0.50*	–9.9	3810	0.82**	–0.128	59.0	0.71**	0.009	20.0
Roma	50	0.00 n.s.	–1.3	1125	0.79**	–0.108	54.5	0.10 n.s.	0.002	36.3
	100	0.03 n.s.	–3.4	1916	0.79**	–0.109	54.6	0.20 n.s.	0.002	34.4
	200	0.17 n.s.	–6.6	3207	0.76**	–0.113	55.6	0.48 n.s.	0.006	26.0

n.s., Not significant at $P = 0.05$; * $P < 0.05$, ** $P < 0.01$.

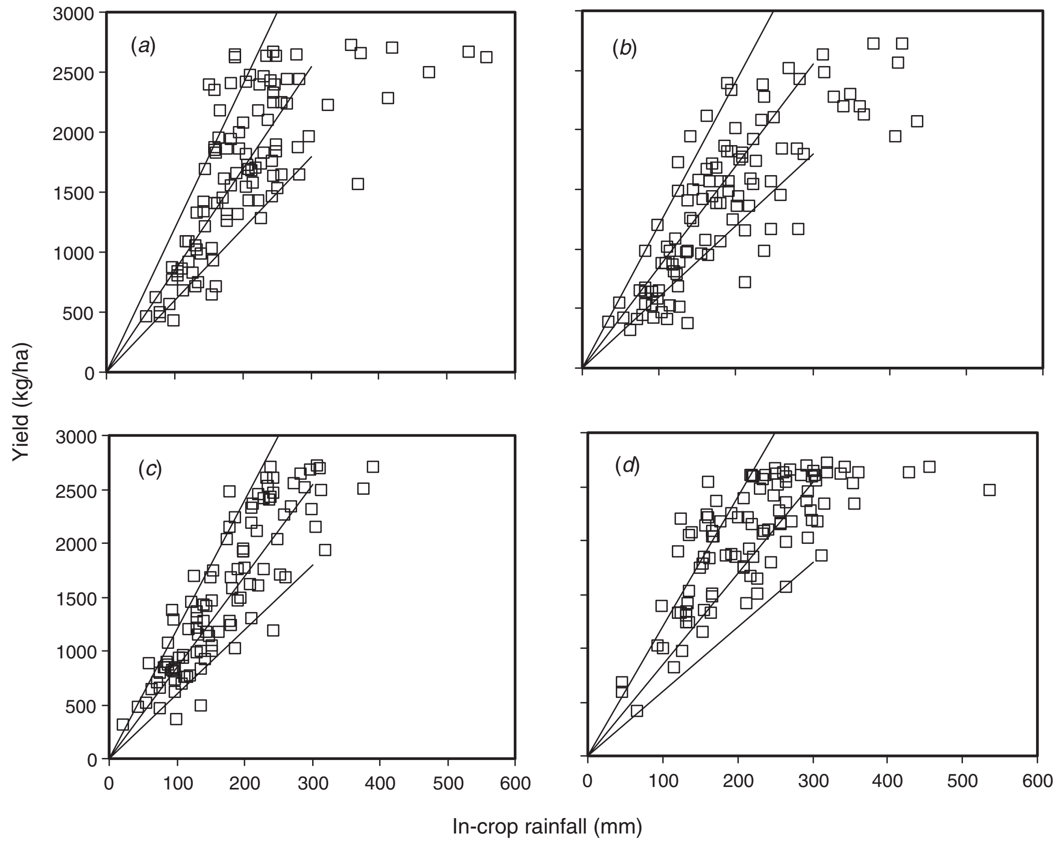

Fig. 6. Scatter plots of grain yield *v.* in-crop rainfall for the 100 mm level of plant-available soil water at sowing at (*a*) Moree, (*b*) Roma, (*c*) Walgett, (*d*) Gunnedah. At each location each point is one of 103 simulated seasons. Lines represent 12, 8.5, and 6 kg/ha.mm water use efficiency values plotted to pass through the origin.

