CROP SCIENCE SOCIETY
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NEWSLETTER

March 2020

The next Crop Science Society Technical Forum is scheduled for Tuesday the 17th March at Roseworthy from 7.30pm.

Dr Alan McKay (SARDI) continues to be a regular contributor to the CSSSA forums. This meeting he will delve into the current season risks with respect to root diseases as well as cover some of the new DNA testing that is being validated, including rhizobia and likely inoculant responses!

Our second speaker is Dr Graham Lyons (Adelaide University) who will present SAGIT trial results from the Lower and Mid North on sodicity & salt tolerance of oats.

Zoom Meeting Details

https://zoom.us/j/274342499
Meeting ID: 274 342 499

We look forward to seeing you there!

Member in Focus - Jamie Wilson

Jamie grew up on the family farm at South Hummocks in the mid north. From here worked for his Uncle's on their farm at Whitwarta before heading to Roseworthy Ag College. Graduating from the University of Adelaide, then during his career he has also completed Post Graduate studies in Agribusiness. During his careers Jamie has worked as a plant pathologist, agronomist and spent 7 years working in the competitive world of fertiliser and running the Viterra Fertiliser business.

For the last 7 years Jamie has been self-employed and re-engaged with his agronomic and research roots through his own company doing contract work for various companies and organisations. Currently he is contracting for Pioneer Seeds and also the Upper North Farming Systems.

As immediate past president of Crop Science I have found the organisation to be invaluable in gaining access to excellent speakers and research. Working with farmers again has re-invigorated my passion for agronomy and research. During the last 2 years I have been advocating for the farming community for the removal of the GM Moratorium and the ability for SA to once again become a centre agricultural research and technology by embracing everything that agriculture has to offer.

Report on the conference Plant Biology 2019: Crop Society

Kara Levin, PhD student University of Adelaide

I had the privilege of attending Plant Biology 2019 in San Jose, California, an event hosted by ASPB (American Society of Plant Biologists) which had over 1400 attendees. Overall the conference had a range of interesting topics. One that was particularly interesting was a symposium on the future of agriculture. A speaker from a company called Impossible Foods talked about their latest product called the Impossible Burger: a burger that is the same taste and nutrition as a beef burger, but completely sourced from plants. The most helpful symposium for my research was the section 'Plant Disease and Resistance Mechanisms'. A very important concept presented was the fact that there is a dynamic relationship in immune response signalling or symbiosis based on the nutrient status of plants. In other words, a plant is more receptive to symbiosis when it is deficient in nutrients but will trigger an immune response if it is nutrient-sufficient. This may have implications in my research on parasitic interactions between nematodes and plants; would the host plant behave differently under different nutrient levels?

I was selected for a talk during the symposia of 'Plant-Biotic Interactions' to present my PhD research on a novel discovery on interactions between cereal cyst nematode and wheat. This was an exciting opportunity because I was speaking to a range of international researchers working on similar plant-pathogen interactions. My presentation sparked the interest of several researchers and lead to insightful discussions which contributed to my project and understanding of the subject even further. Importantly, no other attendees had seen the results I presented, confirming that my discovery is indeed novel. I also presented an electronic poster that contained videos of my discovery. This was an even greater opportunity to talk one-on-one with some interested scientists. One of the event organizers, a leading professor in soybean cyst nematode resistance, was particularly excited by my poster and introduced me to several of his lab researchers. They showed me some exciting new results in gene expression within feeding sites of soybean cyst nematodes. These results directly corresponded to the physical and morphological results that I had presented, further reassuring me that my research provides new evidence for some well-known cyst nematode interactions.

I sincerely thank CSSA for the Duncan Correll travel award to attend this conference. It has helped me to disseminate my novel findings to an audience of international scientists within the field. Additionally, it has opened doors for me to build bridges for future collaborations and research opportunities.

Seeder-based approaches to reduce the impact of water repellence on crop productivity. I. Soil wetter evaluation

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Key messages

1. A soil wetter evaluation trial conducted over 2 years at the same site compared 15 different treatments.
2. Six wetter treatments provided large crop establishment benefits (up to 55-60 p/m^2 at 36DAS) over two years, while 7 wetter treatments achieved no early impact.
3. In Year 1, five of the better wetters produced an extra wheat grain yield (up to 0.22 t/ha), while in Year 2, all 13 wetters achieved a significant increase (0.5-1.07 t/ha) in barley grain yield. This difference in outcome between the 2 seasons is attributed to wide press-wheel furrows which remained stable and provided effective water harvesting over the 2019 season, but backfilled from drift early in 2018.
4. The best soil wetter treatment achieved only 66% of the establishment number and 85% of the grain yield of an on-row (no-wetter) sowing reference in 2019.
5. The early impact of a soil wetter chemistry is likely site-specific, the results suggest the season long impact on grain yield is likely maximised by effective water harvesting furrows. The soil wetter products achieving the highest early impacts also yielded best under the experimental conditions where plant density was a major driver of grain yield.

Why do the trial?

Non-wetting sands have low fertility and suffer from delayed and uneven wetting, which leads to erratic crop establishment, staggered weed germination and generally poor crop productivity due to low plant densities, low nutrient access, poor weed control and crop damage in areas prone to wind erosion. A range of trials in the GRDC funded Sandy Soils Project (CSP00203) are investigating effective solutions available at seeding time to mitigate the impacts of water repellence.

Soil wetter chemistries are varied and complex and little is known of their individual suitability to local water repellence. Modern soil wetters typically have both surfactant and humectant properties. Surfactant chemistry lowers the surface tension between the liquid and non-wetting sand, which allows the liquid to more readily infiltrate. Humectant chemistries are designed to counter the potential for excessive drainage of the surfactant in sandy soils through the use of co-polymers to promote a horizontal spread of the liquid increasing the quantity of liquid retained within the furrow seed zone. Ten years of research testing soil wetters applied at seeding time in WA was recently summarised by Davies et al. (2019) and found that;

- Banded soil wetters were most beneficial for dry sown cereals on repellent forest gravels, with less reliable benefits for break-crops.
- Benefits of banded wetters were minimal or at best sporadic for dry sown crops on deep sands, with no benefit under wet sowing of any crop or in any soil type.
- Benefits are larger in seasons with low and sporadic germinating rains in autumn.

Previous SA research at Wharminda on EP (Ward et al. 2019) conducted over 2015-17 found that two soil wetting agents evaluated among other strategies could significantly improve wheat, barley and lupin establishment and had a positive impact on grain yield, in 2 years out of 3. Building on the above, the Murlong soil wetter evaluation trial aimed to broaden the range of soil wetter types and combinations being evaluated under contrasting furrow placement scenarios.

How was it done?

During 2018-19 soil wetter evaluation trials were conducted at Murlong on Eyre Peninsula (EP) (see 2018 results on p.114 in the 2018 EPFS Summary). In Year 2 (2019), 6 row x 25m long plots set to 0.28m row spacing were sown at 6 km/h using a deep banding knife point operating at 110mm depth, followed by twin seeding discs and a furrow stabilising V press wheel, 140mm wide. Plots were sown at 3-5 cm depth on the 15-17 May with CL Scope barley treated with Vibrance and Cruiser 350 at a seed rate of 68 kg/ha. *Uniform* fungicide at 400 mL/ha and Intake Hi-Load Gold fungicide at 250mL/ha were also applied in furrow in 80 L/ha volume to address medium/high risks of rhizoctonia / yellow leaf sport and take-all, respectively. All plots were inter-row sown to barley in the standing wheat stubble, under a randomised complete block experimental design. There was an additional on-row sowing treatment with no wetter applied. All treatments were replicated 4 times and the 2018 treatments were re-applied to the same plots in 2019.

A stable consolidated furrow surface is often deemed critical to secure the efficacy of furrow surface applied soil wetters, which must be sprayed onto a firm, settled soil, and not mixed into loose backfill. Soil wetter treatments were applied in 100 L/ha volume of rainwater with foam suppressant at 0.05% v/v, using a Teejet TPU1501 low angle flat fan nozzle behind press-wheels to produce a 25-30mm wide band footprint on the furrow surface (FS). In contrast, seed zone (SZ) applications were delivered with a *Keeton* in-furrow seed firmer to achieve accurate co-location with the seeds. Nutrition was supplied at 28 kg N/ha, 12 kg P/ha, 6 kg S/ha, 1.5 kg Zn/ha deep banded at furrow depth. There was also a foliar application of Zn, Cu and Mn at tillering.

Table 1: Soil wetter treatments evaluated at the EP-Murlong site over 2018-19

Product names	Supplier	Rate (L/ha)	Placement zone*	$/ha (2018)
H2Pro® TriSmart	ICL Specialty Fertilisers	2	FS	15
H2Flo™	ICL Specialty Fertilisers	2	FS	16
Soak-n-Wet	Victorian Chemicals	4	FS	14
Aquaforce	SST Australia	2.5	FS	20
SeedWet	SST Australia	2	FS	17
RainDrover	SACOA	2	SZ	12
SE14®	SACOA	3	SZ	21
Aquaboost AG30 FB+AG30NWS	Bio Central Lab	2+2	FS+SZ	24
Precision Wetter + Nutri-Wet	Chemsol GLE	2+2	FS+SZ	21
Divine® Integrate/Agri mix	BASF	1+1	FS+SZ	20
H2Flo ™ + RainDrover	ICL Specialty Fertilisers + SACOA	2+2	FS+SZ	28
Bi-Agra Band	SST Australia	1.5+1.5	FS+SZ	22
Aquaforce + SE14®	SST Australia+ SACOA	2+3	FS+SZ	41

*SZ=Seed Zone; FS=Furrow Surface

What happened?

Barley crop establishment at 5 weeks after sowing is shown in Figure 1 (top). The inter-row control established at 12% of seeds sown (27 plants/m^2, respectively), indicating poor conditions for crop establishment in this severely water repellent sand, while the on-row sowing treatment (with no wetter) offered a significant establishment benefit in excess of 400% (+85 plants/m^2). In contrast, the wetters on inter-row sown treatments showed a variable early impact, and increased barley crop establishment by 17 plants/m^2 on average, with a range of 0-56 plants/m^2.

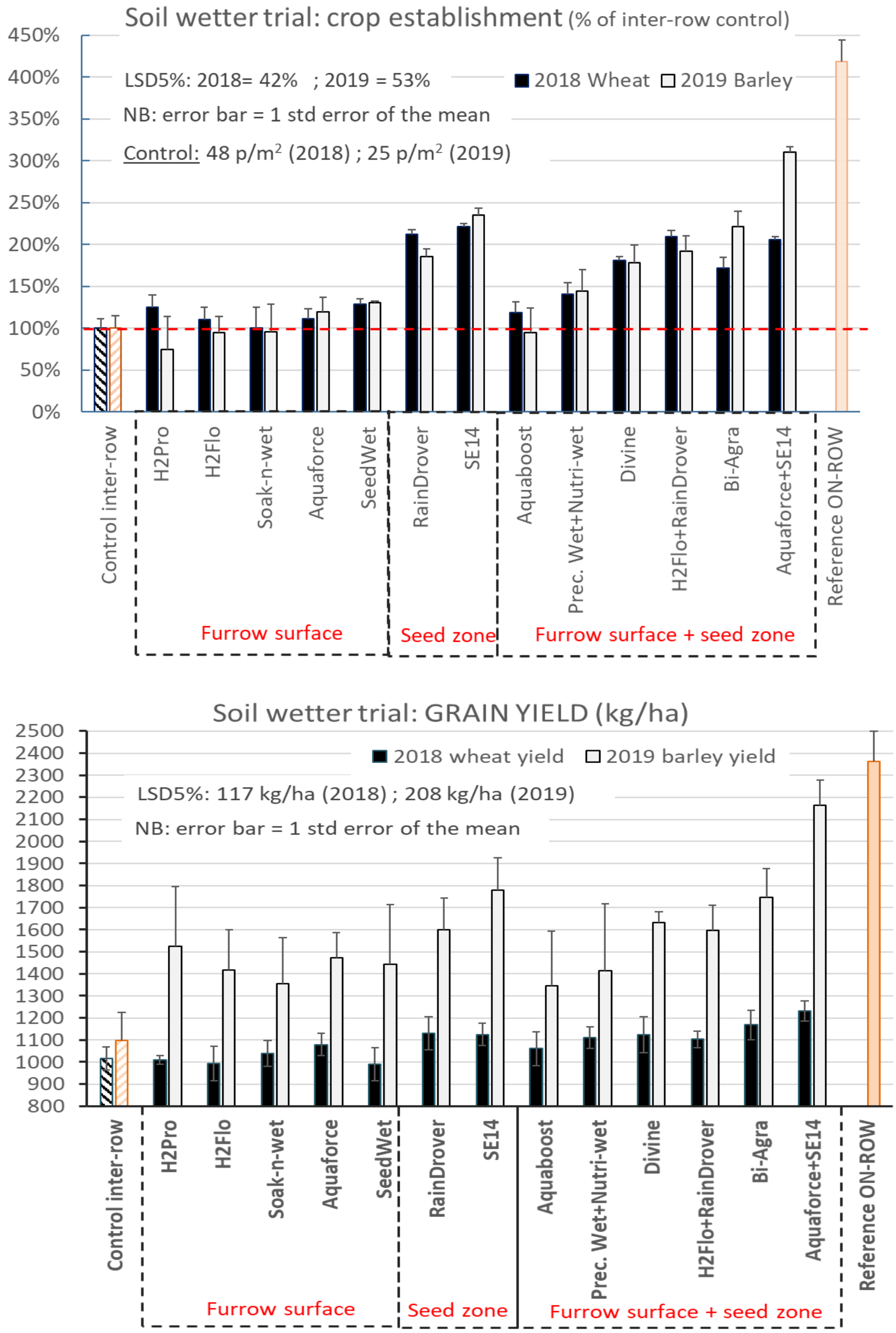

Figure 1: Effect of the 13 soil wetter treatments on: (top) crop establishment over 2 seasons (at 38 and 35 days after sowing) relative to no wetter control (control = 100%) and: (bottom) grain yield (kg/ha), relative to a no-wetter control (left, 2018/19) or on-row (right, 2019). The error bars are the std error of the mean. The 2019 soil wetter treatments and control were sown on the inter-row, with an additional on-row no-wetter reference. The wetter treatments are detailed in Table 1 and their placement varied as indicated.

The impact of soil wetter treatments on crop establishment was similar in both years of the trial, as confirmed by a strongly positive correlation between results in each year (r = +0.849, P<0.001, data not shown). Interestingly, all treatments with only furrow surface applied wetters had a limited effect on crop establishment at Murlong, while the two treatments with a seed zone applied humectant (SE14® or RainDrover) performed well. Overall, 4 out of 6 seed zone + furrow surface wetter combinations provided a significant establishment benefit compared with the control.

Combining a surfactant on the furrow surface (FS, Aquaforce) with a humectant in the seed zone (SZ, SE14®) provided a synergistic response in 2019 (where the treatment combining wetters had a greater effect than adding the effects of the two separate wetter treatments independently), possibly due to the effective water harvesting furrows kept intact over that season. A similar combination based on H2Flo™ (FS) and Raindrover (SZ) did not synergise, with the performance driven mostly by the seed zone wetter.

In 2019 (decile 1 GSR) under inter-row sowing there were significant barley grain yield responses to all soil wetters (Figure 1, bottom). The grain yield in the inter-row sown control averaged 1.10 t/ha. On the inter-row sown plots, soil wetter treatment yield increases ranged from +23 to +97 %, with a maximum response of +1.07 t/ha. The water harvesting furrows kept intact over the 2019 season are thought to have driven a blanket yield response to soil wetters (with total response also product specific), while in 2018, the furrows backfilled early from drift and limited wheat grain yield responses (up to 0.22 t/ha) were measured, while the early impacts on crop establishment was similar.

In comparison, the on-row control yielded the highest (x2.15 the inter-row control), providing a 1.26 t/ha grain yield benefit. A strong positive correlation (r = +0.883, P<0.01, data not shown) was obtained between grain yield and plant density at 36DAS, which means the soil wetters which achieved a greater early impact secured the maximum yield. Overall, the treatment grain yield responses across the 2 seasons were strongly correlated (r = +0.815, P<0.01, data not shown). This is encouraging and suggest that an effective wetter with consistent effects across multiple years, once identified, may be safely recommended to farmers in that environment.

Table 2 provides a synopsis identifying the top 6 performers overall for both crop establishment and grain yield at Murlong. This evaluation was conducted using a precise split seeding system (knife point + independent dual seeding discs) where co-location of seed zone wetter and seed was assured and a stable wide furrow was provided for furrow surface wetters, applied with a nozzle over a 30mm wide band.

Rank	2018 wheat yield	2019 barley yield
1st	SE14® (SZ)+ Aquaforce (FS)	SE14® (SZ) + Aquaforce (FS)
2nd	Bi-Agra Band (SZ+FS)	SE14®(SZ)
3rd	Rain Drover (SZ)	Bi-Agra Band (SZ+FS)
4th	SE14® (SZ)	Divine® Integrate/Agri mix (SZ+FS)
5th	Divine® Integrate/Agri mix (SZ+FS)	RainDrover (SZ)
6th	n/a	RainDrover (SZ)+ H2Flo™ (FS)
Treatment / control	111-121 %	145-197 %
Control yield	1.02 t/ha	1.1 t/ha

Table 2. Top 6 soil wetter products and placement (SZ seed zone or FS furrow surface) with significant yield outcomes. Some treatments might not be significantly from others in the ranking.

What does this mean?

- The top 6 soil wetter treatments used at Murlong were consistent across both years. The findings that i) the 13 product chemistries had a consistent early impact on crop establishment at this site over 2 years and, ii) that maximum grain yield response correlated strongly with greater early impact, are encouraging. Once a suitable product is found for a particular sand environment, it may prove reliable over many seasons and may be recommended to farmers.
- An additional factor likely influencing the cost-effectiveness of a soil wetter is the water harvesting capacity of press wheel furrows, ensuring that capacity is maximised and maintained for as long a period as possible during the season.
- The optimum furrow location, application rate and water volume per ha may require further experimentation on a product by product basis.
- The crop establishment and grain yield benefits achieved with wetters applied under inter-row sowing were not as great as those delivered with an on-row seeded crop without wetters. Analysis of the combined effects of the seeding system and wetters is available in the next article.

Acknowledgements

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Re-evaluating sowing time of spring canola (*Brassica napus* L.) in south-eastern Australia—how early is too early?

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Abstract. Optimising the sowing date of canola (*Brassica napus* L.) in specific environments is an important determinant of yield worldwide. In eastern Australia, late April to early May has traditionally been considered the optimum sowing window for spring canola, with significant reduction in yield and oil in later sown crops. Recent and projected changes in climate, new vigorous hybrids, and improved fallow management and seeding equipment have stimulated a re-evaluation of early-April sowing to capture physiological advantages of greater biomass production and earlier flowering under contemporary conditions. Early-mid-April sowing generated the highest or equal highest yield and oil content in eight of nine field experiments conducted from 2002 to 2012 in south-eastern Australia. Declines in seed yield (-6.0% to -6.5%), oil content (-0.5% to -1.5%) and water-use efficiency (-3.8% to -5.5%) per week delay in sowing after early April reflected levels reported in previous studies with sowings from late April. Interactions with cultivar phenology were evident at some sites depending on seasonal conditions. There was no consistent difference in performance between hybrid and non-hybrid cultivars at the earliest sowing dates. Despite low temperatures thought to damage early pods at some sites (< 28C), frost damage did not significantly compromise the yield of the early-sown crops, presumably because of greater impact of heat and water-stress in the later sown crops. A validated APSIM-Canola simulation study using 50 years of weather data at selected sites predicted highest potential yields from early-April sowing. However, the application of a frost-heat sensitivity index to account for impacts of temperature stress during the reproductive phase predicted lower yields and higher yield variability from early-April sowing. The frost-heat-limited yields predicted optimum sowing times of mid-April at southern sites, and late April to early May at the northern sites with lower median yield and higher yield variability in crops sown in early April. The experimental and simulation data are potentially compatible given that the experiments occurred during the decade of the Millennium drought in south-eastern Australia (2002-10), with dry and hot spring conditions favouring earlier sowing. However, the study reveals the need for more accurate and validated prediction of the frost and heat impacts on field-grown canola if simulation models are to provide more accurate prediction of attainable yield as new combinations of cultivar and sowing dates are explored.

Additional keywords: frost, heat, phenology, simulation, water stress, water use efficiency.

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Introduction

Canola (*Brassica napus* L.) is the third most important grain crop in Australia, worth AU$2.7 billion in 2012-13 (AOF 2015) and is the most widely grown and important broadleaf break crop for cereal-based farming systems (Angus *et al*. 2015). Despite its profitability and acknowledged benefits to the farming system, canola is perceived by many growers to be a risky crop owing to the relatively high input costs and its greater sensitivity to heat and water stress compared with cereals. Consequently, the area of canola grown does not reflect its predicted benefits to farm income (Robertson *et al*. 2010), and the area of canola fluctuates considerably from year to year. For example, from a peak in 1999 of 2 Mha, the area of canola fell to ~0.5 Mha in 2006 during the Millennium drought (mid-1990s to 2010) and has only recovered recently with more favourable seasons to reach 3.7 Mha in 2013-14 (ABARES 2014;

Kirkegaard *et al*. 2016). Strategies to improve the productivity, reduce the risk and increase canola production are therefore of significant interest.