12 kg/ha.mm is similar to that calculated by Hocking *et al.* (1997) as a 'potential' WUE for canola based on field results in southern NSW. Above about 300 mm of in-crop rainfall, yield did not respond positively to further increases in in-crop rainfall. In contrast to the experience in farming systems in southern and western Australia (e.g. Siddique *et al.* 2001) there was little evidence of a positive intercept between in-crop rainfall and yield. Traditionally, the positive intercept between in-crop rainfall and yield has been interpreted as equivalent to evaporation from soil prior to full crop cover, after which time water use is linearly related to biomass production. The partitioning of water use between evaporation from soil and transpiration (which is related to biomass production) will depend upon the frequency of soil wetting, particularly before full crop cover is reached. The size of this intercept, therefore, may be expected to vary with early-season rainfall, as well as stored soil water (Connor and Loomis 1991).

Relationships shown in Fig. 6 can be used to establish yield expectations on the basis of rainfall, compare production between situations on the basis of rainfall received (benchmarking), and be used to diagnose potential constraints to yield other than lack of water.

Variation in oil content due to location, season, and starting soil water

CDFs for oil content for the 4 locations at 100 mm soil water are given in Fig. 7. Simulated oil content varied from 29 to 48%, similar to the range in the dataset used to develop the algorithm (Table 1 and Fig. 2). There was little effect of starting soil water on CDFs for oil content with curves parallel for each level of starting soil water, with each offset by *c.* 0.3% (data not shown), and suggesting that fallow management for soil water will have little effect on the risk distribution for oil content. Hence, only data for one soil water level (100 mm) are shown (Fig. 7).

In contrast to the case with starting soil water, location effects on oil content distributions were noticeable. For the 100 mm starting soil water level, median oil content was 38, 39, 40, and 42% for Roma, Walgett, Moree, and Gunnedah, respectively. The cut-off for the bonus/penalty in grain price for canola is currently 42%. The probability of exceeding this cut-off for the 100 mm starting soil water level was 0.25, 0.40, 0.40, and 0.55 for Roma, Walgett, Moree,

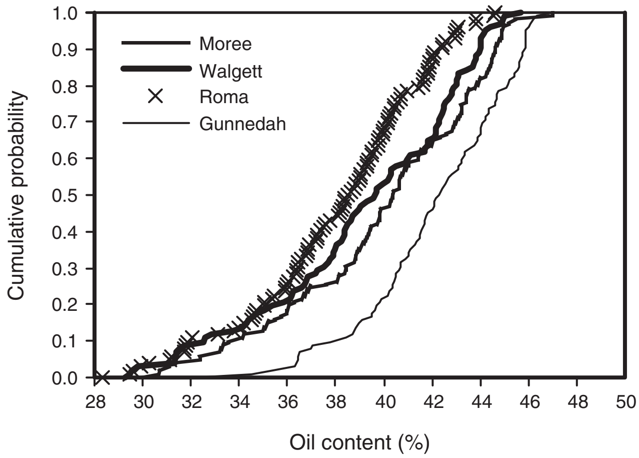

Fig. 7. Cumulative distribution functions of simulated oil content for Moree, Walgett, Roma, and Gunnedah at the 100 mm level of plant-available soil water at sowing. Each curve is composed of 103 simulated seasons.

and Gunnedah, respectively. This emphasises the difficulty that canola growers face in the north-eastern wheatbelt in producing canola grain of high oil content that will attract a price bonus. This challenge is particularly strong in the higher-temperature northern locations, such as Roma.

Much of the variation in oil content was a consequence of variation in sowing date; there were weaker correlations between oil content and in-crop rainfall and the average level of water stress during grain filling (Fig. 8). Figure 8*a* shows the correlation between sowing date and oil content for Moree at the 100-mm starting soil water level. Similar trends were observed at the other 3 locations and regression statistics for the association between oil content and sowing date are given in Table 2. R^2 values between oil content and sowing date were all above 0.76. Overall, across locations and starting soil water levels, for each day's delay in sowing date, oil content declined by 0.10–0.13%. The oil content at the earliest possible sowing date (represented by the intercept value of the linear regression) tended to be 1–2% higher for a 200 compared with 50 mm starting soil water, which suggests that high soil water status at sowing can play some role in alleviating the negative effect of later sowing. However, it can be shown that the value of 200 over 50 mm available soil water at sowing was worth only 8–16 days in later sowing. Even though sowing date was the strongest determinant of oil