Traditionally, the recommended sowing time for canola in the major growing regions of southern New South Wales (NSW) has been from mid-April to mid-May (Colton and Sykes 1992; Matthews *et al*. 2015), with somewhat later optimum sowing times in northern regions. A significant body of previous research (Taylor and Smith 1992; Hocking *et al*. 1997; Hocking and Stapper 2001) emphasised the importance of timely sowing to maximise yield potential and water-use efficiency (WUE) in canola. Robertson *et al*. (1999*b*) summarised the research on sowing-date effects on canola in Australia up to that time, and found that the effect of late sowing on yield varied from -10% to +4% per week delay after late April, but suggested a rule-of-thumb based on 5% reduction per week delay in sowing. Subsequent research, which has included experimental plot studies (Farré *et al*. 2002; Robertson *et al*. 2004; Robertson and Kirkegaard 2005; Kirkegaard *et al*. 2006), paddock-scale surveys (Lisson *et al*. 2007) and simulation studies (Farré *et al*. 2002; Robertson *et al*. 2004) has largely confirmed this range in yield penalty with late-sowing in southern, northern and western regions of Australia.

The physiology that underpins the response to sowing time is relatively well understood. For a given environment, there will be an optimum flowering window that balances the risk of frost in crops flowering too early with that of heat and water stress in crops that flower too late. As well as avoiding temperature extremes, there is a need to optimise the balance of water supply between vegetative and reproductive growth. Increased vegetative growth can support a higher yield through greater pod numbers, but in areas of low and medium rainfall, this must be balanced to ensure availability of sufficient water during the reproductive stage for a high harvest index (HI). In the absence of significant water or temperature stress, yield will be positively correlated with biomass production, so crops flowering too early will have lower yield potential (Robertson *et al*. 2004). Consequently, sowing date recommendations vary for cultivars with different phenology to optimise these physiological trade-offs under the climatic conditions in specific regions (Matthews *et al*. 2015). In specific experiments or simulation studies, the interactive effects of sowing date, cultivar and seasonal conditions can generally be explained by the impacts of temperature extremes and the balance of vegetative and reproductive growth in relation to the supply of resources (water, nitrogen (N)). This holds true for canola grown in other regions of the world including Canada (Degenhardt and Kondra 1981), the Middle East (Ozer 2003) and China (Wang *et al*. 2012). Although optimum sowing dates can be identified based on physiology, other aspects of the farming system, including the equipment to establish crops reliably in different seedbed conditions, timing of autumn rainfall, and the risk of pests, diseases and effective weed control, may influence sowing-date decisions at the farm level.

In recent years, changing seasonal conditions, improved agronomy and new varieties have prompted a re-evaluation of sowing date recommendations in canola. The traditional autumn ‘breaking rain’ to establish crops has become less reliable since 1996 (Pook *et al*. 2009; Cai *et al*. 2012), and especially during the Millennium drought from mid 1990s to 2010 (Verdon-Kidd *et al*. 2014), a trend thought likely to persist. Improved summer-fallow management to conserve rainfall (Hunt and Kirkegaard 2011), modern no-till seeding equipment, and new fungicides, herbicides and insecticides have all provided improved options for successful establishment and protection in early-sown crops. There has also been a steady increase in the release of herbicide-tolerant hybrid cultivars with much higher vigour than the widely grown open pollinated (OP) triazine-tolerant (TT) varieties. There is a perception that excessive water use by early-sown, high-vigour hybrids may increase the risk of water stress during flowering and podfill in low- and medium-rainfall environments. Conversely, vigorous early-sown hybrids may reduce the evaporative loss and improve crop water relations. Some early-sown canola grazing experiments have revealed the potential for success with crops sown earlier in April, even when not grazed (Kirkegaard *et al*. 2012). As farm size and cropping areas increase, the capacity to sow crops in a timely way also favours an earlier start to the sowing program. These changes in climate, varieties and management options have prompted a re-evaluation of sowing date recommendations and interest in earlier sowing opportunities.

Theoretically, provided flowering dates can be maintained to hold the risk of temperature extremes constant, earlier sowing should provide a higher yield potential. From a physiological point of view, the WUE of early-sown canola could be increased through: (*i*) rapid soil coverage to reduce evaporative loss (E) and increase transpiration; (*ii*) more efficient transpiration during vegetative growth with the cooler conditions and lower vapour-pressure deficit (VPD); (*iii*) increased access to deep stored water due to longer vegetative stage and deeper rooting; and (*iv*) reduced heat and water stress during reproductive stages in spring (Robertson and Kirkegaard 2005). Excluding the recent experience in the higher rainfall zones involving later maturing, winter-type canola (Christy *et al*. 2013) or experience in grazing experiments (Kirkegaard *et al*. 2012; Sprague *et al*. 2015), there is little commercial or experimental experience of spring-type canola sown in early April in low-medium-rainfall zones of eastern Australia.

We report a series of nine field experiments in south-eastern Australia investigating sowing time cultivar interactions in spring canola, all of which included sowing times in early or mid-April. A range of cultivars that varied in phenology and/or vigour was included to provide further mechanistic insights. The outcomes of the experiments were supplemented by simulation studies using APSIM-Canola (Holzworth *et al*. 2014) to investigate the potential to improve yield and WUE in canola sown in early to mid-April, rather than in late April as currently recommended.

Materials and methods

Sites and experimental design

Nine field experiments were conducted during 2002-12 at sites across NSW and the Australian Capital Territory (ACT) from Tamworth in the north to Wagga Wagga in the south (Table 1). The experiments included a range of spring canola varieties that differed in phenological development (e.g. early, early-mid or mid-maturity) and crop vigour (TT and non-TT hybrids and OP

Table 1. Site and management details for nine field experiments investigating sowing date cultivar effects on canola production in south-eastern Australia

Growing-season rainfall (GSR) shows in-crop rainfall + irrigation (if irrigated), and in parentheses the measured or estimates of soil water at sowing (see footnotes); LTM, long-term mean. Hybrid cultivars are indicated by bold type and triazine-tolerant (TT) by italics. Soil N values are N present in soil at sowing, and added as fertiliser

Expt	Site	Soil type	GSR (Apr.-Oct.) (mm)		Sowing dates	Cultivars	Reps	Individual plot sizes (m)	Soil N (kg/ha)	Population (plants/m^2)
			Season	LTM						
1 (2002)	Condobolin	Chromosol	138 + 22 (76[B])	232	22 Apr.; 17 May; 14 June	**Hyola60**, Rainbow, Ripper, Oscar, Dunkeld, Ag-Outback, Ag-Emblem, Rivette	3	20 by 2.1	243, 0	54
2 (2003)	Condobolin	Chromosol	199 + 60 (61[B])	232	2, 22 Apr.; 13 May; 6 June	**Hyola60**, Rainbow, Ripper, Oscar, Dunkeld, AgOutback,	3	20 by 2.1	183, 0	40
3 (2003)	Grenfell	Kandosol	264 (41[A])	366	17 Apr.; 12 May; 11 June	*ATR-Beacon*, *Surpass501TT*	3	16 by 1.4	165, 44	30
4 (2007)	Canberra	Chromosol	323 + 110 (33[B])	330	21 Mar.; 5, 23 Apr.	**Hyola75**, AV-Garnet, Skipton	3	12 by 1.8	144, 50	50-60
5 (2007)	Wagga Wagga	Chromosol	218 + 158 (50[A])	331	4, 18 Apr.; 3 May	**Hyola75**, AV-Garnet, Skipton	3	12 by 2.2	161, 30	50-60
6 (2009)	Young	Kandosol	362 (24[B])	400	16, 29 Apr.	**Hyola601RR, 46Y20**, 46C76, **46Y78**, AV-Garnet, **Hyola50**, *Tawriffic*, *Triumph*	4	10 by 2.2	111, 50	40
7 (2009)	Trangie	Grey Vertosol	205 (150[A])	253	21 Apr.; 18 May	**Hyola50**, 44C79CL, Tarcoola	3	10 by 1.65	180, 50	20-30
8 (2012)	Trangie	Grey Vertosol	109 (180[A])	253	13, 26 Apr.; 14 May	**44Y84CL**, AV-Garnet, 43C80CL, **43Y85CL**, *ATR-Stingray*, ATR-Jackpot, *Hyola555TT*	3	10 by 1.65	112, 50	20-30
9 (2012)	Tamworth	Vertosol	239 (285[A])	315	20 Apr.; 16 May; 12 June	**Hyola50**, AV-Garnet, CB Agamax, 45Y82CL, Victory V3002, **Hyola575CL**, 44Y84CL, *Hyola559TT*, *Hyola555TT*, *ATRGem*, *CB JuneeHT*, 43C80CL, **43Y85CL**, *ATR-Stingray*	3	10 by 1.65	121, 75	40

[A]Measured at sowing.
[B]Calculated as 30% of fallow rainfall between January and first sowing date.

varieties), and represented a range of different herbicide-tolerance groups relevant in the regions. All experiments included at least one sowing date before April 25, which provided an opportunity to investigate varietal characteristics that may suit earlier sowing under a wide range of different conditions. The experiments were conducted on a range of soils and seasonal conditions that varied from extreme drought (e.g. Wagga Wagga 2007) to the higher yielding conditions at Tamworth in 2012 (Table 1).

Seeding rates in all experiments were adjusted for seed size and germination to establish a target population of ~40 plants/m^2 and experiments were sown with plot seeders into rows 0.18-0.33 m wide. All experiments received starter fertiliser with the seed, generally 100 kg/ha of Starter15 (Incitec Pivot, Melbourne; kg/ha: 14 N, 13 potassium, 11 sulfur), and subsequent N application at each experiment was based on pre-sowing, deep soil N tests and seasonal conditions to avoid nutrient limitations to yield (Table 1). At the southern sites (Grenfell, Young, Canberra and Wagga Wagga), fungicide treatments on the seed (Jockey, active ingredient (a.i.) fluquinconazole) or fertiliser (Impact, a.i. flutriafol) were also used to reduce the impact of the fungal disease blackleg (caused by *Leptosphaeria maculans*), and recommended pre- and post-emergent herbicides were used to control weeds. Observations of phenological development of crops in most experiments were made regularly to assess the start and end of flowering (Sylvester-Bradley and Makepeace 1984), and to optimise mechanical harvest time to avoid pod shattering. For mechanical harvest, the plots were desiccated using Reglone at 2.5 L/ha when 60-70% seeds showed colour change, and harvested 9-10 days later by using a plot harvester. Seed yield and HI were also measured from two bordered quadrats (each 0.4 m^2) cut by hand before desiccation. The samples were dried, threshed and weighed to determine HI, and a subsample of seed was used to measure oil content by wide-band nuclear magnetic resonance as described by Hocking *et al*. (1997).

Experiments 1 and 2 (2002, 2003): Condobolin

The experiments at Condobolin Agricultural Research and Advisory Station in central western NSW comprised factorial treatment structures involving two watering treatments, three or four sowing times, and eight (2002) or six (2003) cultivars. There were three replicates and a subplot size of 20 m by 2.1 m (Table 1). In both seasons, irrigation was applied to all treatments to ensure even establishment and to supplement the low seasonal rainfall. The supplementary water treatment comprised an additional 22 mm in 2002 (on 15 August), and an additional 60 mm in 2003 (30 mm on each of 15 July and 8 September). At harvest, HI was measured on only four cultivars in 2002 and three cultivars in 2003 (see Table 1) from two bordered quadrats (each 0.4 m^2) taken before desiccation. Seed yield and oil content were measured on all plots.

Experiment 3 (2003): Grenfell

The experiment was sown on a commercial farm site at Grenfell in southern NSW and consisted of a split-plot design with three sowing dates as main plots arranged in three blocks, and the factorial combination of two varieties (hybrid and conventional) and four fungicide treatments with individual plot size of 16 m by 1.44 m (see Kirkegaard *et al*. 2006). Only the full fungicide-treated plots with disease control were used in the analysis of sowing-date effects presented here. Seed yield was measured from harvested samples in each plot but no HI or oil content measurements were made at this site.

Experiments 4 and 5 (2007): Canberra, Wagga Wagga

Experiments with similar design were established in 2007 at Ginninderra Experimental Station (GES) at Canberra, ACT, and at NSW DPI Wagga Wagga Agricultural Research Institute. The experiments were designed to investigate the effects of winter defoliation on a range of canola varieties sown at different times (Sprague *et al*. 2010); only the undefoliated treatments are reported here. The experiments were designed as split-plots with sowing time as the main plots arranged in three blocks and the cultivars randomised within main-plots in subplots, which were 15 m by 1.8 m. Crop biomass was measured at around the 6-leaf stage from 0.4-m^2 quadrats taken in each plot as an estimate of early biomass production. A reliable estimate of seed yield from mechanical harvesting was not possible in the experiment because of the range in maturity times generated in adjacent plots by the sowing date cultivar grazing combinations. Therefore, seed yield at both sites was measured only from the two bordered quadrat cuts (0.4 m^2 in each plot), and a subsample of grain was used to determine oil content.

Experiment 6 (2009): Young

The experiment was conducted on a commercial farm at Young in southern NSW. The impacts of grazing treatments in the experiment have been described previously (Kirkegaard *et al*. 2012). The experiment was designed as a split-plot with two sowing dates as main plots arranged in four blocks, and the eight canola cultivars randomised as subplots (10 m by 2.2 m). The eight cultivars comprised hybrid and non-hybrid pairs from each of four herbicide groups (conventional, TT, Clearfield (CLF) and Round Up Ready (RR)). All herbicide groups were sprayed with the relevant herbicide as recommended for weed control. Due to the variation in maturity time generated by the treatments, the yield was assessed from both hand-cut quadrats (each 0.4 m^2) and from machine-harvested strips. The hand-cut and mechanically harvested samples showed close agreement (data not shown), indicating that significant pod-shattering and seed loss were not an issue. Seed oil content was measured on subsamples from the hand-harvested grain.

Experiments 7 and 8 (2009, 2012): Trangie

Experiments were carried out in 2009 and 2012 at the NSW DPI Trangie Agricultural Research Centre in central western NSW. In 2009, the experiment included two times of sowing and three canola cultivars with three replications and an individual plot size of 10 m by 1.65 m. In 2012, there were three sowing dates and seven canola cultivars with three replications. The experiments were designed as split-plots with sowing dates as main plots and cultivars randomised within sowing dates. Grain yield and HI were measured from bordered hand-harvested quadrats (1 m^2) taken at physiological maturity. A subsample of grain from machine-harvested strips was used to determine oil content.

Experiment 9 (2012): Tamworth

The experiment was conducted at the NSW DPI Tamworth Agricultural Institute and included three sowing dates and 14 commercial canola cultivars comprising four conventional, five TT and five CLF cultivars (Table 1). Cultivars were selected from different herbicide resistance groups as well as a mix of OP and hybrid varieties from different phenology groups. Observations included established plant populations, the start and end of flowering, and grain yield and HI measured from hand-harvested quadrats at physiological maturity. A subsample of grain was used to determine seed oil content.

Soil water and water-use efficiency

The amount of plant available water (PAW) before the first time of sowing was measured in most experiments as part of the pre-sowing N estimates and was generally assessed from soil cores taken to the estimated maximum rooting depth (1.6-2.0 m) at each site. The amount of water at wilting point was measured on disturbed soil using a pressure-plate apparatus at -1500 kPa suction in order to calculate PAW. In some experiments, PAW was also measured at harvest, although in most cases, the seasonal conditions were especially dry and PAW at harvest was assumed to be zero because of significant terminal stress. To compare the WUE at different sowing dates, the highest yielding cultivar was selected and water use was estimated from the time of the first sowing; we considered that this set the potential season length and potential evapotranspiration (ET) in each case. Seasonal WUE was estimated as yield/seasonal ET, where ET was estimated as the in-crop rainfall (from the first time of sowing to harvest) plus the change in PAW between the first time of sowing and harvest. At sites where soil water measurements were not taken before sowing, the starting PAW was assumed as 30% of total fallow rainfall (January to time of first sowing).

Statistical analyses

The experimental data were analysed by analysis of variance using GENSTAT versions 10-14 (Payne *et al*. 2007) with appropriate models to assess treatment effect and interactions. The experiments were analysed separately by year for main effects and interactions of sowing date and cultivar. In general, where significant effects were observed, means were compared using l.s.d. values at $P = 0.05$ unless otherwise stated.

Simulation study

The Agricultural Production Simulation (APSIM) model version 7.7 (Holzworth *et al*. 2014; www.apsim.info) was used to investigate the effect of early sowing on canola yield at a subset of the locations included in this study (Condobolin, Wagga, Young, Tamworth). APSIM-Canola has been widely validated across a broad range of environments (Robertson *et al*. 1999*a*, 2002; Farré *et al*. 2002; Robertson and Holland 2004; Robertson and Kirkegaard 2005; Wang *et al*. 2012; McCormick *et al*. 2015). However, because we were interested in sowing times earlier than those included in many previous studies, we also validated the model against the experimental data collected and present in this here.

Model validation

Crops were simulated according to available crop management and soil data at specific sites. Where soil water and mineral N were not measured at sowing, the simulation commenced at harvest of the preceding crop by using measured values if available, or the soil water and N content were assumed to be low (PAW 0 mm; 50 kg N/ha). Climatic data were extracted from the SILO Patched Point Dataset (www.longpaddock.qld.gov.au/silo/ppd/). Rainfall and temperature were corrected for readings obtained at the sites when available. At each of the sites, soils were described according to data collected by soil coring (Wagga Wagga, McCormick *et al*. 2015; Condobolin, Lilley *et al*. 2003; Young, Kirkegaard *et al*. 2012; Canberra; Sprague *et al*. 2014), or local soils were obtained from the APSoil database (Tamworth, Grey Vertosol Breeza No 123; Trangie No 684). Where cultivars had not been parameterised, cultivar phenology parameters were adjusted as described in Robertson and Lilley (2016), so that the simulation reflected the observed flowering dates for the cultivars in the experiments. In this case, the parameters altered were 'tt_emergence' (thermal time from emergence to end of the juvenile stage) and 'tt_end_of_juvenile' (thermal time from end of juvenile to floral initiation). Simulation outputs for yield and flowering date were compared with observed data. Regression analysis and root mean square deviation (RMSD) from the regression between observed and simulated values was calculated (Wallach and Goffinet 1989).

Simulating effects of sowing date

To expand the experimental results to a greater range of seasonal conditions, we conducted a simulation analysis to investigate the effect of earlier sowing on canola yield. We set up a factorial combination of six sowing dates three cultivars four locations. The study was conducted at four contrasting sites from the experimental study (Tamworth, Young, Condobolin and Wagga Wagga). For all sites, long-term daily climatic data were extracted from the SILO Patched Point Dataset (Jeffrey *et al*. 2001). Sowing was simulated at 2-week intervals from 1 April to 9 June with early maturity (e.g. Diamond), early-mid-maturity (e.g. ATR-Gem) and mid-maturity (e.g. AV-Garnet) cultivars. For these cultivars, the tt_emergence parameters were 235, 300 and 300, and tt_end_of_juvenile parameters were 395, 500 and 600, respectively. All cultivars were assumed to have conventional, OP growth type. The simulation ran continuously without resetting; therefore, soil water content at sowing was the result of soil water content at maturity of the previous annual crop and accumulation of soil water in a weed-free summer fallow. Soil N was maintained at levels non-limiting to plant growth in these simulations by setting soil mineral N to 250 kg N/ha at sowing and applying 100 kg N/ha at the bud-visible stage. Simulations were run for 60 years (1955-2014), with the first 10 years discarded so that the initial conditions had little bearing on the results. Currently, the APSIM-Canola model does not account for the effects of heat or frost stress events on flower or grain survival during the sensitive period around flowering and early grain growth. In our factorial simulation analysis, some sowing date and cultivar combinations resulted in this sensitive phenological period coinciding with periods of high risk of frosts or heat stress, resulting in likely yield reductions. Consequently, we estimated the impact of frost and heat stress during the sensitive phenological stages of the crop on grain yield following the method of Lilley *et al*. (2015), where indices related to likely impacts are applied to reduce the yield according to published physiological evidence. Biomass and yield outputs from the simulations were compiled to provide insights into the response to sowing date of the three cultivar-phenology types at each site with and without the predicted impacts of frost and heat stress.

Results

Seasonal conditions

The sites experienced a range of growing conditions from extremely dry (<150 mm growing season rainfall (GSR)) and hot conditions at Condobolin (2002) and Wagga (2007) where supplementary irrigation was required to establish and maintain growth, to more favourable conditions at Canberra (2007) and Tamworth (2012) (Table 1). Extreme temperatures, both frost and heat, occurred during the critical reproductive periods at some sites (see later), which may have influenced seed yield at those sites. These conditions generated a range in canola yield across the sites from 0.5 to 4.0 t/ha. The specific seasonal conditions influencing the response to treatments at each site are discussed in more detail in following sections.