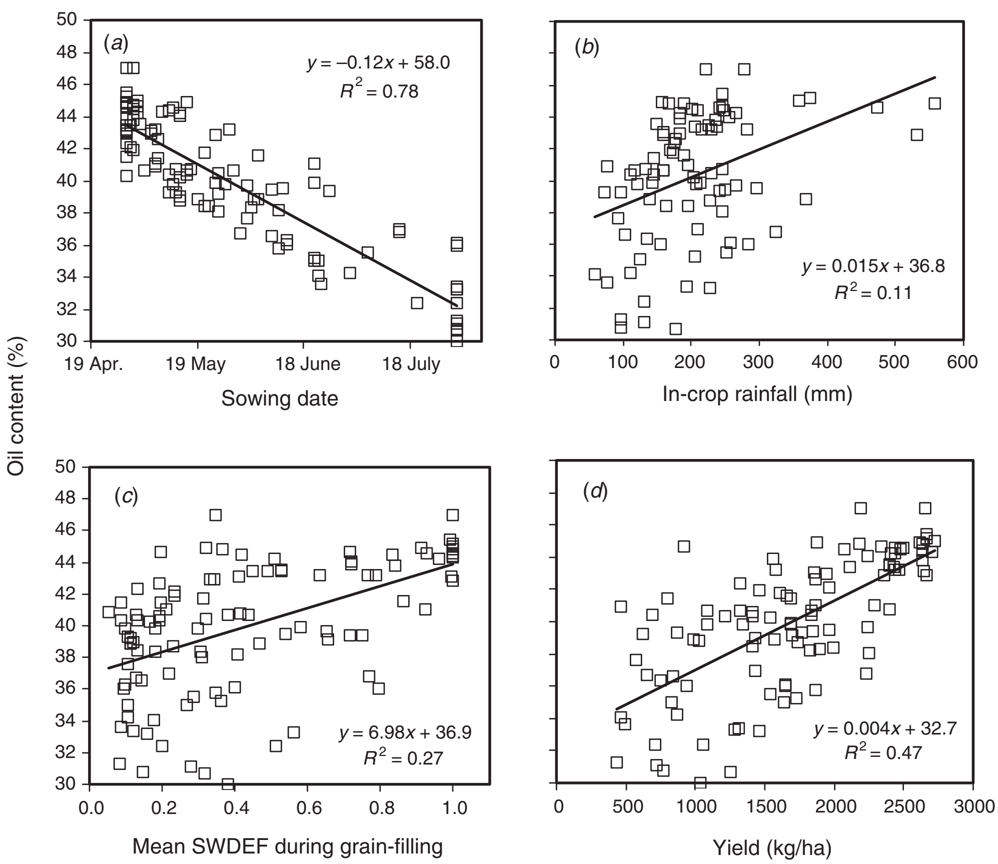

Fig. 8. Scatter plots of factors driving inter-annual variability in oil content at one example location, Moree with 100 mm available soil water at sowing. Oil content *v*. (*a*) sowing date, (*b*) in-crop rainfall, (*c*) mean soil water deficit factor between flowering and maturity, and (*d*) grain yield. In each plot, each point is one of 103 simulated seasons.

content variation, at any given sowing date oil content varied by up to 5%, presumably due to variation in temperature and water deficit conditions during grain filling. Robertson *et al*. (2004) showed the strong influence of sowing date on oil content in northern environments similar to that found in southern (Hocking and Stapper 2001) and Western Australia (Walton 1999).

Oil content was related positively to grain yield (Fig. 8*d*); however, the strength of the correlation was overall weaker than that with sowing date and also varied somewhat across locations. In general, the wetter the location the stronger the correlation between oil content and grain yield (Table 2). Moreover, within a location, at higher levels of starting soil water the correlation was also stronger, suggesting that where water supply is more reliable, higher yields will be associated with higher oil contents. The corollary to this is that with low levels of starting soil water or in dry locations, high yield will not necessarily be associated with high oil content. At the 200-mm soil water level, 66–71% of the variation in oil content could be explained by grain yield, except at the driest location, Roma where the R^2 value was 48%.