Effects on seed yield and harvest index

Overall impacts of sowing date

Overall, sowing date had a significant main effect on canola yield at six of the nine sites and there was a sowing date cultivar interaction at four of the sites (Table 2). The interactions were partly driven by the larger number of cultivars included at those sites that varied in phenological development and provided a greater opportunity to generate interactions. The significant reduction in overall yield (mean across cultivars) as sowing was delayed is clear at six of the sites (Fig. 1), whereas at three sites (Canberra 2007, Tamworth 2012 and Wagga 2007), the earliest sowing date had yield either similar to or lower than the second sowing date. The overall decline in yield was reasonably consistent at 6.0-6.5% per week delay in sowing across the sites (calculated from Fig. 1). At Grenfell, Canberra, Wagga Wagga and Young, there was no significant sowing time cultivar interaction because the cultivars used were closely matched for phenology and responded similarly to sowing time despite differences in inherent crop vigour (i.e. hybrid, OP and TT). At Condobolin (2002 and 2003), Trangie (2009) and Tamworth (2012) where cultivars of different phenology were included, there were significant cultivar sowing date interactions for seed yield (Table 2, Fig. 2). At Condobolin in 2002, the early-maturing cultivars (Ag-Outback) and mid-maturity cultivar (Hyola60) performed better at the latest sowing date than the mid-maturity cultivar Oscar (Fig. 2*a*). By contrast, in 2003 the mid-maturing cultivars (Oscar and Rainbow) yielded better from the early-April sowing than did the earlier maturing cultivar (Ripper) (Fig. 2*b*). At Trangie in 2009, the early-maturing cultivar Tarcoola performed much better than the other cultivars from the mid-April sowing (Fig. 2*c*). At Tamworth (Fig. 2*d*), all cultivars had lowest yield from the latest sowing in June, but differed in response to earlier sowing. The earliest maturing cultivar ATR-Stingray had highest yield from the earliest sowing, whereas cv. 43C80CL had the highest yield from the second sowing, and reduced yield with earlier sowing. The other cultivars had similar yield at the first and second sowings.

Site-specific factors influencing sowing-date responses

Generally, cultivar responses to sowing date could be explained by the occurrence of temperature (frost, heat) or water stress across the sites, or by differences in the duration of growth phases. The responses in HI, along with the timing of temperature and water stress, often provided a clue to the major yield-limiting factors at specific sites. Factors operating at each site are considered below.

Expts 1 and 2 (Condobolin). In 2002 and 2003, the overall reductions in yield with later sowing likely resulted primarily from the increased heat and water stress at flowering (Fig. 3*a*, *b*). In both years, temperatures ~358C were experienced in late September (22-25 Sept.) when the later sowings were in full flower, whereas earlier sowings had commenced flowering in July to mid-August and largely avoided significant heat stress at that time (Fig. 3*a, b*). The impact of increasing stress is evident in the reduced HI with later sowing (Fig. 4*a*).

In the hotter and drier year of 2002, the highest yield came from the early-maturing cultivars across all sowing times, but especially at later sowing times because they avoided the heat

Table 2. Statistical summary showing main effects and interactions for sowing date and cultivar effects at nine experimental sites in south-eastern Australia

**P* < 0.05; ***P* < 0.01; ****P* < 0.001; ns, not-significant

Experiment	Site	Yield			Oil			HI		
		Sowing	Cultivar	Sow cult	Sowing	Cultivar	Sow cult	Sowing	Cultivar	Sow cult
1 (2002)	Condobolin	*	*	**	*	*	n.s.	**	n.s.	n.s.
2 (2003)	Condobolin	*	*	**	*	*	n.s.	**	**	ns
3 (2003)	Grenfell	*	n.s.	n.s.	-	-	-	-	-	-
4 (2007)	Canberra	***	n.s.	n.s.	*	n.s.	n.s.	***	*	n.s.
5 (2007)	Wagga	n.s.	n.s.	0.10	*	***	0.06	***	**	**
6 (2009)	Young	***	**	n.s.	***	**	n.s.	0.07	***	n.s.
7 (2009)	Trangie	n.s.	***	**	0.08	***	n.s.	n.s.	***	*
8 (2012)	Trangie	n.s.	*	n.s.	n.s.	***	n.s.	***	n.s.	**
9 (2012)	Tamworth	**	**	*	***	***	***	*	***	n.s.

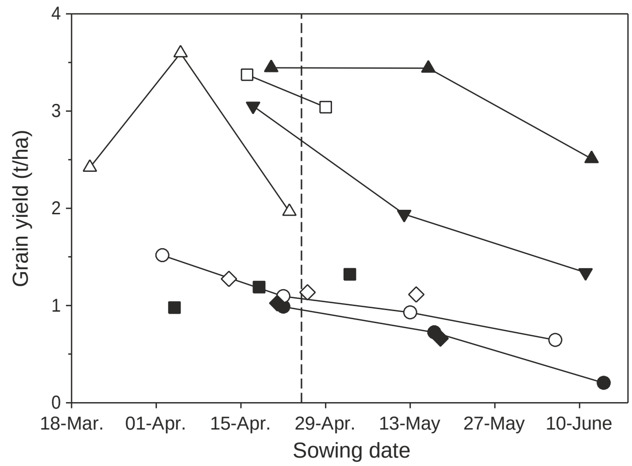

Fig. 1. Main effect of sowing date on canola yield at nine sites in south-eastern Australia. Solid lines show sites where significant main effects were observed and dotted lines where effects were non-significant (see Table 2). Sites (values of l.s.d. (*P* = 0.05) in parentheses): Condobolin 2002 (*, 0.14); Condobolin 2003 (*, 0.21); Grenfell 2003 (!, 0.66); Canberra 2007 (~, 0.56); Wagga Wagga 2007 (&, n.s.); Young 2009 (&, 0.15); Trangie 2009 (¤, n.s.); Trangie 2012 (^, n.s.); Tamworth 2012 (~, 0.28).

and water stress (Figs 2*a*, 3*a*). In 2003, the later maturing cultivars performed best from early sowing because the season overall was less stressed. Heat was restricted to one hot day (22 September), and the heavy frost on 10 August occurred during early flowering (August 20-August 31) (Fig. 3*b*). The impact of high temperature and water stress are evident in reduced HI with late sowing, more dramatic in 2002 than in 2003 (Fig. 4*a*).

Expt 3 (Grenfell). There was no frost at the Grenfell site, and no hot days until 9-20 November, which was well after flowering had ceased (data not shown), but would have had most impact during the pod-filling stage on cultivars at the latest sowing date. Thus, cultivars sown early would have benefitted from generating higher biomass and higher yield potential, with no frost events and less heat and water stress compared with later sowings, to achieve a much higher yield (3 t/ha with 17 April sowing *v.* 2 t/ha with 12 May sowing).

Expt 4 (Canberra). In 2007, the first sowing time showed significantly lower yield (Fig. 1), which was related to low HI (Fig. 4*a*). Although significant frosts occurred from late June and throughout July (-2.58C to -3.58C), August was mild, and only one significant frost, of -2.38C, occurred on 17 September during the sensitive reproductive period for the first sowing (Fig. 3*c*). Plants from the first sowing time would have

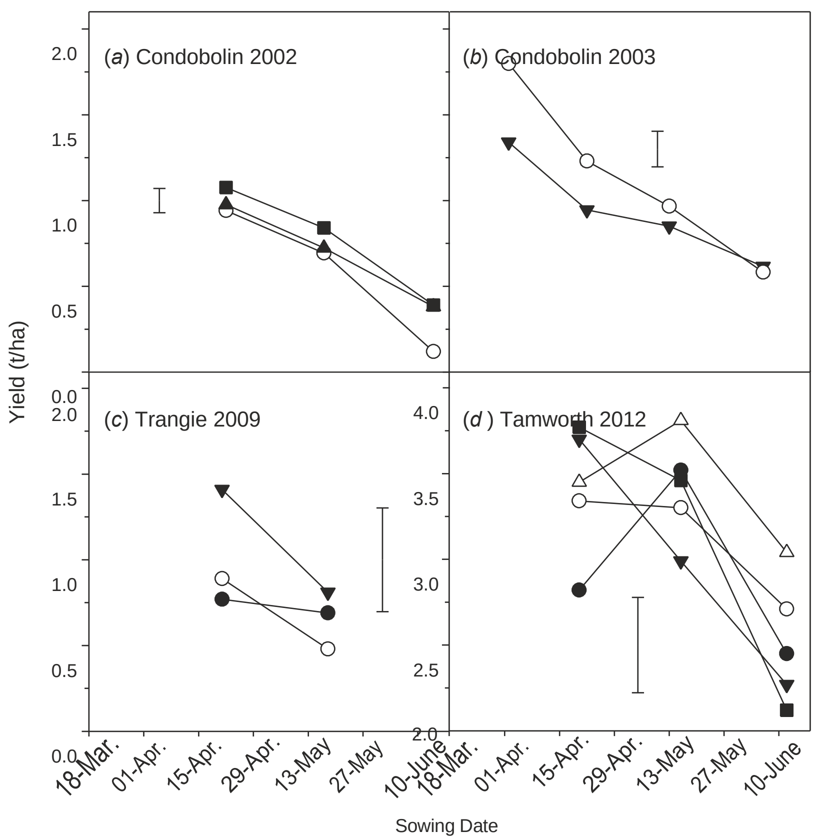

Fig. 2. Interactive effect of sowing date and cultivar on canola yield at four sites in south-eastern Australia where significant interactions were observed (see Table 2): (*a*) Condobolin 2002 (*, Oscar; &, Hyola60; ~, Ag-Outback); (*b*) Condobolin 2003 (!, Ripper; *, Oscar); (*c*) Trangie 2009 (*, 44C79; *, Hyola50; !, Tarcoola); (*d*) Tamworth 2012 (*, 43C80; *, 43Y85; !, ATR-Stingray; ~, Hyola50; &, Hyola575CL). Vertical bars show l.s.d. (*P* = 0.05) for the sowing date cultivar interaction.