The positive correlation between yield and oil content has implications for riskiness of profit, as gross margin will be reduced in dry years to a greater extent than yield, whereas in good years, gross margin will increase in a greater proportion to yield. This suggests that canola is more risky than other crop enterprises (e.g. wheat) where yield and protein content are often inversely related, which confers some stability to profit.

Relationship of grain yield, oil content, and gross margin variation with SOI phase

Variation in grain yield and oil content was analysed by SOI phase in the April–May period. In the 103 seasons analysed, there were 16, 22, 14, 26, and 25 seasons that fell into the negative, positive, falling, rising, and zero categories, as defined by Stone and Auliciems (1992), respectively. Simulated grain yield and oil contents for the case of 100-mm starting soil water at Moree were analysed by SOI phase to see if some skill in seasonal climate forecasting could be achieved. It was expected that grain yield would be forecast with some skill, as has been shown previously

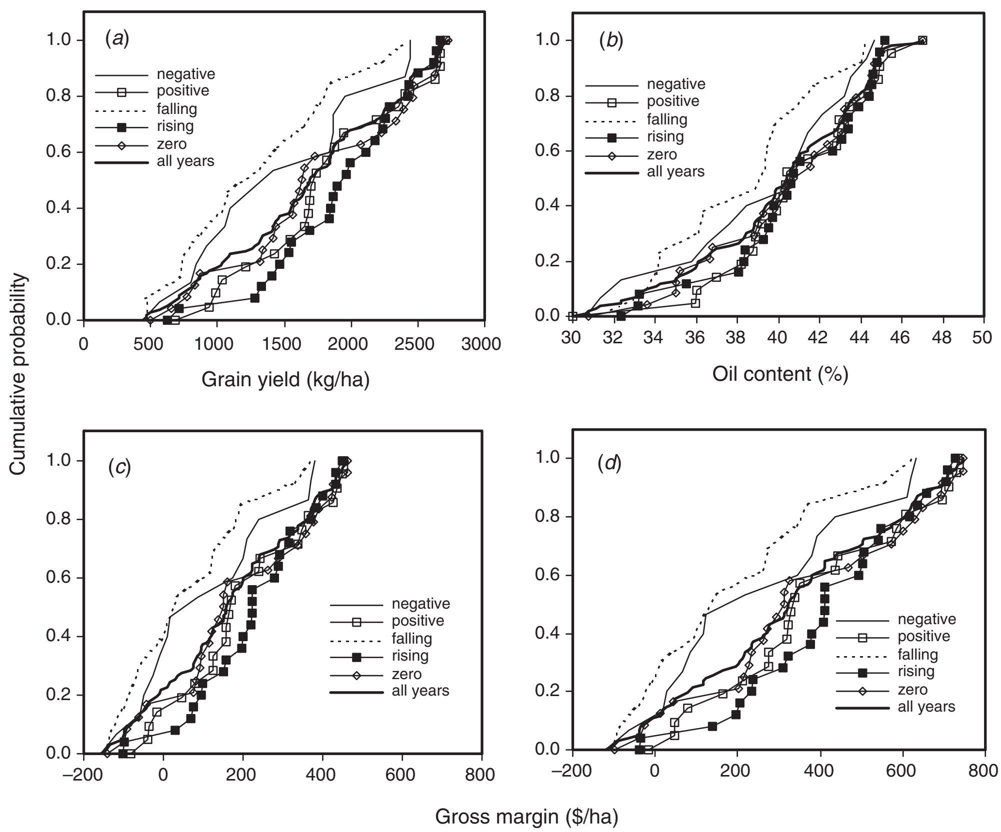

Fig. 9. Cumulative distribution functions of simulated (*a*) grain yield, (*b*) oil content, (*c*) gross margin for a grain price of $250/t, and (*d*) gross margin for a grain price of $350/t for Moree with 100 mm available soil water at sowing. In each plot, CDFs of particular phase categories of the SOI in April–May are compared with the distribution from all years simulated. In the 103 seasons simulated, there were 16, 22, 14, 26, and 25 seasons that fell into the negative, positive, falling, rising, and zero categories, respectively.