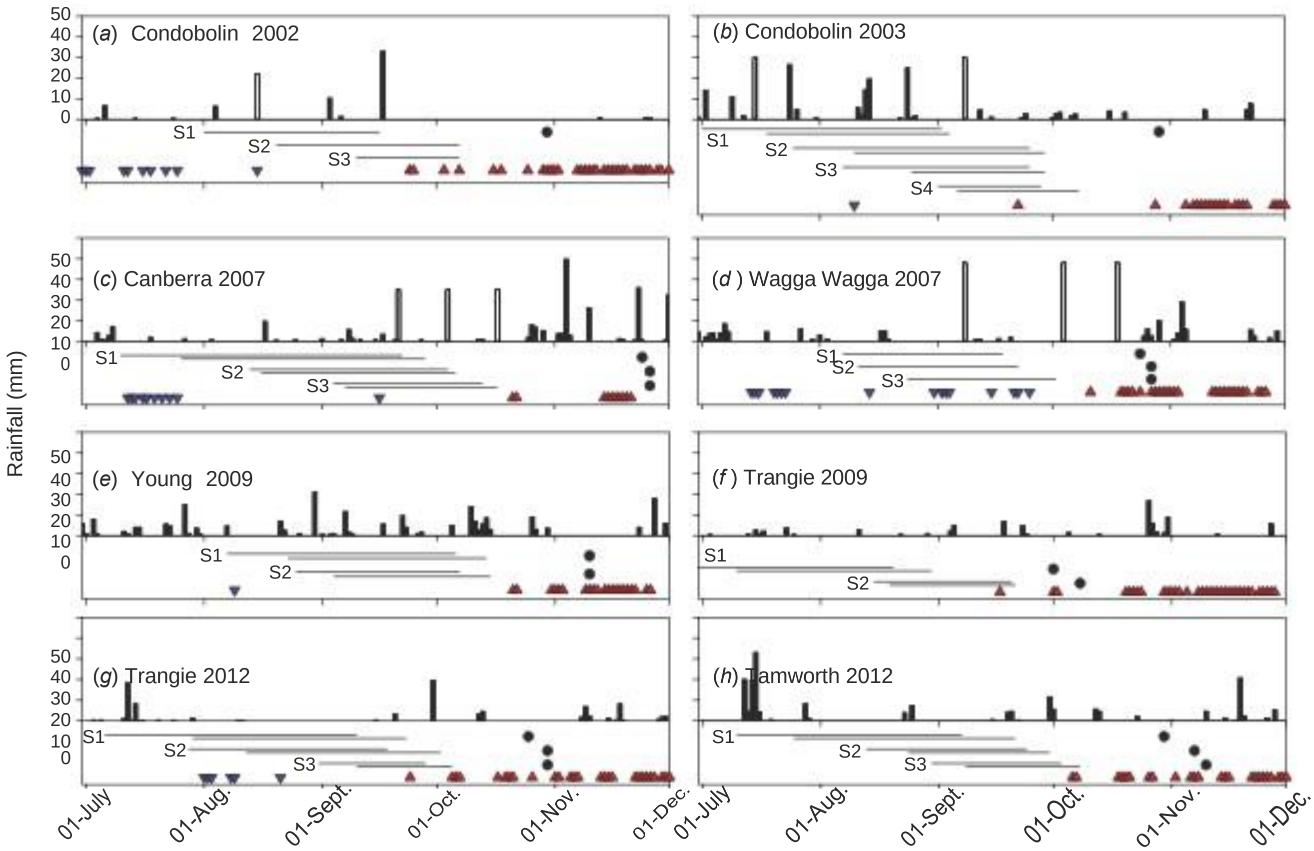

Fig. 3. Rainfall, flowering window and frost and heat events at eight of the experimental sites. Closed vertical bars, rainfall; open bars, irrigation; solid horizontal lines indicate flowering window for earliest (upper) and latest (lower) cultivar at each sowing (S1, S2, S3, S4); *, harvest date; !, minimum temperature < 28C; ~, maximum temperature >308C.

experienced the period of prolonged frost during early flowering, and the frost on 17 September in late flowering when small, vulnerable pods would have been present. Plants from the second and third times of sowing would have experienced a single frost on 17 September during mid- and early flowering (Fig. 3*c*). Only two hot days occurred, on 22 and 23 October, after flowering had ceased in all sowings. Water stress is likely to have been the key issue in the first sowing due to very dry conditions. Stressed plants were observed on 24 August, and irrigation was not applied until 21 September (Fig. 3*c*). Thus, the earliest sowing was under significant water stress for much of its flowering period, with little time to respond to the irrigation (flowering ceased 28 September). The earlier flowering of the early-sown spring cultivars, together with the possible effects of frost and certainly water stress, is likely to have reduced the yield and HI in the March sowing. The lower yield in the May sowing was presumably due to lower biomass as a result of less thermal and calendar time for vegetative growth, because the HI remained high (Fig. 4*a*). The effects of heat and water stress were not significant factors in the reduced yield of the later sown treatment at this site.

Expt 5 (Wagga Wagga). Later sowing did not penalise yield at Wagga Wagga, which is somewhat surprising given the dry conditions that would normally favour earlier sowing (Fig. 1). The early sowing had very low HI (Fig. 4*b*), suggesting that significant frost, heat or water stress has influenced yield. Several significant frost events were likely to have influenced all sowing dates (Fig. 3*d*). Heat events first commenced in the 4-day period 19-22 October, which was during later podfill stage for all sowing dates, and should have affected the early sowing the least. In common with Canberra, there was severe water stress during August, with no irrigation water available until 8 September, by which time the first sowing had ceased flowering. Two further irrigations applied on 4 and 18 October would have benefitted the later sowing times during critical stages of late flowering and early podset. Thus, the earliest sowing suffered from severe water stress at the most critical growth stages, having generated high early biomass and exhausted soil water reserves, and suffered more severe water stress throughout the flowering period (Fig. 3*d*). It is interesting that, despite the setback, the first sowing yielded the same as the later sowings, which presumably produced less biomass and suffered more from the terminal heat stress on developing pods.

Expt 6 (Young). There was no significant sowing cultivar interaction at Young, presumably because the eight cultivars were matched closely for phenology. The site was on a hillside with low frost risk, and only one frost was recorded at the start of flowering in the early-sown treatment (Fig. 3*e*). Hot days commenced on 22-23 October (318C), and throughout November temperatures were regularly >358C, which led to

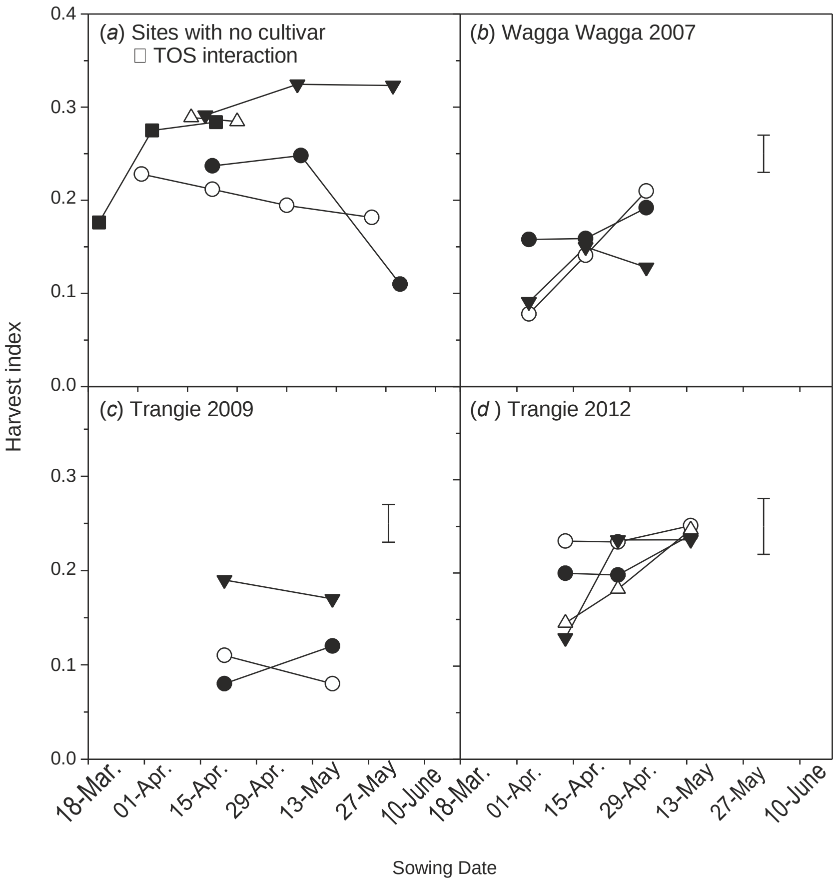

Fig. 4. (*a*) Main effect of sowing date on canola harvest index at five sites: Condobolin 2002 (*), Condobolin 2003 (*), Tamworth 2012 (!), Young 2009 (~), Canberra 2007 (&). The interactive effect of sowing date and cultivar on canola harvest index at three sites: (*b*) Wagga Wagga 2007 (*, Hyola75; *, AV-Garnet; !, Skipton); (*c*) Trangie 2009 (*, 44C79; *, Hyola50; !, Tarcoola); (*d*) Trangie 2012 (*, 44Y84; *, AV-Garnet; !, Hyola555TT; ~, ATR-Stingray). Vertical bars show sowing date cultivar interaction (l.s.d. at $P = 0.05$).

the rapid onset of maturity for both sowing dates (harvested 10 November). Earlier sown crops commenced flowering 1-2 weeks earlier than the late-sown crops and presumably suffered less terminal stress. Harvest index was high overall and declined somewhat ($P < 0.07$) with later sowing (Fig. 4*a*), supporting the suggestion that increased water stress and heat, and not frost, were responsible for lower yield with later sowing.

Expt 7 (Trangie 2009). Conditions were favourable in the early half of the season, with adequate rainfall during April-June (data not shown), but very dry thereafter (Fig. 3*f*). The early-maturing cultivar Tarcoola was the highest yielding, especially at the early sowing, and this was mainly related to a higher HI (Fig. 4*f*). Tarcoola was the earliest flowering variety (by 7-10 days) and its early flowering reduced the impact of the dry finish from July to maturity (Fig. 3*f*). The yield of individual treatments was more closely related to HI than to total biomass, although the biomass produced decreased in the later sowing. Minor frosts on 8 and 9 August (-1.38C, not shown) appear not to have penalised the earlier sown treatments, but the yield responses relate more to the hot, dry conditions from 17 September (32.98C) and 1-2 October (348C), which would have terminated the crops.

Expt 8 (Trangie 2012). Cultivar choice had a significant effect on grain yield, but there was no effect of sowing date or any interaction (Table 2). The hybrid CLF cultivars and AV-Garnet were the highest yielding cultivars, whereas the TT cultivars yielded least (data not shown). A series of frosts (-2.58C to -3.58C) from 31 July to 8 August (Fig. 3*g*) would have coincided with the early pod stage in the first sowing for the early-maturing cultivars, and reduced the HI of some cultivars in this sowing, most noticeably TT cultivars (Fig. 4*d*). However, the HI of the non-TT cultivars was similar at all sowing dates, which raises questions about the overall effect of frost on final grain yield at the site.

Expt 9 (Tamworth 2012). Overall HI at the Tamworth site was high, with small increases as sowing time was delayed (Fig. 4*a*). There were no frost events at Tamworth in early August (Fig. 3*h*), and for the faster developing cultivars (which flowered before 15 July) including Hyola575CL, 43Y85CL and ATR-Stingray, generally their yield at the first sowing was similar to or better than at the second sowing (Fig. 2*d*). These three relatively fast-maturing cultivars produced more biomass at the first sowing than the second and third sowings, and although there was a small reduction in HI

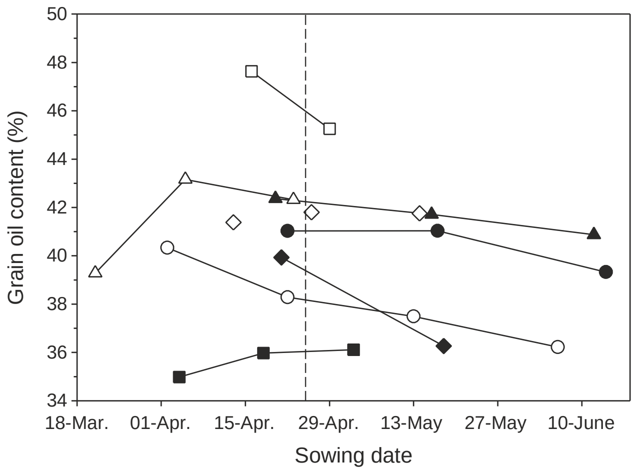

Fig. 5. Main effect of sowing date on canola seed oil content at eight sites in south-eastern Australia. Solid lines show sites where significant main effects were observed and dotted lines where effects were non-significant (see Table 2). Sites (values of l.s.d. (*P* = 0.05) in parentheses): Condobolin 2002 (*, 0.6); Condobolin 2003 (*, 0.65); Canberra 2007 (~, 2.8); Wagga Wagga 2007 (&, 1.0); Young 2009 (&, 0.9); Trangie 2009 (¤, 1.6); Trangie 2012 (^, *ns*); Tamworth 2012 (~, 0.3).

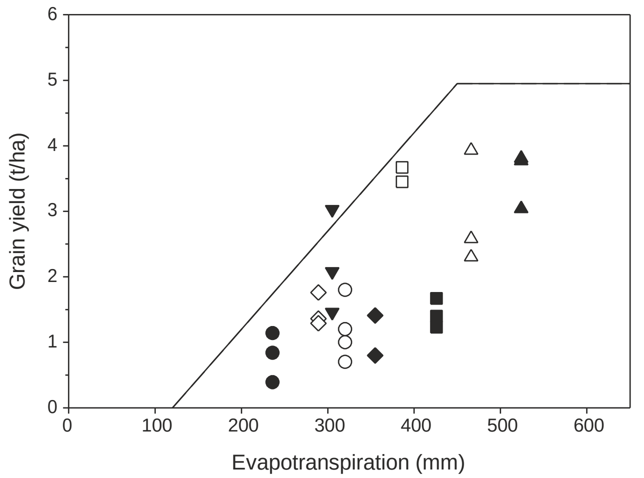

Fig. 6. Relationship between grain yield and evapotranspiration (ET) for each sowing date at nine sites in south-eastern Australia (*, Condobolin 2002; *, Condobolin 2003; !, Grenfell 2003; ~, Canberra 2007; &, Wagga Wagga 2007; &, Young 2009; ¤, Trangie 2009; ^, Trangie 2012; ~, Tamworth 2012). Solid line represents the upper boundary for transpiration efficiency of 15 kg/ha.mm as reported by Robertson and Kirkegaard (2005) assuming evaporative loss (E) = 120 mm, and that yield plateaus owing to unproductive water use above total ET of 450 mm. At most sites, the earliest sown treatment was closest to the upper boundary and water-limited yield declined with later sowing, with the exception of Canberra (site 2, closest to boundary) and Wagga Wagga (no significant difference).

from the early sowing, the additional biomass and yield potential from the early sowing combined with favourable conditions increased yield at the site. Grain yield of all cultivars was lowest at the third sowing, largely a result of reduced biomass, with much of the growth occurring in the relatively warm and dry conditions after August. Heat stress commenced on 5 October (328C) (1 month after flowering commenced in TOS3) (Fig. 3*h*), but it became consistent from mid-October to mid-November.

Effects of sowing date and cultivar on oil content

Oil content declined as sowing was delayed at six of the eight sites where it was measured (Fig. 5, Table 2). There was no change at Trangie (2012), and a small increase with later sowing at Wagga Wagga in 2007. There were significant differences among cultivars at eight of the nine sites (data not shown), but there was an interaction with sowing date at only one site, Tamworth in 2012 (Table 2). This suggests that cultivars may vary in potential for higher oil content, but all cultivars are affected in much the same way by later sowing, generally with reduced oil content. At sites where later sowing reduced oil content, the reduction ranged from 0.5% to 1.5% per week delay in sowing (Fig. 5).

At Tamworth, the interaction with cultivar was mostly a result of differences in the size and pattern of the reduction in oil content with delayed sowing. This ranged from extreme reductions in cultivars such as ATR-Stingray and ATR-Gem (reduced from 44% to 41%) to relatively little change (AV-Garnet, constant at 41.5%) and a decline from April to May but no decline in June (e.g. CB Junee TT).

Water-use efficiency

The WUE varied from ~9-10 kg/ha.mm at the earliest sowing at Grenfell and Young to 1-2 kg/ha.mm for the late sowing at Condobolin in 2002 (Fig. 6). WUE declined with later sowing at eight of the nine sites, reflecting the less efficient use of the available seasonal rainfall to produce grain yield when crops were sown late. The reduction in WUE across those eight sites varied from -3.8 to -5.5% per week delay in sowing (calculated from Fig. 6). In Fig. 6, the previously established upper boundary for transpiration efficiency (TE) for seed yield (15 kg/ha.mm) above an E of 120 mm established by Robertson and Kirkegaard (2005) for 42 canola crops grown in southern NSW is approached for the early-sown crops at Grenfell and Young. The levels were low, even with early sowing at Wagga Wagga where significant frost damage, water-stress and high VPD presumably reduced grain yield, TE and WUE. In all cases except two (Canberra and Wagga), the highest WUE was achieved by the earliest sown treatments; the second sowing generated highest efficiency in Canberra, and there was no significant difference among the treatments at Wagga Wagga.

Simulation outcomes

The validation of APSIM-Canola at the field sites demonstrated that the model could predict flowering date (Fig. 7*a*) and biomass (Fig. 7*b*) with levels of accuracy previously achieved in other studies; however, the simulated potential yield was consistently ~0.5 t/ha higher than the measured yield, with large RMSD of 0.7 t/ha (Fig. 7*c*). This is perhaps not surprising given that the simulated potential yield does not account for either biotic constraints (weeds, disease) or temperature stresses such as frost and heat. Because weeds and disease were controlled, use of the frost-heat indices published by Lilley *et al*. (2015) provided a significantly better prediction of measured yield

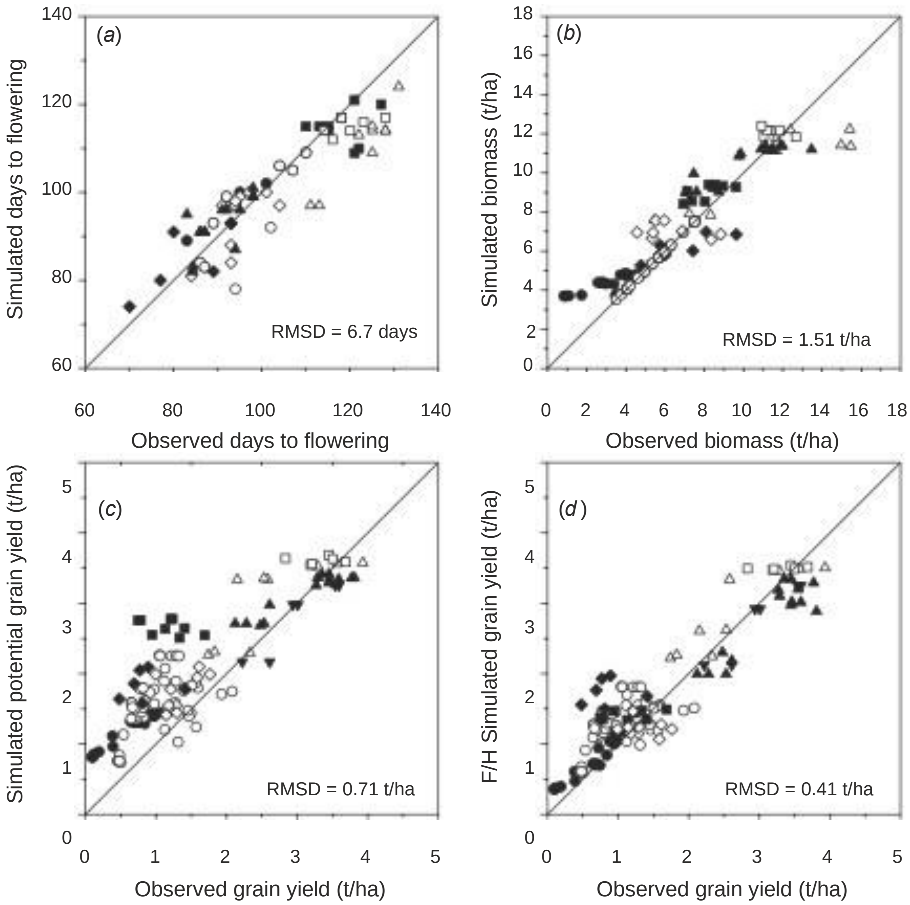

Fig. 7. Comparison of observed and simulated data across the nine experiments for (*a*) duration from sowing to flowering, (*b*) biomass at maturity, (*c*) grain yield, (*d*) frost-heat adjusted grain yield. The 1 : 1 line is shown and the root-mean-square deviation (RMSD) from the 1 : 1 line is also shown. Condobolin 2002 (*), Condobolin 2003 (*), Grenfell 2003 (!), Canberra 2007 (~), Wagga Wagga 2007 (&), Young 2009 (&), Trangie 2009 (¤), Trangie 2012 (^), Tamworth 2012 (~).

and reduced the RMSD from 0.7 t/ha to ~0.4 t/ha (Fig. 7*d*), thus providing further validation of the frost and heat indices shown in Table 3. In particular, the application of the frost-heat indices significantly improved the yield prediction at Wagga Wagga in 2007 (compare Fig. 7*c* and *d*), where frost and heat were known to influence yield (Fig. 3*d*). By contrast, there was little improvement in the yield prediction at Trangie in 2009, suggesting other yield-limiting factors may have been operating at that site.

The long-term mean simulated potential and frost-heat-affected yields for three crop phenology types at four sites in the study are shown in Fig. 8. In general, the relative yield levels follow the expected trends across sites in accordance with the growing conditions, with higher predicted yields at Young and Tamworth, somewhat lower yields at Wagga Wagga, and the lowest yield at Condobolin. Potential yields (in the absence of frost and heat) are higher than the frost-heat affected yield at all sites, and show declining yield trend with later sowing from early April, and with little difference between the cultivar types. Potential yield declined at ~3% per week (from ~4.0 t/ha) at the three higher yielding sites, and ~6% per week at Condobolin (from 2 t/ha) as sowing was delayed from early to mid-April.