Table 3. Analysis of grain yield, oil content, and gross margin for 2 grain prices by SOI phase for Moree and 100 mm starting soil water
The SOI phase used was that in April–May of the year that the crop was sown

SOI phase	No. of years	Grain yield (kg/ha)			Oil content (%)			Gross margin ($/ha)					
								Grain price $250/t			Grain price $350/t		
		Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
Negative	16	1449	2442	436	39.0	44.7	30.7	102	381	–159	243	634	–122
Positive	22	1797	2707	686	40.7	47.0	30.0	196	451	–83	375	732	–16
Falling	14	1289	2412	464	38.1	44.2	31.1	59	373	–148	183	623	–107
Rising	26	1898	2665	626	40.6	45.2	32.4	220	448	–100	408	727	–40
Zero	25	1741	2726	498	40.2	47.0	30.7	181	462	–141	354	747	–98
All years	103	1686	2726	436	39.9	47.0	30.0	165	462	–159	331	747	–122

for wheat in the north-eastern wheatbelt (Hammer *et al*. 1996). As well, of particular interest was the proposal that oil content could be forecast with some skill, because the climatic influences on it occur at a different time of the season to yield. As the combination of yield and oil content determines gross margin, and yield and oil content are only moderately correlated (Figs 3*d*, 8*d*) then it was also of interest if the SOI phase system could forecast variation in gross margin.

The CDFs of grain yield and oil content are presented in Fig. 9. Mean, minimum, and maximum values for these attributes and gross margin calculated with two grain prices (AU$250 and 350/t) are listed by SOI phase in Table 3. For yield (Fig. 9*a*) there is a clear negative separation of the yield distribution from seasons in which the SOI in April–May is 'negative' or 'falling' compared with the 'all years' case. The mean yields for these categories of season were *c*. 300 kg/ha less than the 'all years' case and *c*. 500 kg/ha less than the 'rising' or 'positive' phases (Table 3). The 'rising' phase gave a yield distribution that was higher yielding in two-thirds of years than the 'all years' case and a mean grain yield that was 200 kg/ha greater. These results are similar to those found by Hammer *et al*. (1996) for wheat in this region and hence not unexpected for another winter crop such as canola.

For oil content (Fig. 9*b*), the 'negative' and 'falling' phases have lower oil content distributions than the 'all years' case. The CDFs for these categories of season gave oil contents on average *c*. 1–2% less than other season types. In contrast to the case for yield, there was no indication that a 'rising' phase of the SOI gave a higher expectation for oil content than the 'all years' case. For both yield and oil content the 'zero' phase had a distribution and mean value similar to that for the 'all years' case.

Yield and oil content were combined for each season and the gross margin calculated. Assumptions were: cut-off for oil bonus/penalty of 1.5% per 1% change in oil content was 42% oil content, variable costs were AU$250/ha (Cawley and Robertson 2003), and grain price was either AU$250 or 350/t. With the tendency for both yield and oil to be lower in 'negative' or 'falling' SOI phases, this translated into large differences in gross margin (Table 3, Fig. 9*d*, *e*). For the low grain price of $250/t there was a $60–100/ha mean difference from the 'all years' case. At the higher grain price of $350/t the difference was $90–150/ha. There was, depending upon grain price, a $60–70/ha positive difference between the gross margin in the 'rising' SOI phase years compared to the 'all years' case. Overall, those SOI phase years that had higher mean outcomes than the 'all years' case also had larger minimum and maximum values (Table 3).

Conclusions

This study has highlighted the dominant climatic influences on the variability of canola yield and oil content in a semi-arid subtropical climate. Location, plant-available soil water at sowing (PAW), and in-crop rainfall had greatest influences on grain yield expectations, whereas variation in oil content was most strongly affected by sowing date, followed by location, with PAW having a minor effect. The analysis underscored the importance of early sowing for both yield and high oil content. Significantly, the price bonus cut-off for oil content of 42% was only exceeded in 25, 40, 40, and 55% of seasons for Roma, Walgett, Moree, and Gunnedah, respectively, placing a high reliance on achieving high yields to ensure profitability. Some of this risk can be managed with the use of the SOI phase system, as negative and falling phases of the SOI in April–May were associated with lower, whereas positive and rising phases with higher, grain yield and oil content. The choice to sow canola could be a tactical decision that depends upon the seasonal climate outlook. Finally, the algorithm developed to predict oil content needs wider testing. The framework could also be employed to explore the nature of cultivar by environment effects on oil content.

Acknowledgments

Rod Bambach (NSW Agriculture), Brett Cocks, Natalie Hillcoat, and Shayne Cawthray (CSIRO Sustainable Ecosystems), and Scott Cawley (QDPI) assisted with collection of the field datasets. This work was supported in part by the Grains Research and Development Corporation, CSIRO, and NSW Agriculture.

References

Andersen MN, Heidmann T, Plauborg F (1996) The effects of drought and nitrogen on light interception, growth and yield of winter oilseed rape. *Acta Agriculturae Scandinavica, Section B – Plant Soil Science* **46**, 55–67.

Canvin DT (1965) The effect of temperature on the oil content and fatty acid composition of the oils from several oil seed crops. *Canadian Journal of Botany* **43**, 62–69.

Cawley S, Robertson MJ (2003) 'Canola.' Queensland Department of Primary Industries Winter Crop Management Notes for the Darling Downs and Maronoa. CD-ROM, Range Media.

Champolivier L, Merrien A (1996) Effect of water stress applied at different growth stages to *Brassica napus* L. var. *oleifera* on yield, yield components and seed quality. *European Journal of Agronomy* **5**, 153–160. doi: 10.1016/S1161-0301(96)02004-7

Connor DJ, Loomis RM (1991) Strategies and tactics for water-limited agriculture in low-rainfall Mediterranean climates. In 'Proceedings of the International Symposium on Improvement and Management of Winter Cereals under Temperature, Drought and Salinity Stresses'. Cordorda, Spain, 26–29 October 1987, Monographia no. 76. (Eds E Acevedo, C Gimenez, E Fereres, JP Srivasta) pp. 441–464. (Instituto Nacional de Investigacionnes Agrarias, Ministerio de Agricultura: Madrid)

Farre I, Robertson MJ, Walton GH, Asseng S (2002) Simulating phenology and yield response of canola to sowing date in Western Australia using the APSIM model. *Australian Journal of Agricultural Research* **53**, 1155–1164. doi: 10.1071/AR02031

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* **35**, 743–764.

Gabrielle B, Denoroy P, Gosse G, Justes E, Andersen MN (1998) Development and evaluation of a CERES-type model for winter oilseed rape. *Field Crops Research* **57**, 95–111. doi: 10.1016/S0378-4290(97)00120-2

Hammer GL, Holzworth DP, Stone R (1996) The value of skill in seasonal forecasting to wheat crop management in a region with high climatic variability. *Australian Journal of Agricultural Research* **47**, 717–737.

Hocking PJ, Kirkegaard JA, Angus JF, Gibson AH, Koetz EA (1997) Comparison of canola, Indian mustard and Linola in two contrasting environments. I. Effects of nitrogen fertilizer on dry-matter production, seed yield and seed quality. *Field Crops Research* **49**, 107–125. doi: 10.1016/S0378-4290(96)01063-5

Hocking PJ, Stapper M (2001) Effects of sowing time and nitrogen fertiliser on canola and wheat, and nitrogen fertiliser on Indian mustard. I. Dry matter production, grain yield, and yield components. *Australian Journal of Agricultural Research* **52**, 623–634. doi: 10.1071/AR00113

Hodgson AS (1979) Rapeseed adaptation in northern New South Wales. II. Predicting plant development of Brassica campestris L. and Brassica napus L. and its implications for planting time, designed to avoid water deficit and frost. *Australian Journal of Agricultural Research* **29**, 711–725.

Holland JF, Robertson MJ, Cawley S, Thomas G, Dale T, Bambach R, Cocks B (2001) Canola in the northern region: where are we up to? In '12th Biennial Australian Research Assembly on Brassicas, Victoria'. pp. 213–217.

Holmes MRJ (1980) 'Nutrition of the oilseed rape crop.' (Applied Science Publishers: London)

Jensen CR, Mogensen VO, Mortenson G, Fieldsend JK, Milford GFI, Anderson MN, Thage JH (1996) Seed glucosinolate, oil and protein contents of field grown rape (*Brassica napus*) affected by soil drying and evaporative demand. *Field Crops Research* **47**, 93–105. doi: 10.1016/0378-4290(96)00026-3

Mailer RJ, Cornish PS (1987) Effects of water stress on glucosinolate and oil concentrations in the seed of rape (*Brassica napus* L.) and turnip rape (*B rapa* L. var *silvestris* [Lam] Briggs). *Australian Journal of Experimental Agriculture* **27**, 707–711.

Mendham NJ, Salisbury PA (1995) Physiology: crop development, growth and yield. In 'Brassica oilseeds: production and utilization'. (Eds DS Kimber, DI McGregor) pp. 11–64. (CAB International: Wallingford, UK)

Pritchard FM, Eagles HA, Norton RM, Salisbury PA, Nicolas M (2000) Environmental effects on seed composition of Victorian canola. *Australian Journal of Experimental Agriculture* **40**, 679–685. doi: 10.1071/EA99146

Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998) APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* **56**, 1–28. doi: 10.1016/S0308-521X(97)00028-0

Ritchie JT (1973) Influence of soil water status and meteorological conditions on evaporation from a corn canopy. *Agronomy Journal* **65**, 893–897.

Robertson MJ, Carberry PS, Huth NI, Turpin JE, Probert ME, Poulton PL, Bell M, Wright GC, Yeates SJ, Brinsmead RB (2002*a*) Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agricultural Research* **53**, 429–446. doi: 10.1071/AR01106

Robertson MJ, Holland JF, Bambach R (2004) Response of canola and Indian mustard to sowing date in the grain belt of north-eastern Australia. *Australian Journal of Experimental Agriculture* **44**, 43–52. doi: 10.1071/EA02214

Robertson MJ, Holland JF, Cawley S, Bambach R, Cocks B, Watkinson AR (2001) Phenology of canola cultivars in the northen region and implications for frost risk. In 'Proceedings of the 10th Australian Agronomy Conference, Hobart'. www.regional.org.au/au/asa/2001/

Robertson MJ, Holland JF, Cawley S, Potter TD, Burton W, Walton GH, Thomas G (2002*c*) Growth and yield differences between triazine-tolerant and non triazine-tolerant cultivars of canola. *Australian Journal of Agricultural Research* **53**, 643–651. doi: 10.1071/AR01159

Robertson MJ, Holland JF, Kirkegaard JA, Smith CJ (1999) Simulating growth and development of canola in Australia. In 'Proceedings of the 10th International Rapeseed Congress, Canberra, ACT'. www.regional.org.au/au/gcirc/index.htm.

Robertson MJ, Watkinson AR, Kirkegaard JA, Holland JF, Potter TD, *et al.* (2002*b*) Environmental and genotypic control of time to flowering in canola and Indian mustard. *Australian Journal of Agricultural Research* **53**, 793–809. doi: 10.1071/AR01182

Si P, Walton GH, Galwey N, Turner D (1999) Post-anthesis duration and rainfall affect oil content of canola. In '1999 Oilseeds Update-Western Australia'. (Ed. P Carmody) pp. 19–20. (Agriculture Western Australia: South Perth, W. Aust.)

Slatter J (1989) Canola in northern Australia. In '7th Australian Research Assembly on Brassicas, Toowoomba, Australia, September 1989'.

Stone RC, Auliciems A (1992) SOI phase relationships with rainfall in eastern Australia. *International Journal of Climatology* **16**, 625–636.

Siddique KHM, Regan KL, Tennant D, Thomson BD (2001) Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. *European Journal of Agronomy* **15**, 267–280. doi: 10.1016/S1161-0301(01)00106-X

Triboi-Blondel AM, Renard M (1999) Effects of temperature and water stress on fatty acid composition of rapeseed oil. In '10th International Rapeseed Congress, Canberra, ACT'. www.regional.org.au/au/gcirc/index.htm.

Walton GH (1999) Cultural practices and their effects on canola yield and oil in Western Australia. In 'Oilseeds crop updates'. www.agric.wa.gov.au/cropupdates/1999/oilseeds/Walton.htm.

Walton G, Si P, Bowden B (1999) Environmental impact on canola yield and oil. In 'Proceedings of the 10th International Rapeseed Congress, Canberra, ACT'. www.regional.org.au/au/gcirc/index.htm.

Manuscript received 24 October 2003, accepted 9 March 2004