The mid- and early-mid-maturing cultivars showed a somewhat higher mean potential yield from earlier sowing at the higher yielding sites (Young and Tamworth) but similar potential yield at Wagga Wagga and Condobolin. This presumably results from the reduced biomass and yield potential achieved by the earlier flowering cultivars in high-yield-potential sites in the absence of frost or heat stress. By contrast, the predicted frost-heat-affected yields were lower at the earliest sowing times, and a much larger reduction in the yield of early-maturing types with earlier sowing was evident. Based on the mean yields, the optimum sowing date suggested by the simulation for mid- and early-mid-maturing cultivars was 15 April at Young, Condobolin and Wagga Wagga and 29 April at Tamworth. For the early-maturing cultivars, optimum dates were 2 weeks later at all sites. At no site would sowing on 1 April would be recommended over 15April sowing on the basis of the predicted mean frost-heat-affected yields alone. However, for the later maturing cultivars at Wagga Wagga, Condobolin and Young, the difference in mean yield between 1 and 15 April sowing is relatively small, suggesting there may be a relatively wide optimum window for earlier sowing at those sites.

Table 3. Minimum and maximum temperature criteria for frost and heat stress during phenologically sensitive stages and the estimated resulting yield reductions used for frost/heat-affected yield

Yield reductions were calculated for each day and accumulated (multiplicatively), so that increasing numbers of stress events resulted in cumulative reductions in the yield. The extended duration of flowering in canola is accounted for by the ~6-week duration of the sensitive period. Reproduced from Lilley *et al*. (2015) who developed these criteria to reproduce similar relationships between yield reduction and temperature stress observed for heat by Morrison and Stewart (2002) and for frost by Takashima *et al*. (2013)

Stress	Level	Daily temperatures (minimum-maximum)	Sensitive period	Yield reduction per day
Frost	Moderate	28C to 08C	140-800 degree-days after first flower	2%
	Severe	< 28C	(early pod-filling period)	10%
Heat	Mild	30 338C	0-630 degree-days after first flower	10%
	Moderate	33 368C	(flowering period)	18%
	Severe	>368C		35%

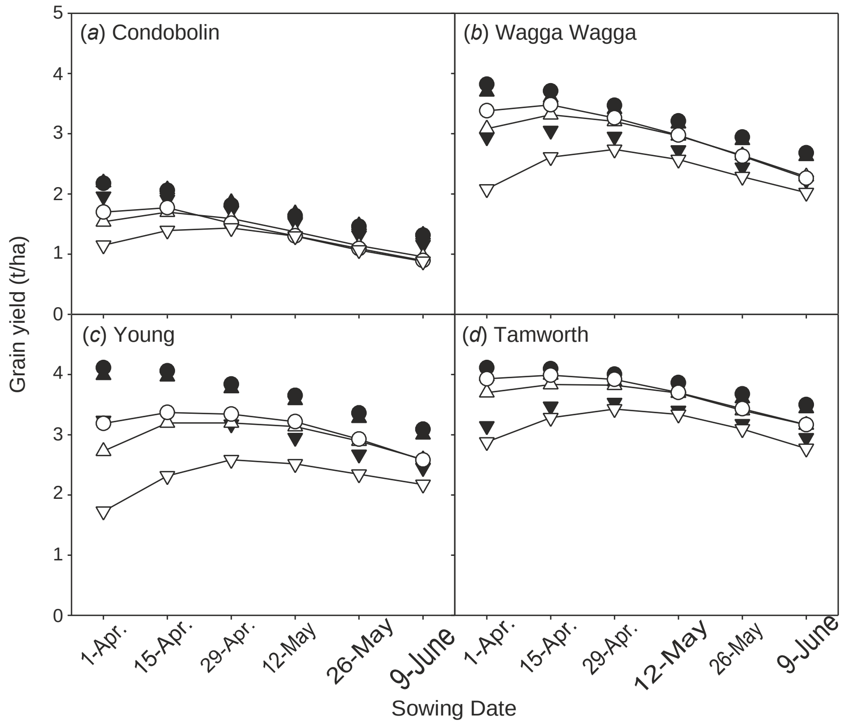

Fig. 8. Long-term average simulated potential (solid symbols) and frost-heat adjusted grain yields (open symbols) for three cultivar maturity types (!, early; ~, early-mid; *, mid) sown at 2-week intervals at four locations from the experimental series. Data are average yields over 50 years (1965-2014). Frost and heat adjustment applied to potential yields are calculated according to Table 3.

Simulated mean yields conceal the variability and risk associated with different management strategies, and to exemplify this, Fig. 9 shows the variability in the simulated frost-heat yield outcomes for the early-mid-maturing cultivar as sowing time was delayed. Generally, there is no advantage in moving the sowing date from 15 April back to 1 April in terms of reducing risk or increasing outcomes at the three southern sites, and the same goes for moving from 29 April back to 15 April at Tamworth. Both the predicted median yield and the risks increase, along with reduced outcomes with the 1 April sowing. Interestingly, the outcome from sowing an early-mid cultivar in early April at Condobolin and Young was not very different from sowing in late April as currently recommended.

The difference in the predicted potential yield and the frost-heat-limited yield outcomes is clearly dictated by the indices chosen for these temperature stresses (Table 3). Figure 10 shows the magnitude of the indices for each phenology type across the sites as sowing date is delayed. The frost indices reducing yield were very significant (0.6-0.8) for early-April-sown crops at all sites except Tamworth (site is high in the landscape), whereas the heat indices were mostly moderate (>0.8), except at Condobolin where they were of

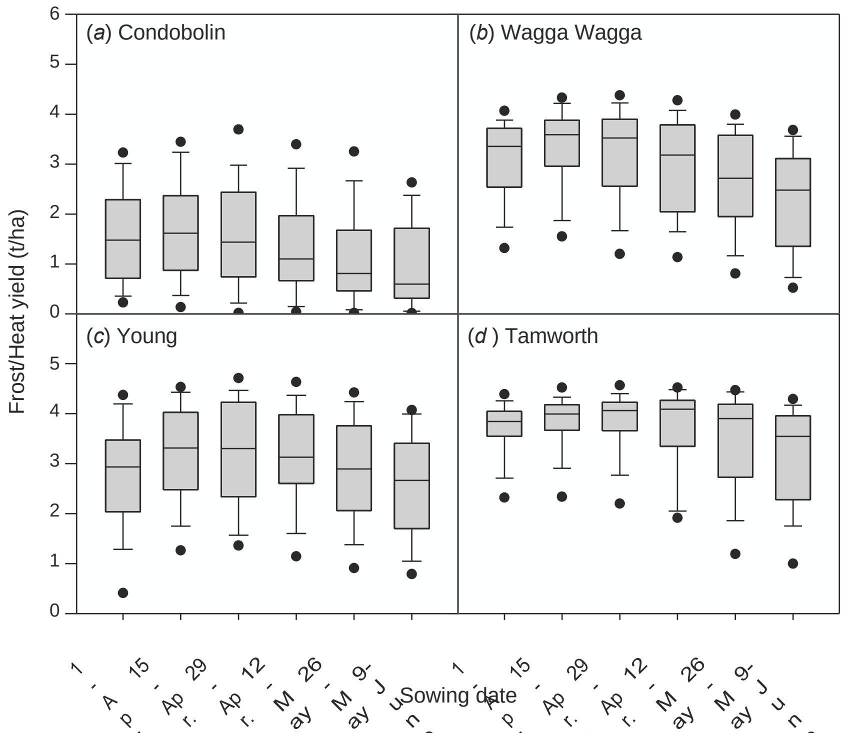

Fig. 9. Variability in simulated frost-heat-adjusted grain yields of an early-mid-maturity cultivar sown at 2-week intervals at four locations from the experimental series. Boxes depict the 25th, 50th, 75th percentile and whiskers the 10th and 90th percentile of simulated yields over 50 years (1965-2014).

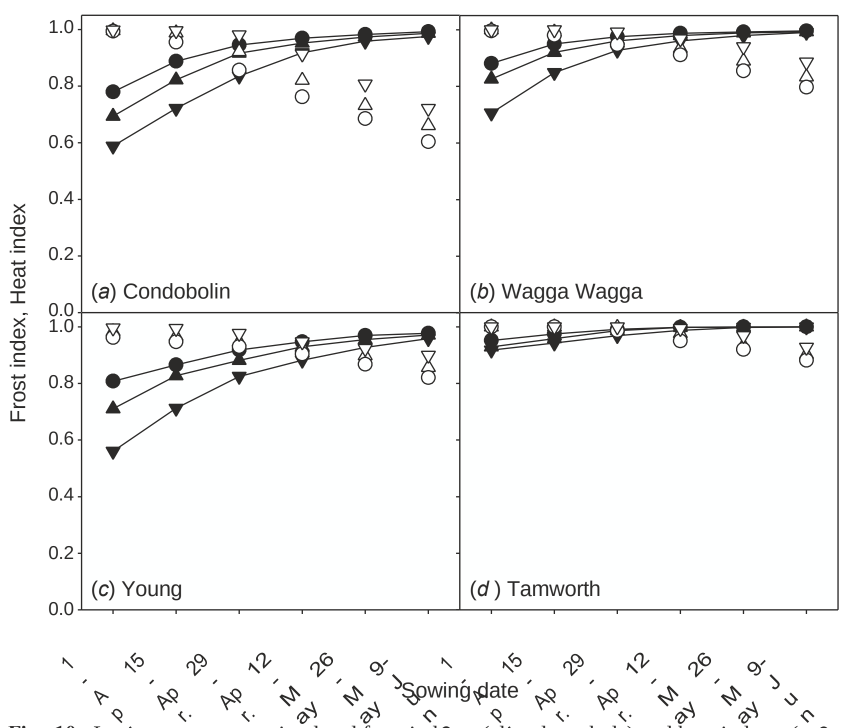

Fig. 10. Long-term average simulated frost index (closed symbols) and heat index (open symbols) for three cultivars (maturity types: !, early; ~, early-mid; *, mid) sown at 2-week intervals at four locations. Data are simulated average over 50 years (1965-2014). Frost and heat index calculated according to Table 3.

similar magnitude to the frost indices. If the 'optimum' sowing dates are selected simply as the point where the frost and heat index lines intersect (to optimise frost and heat risk trade-offs assuming each has a similar relative impact on yield), the resulting sowing dates are generally later than those that emerged from the simulated yield estimates (in Figs 8 and 9). This suggests that other factors, presumably the timing of water availability and patterns of biomass production, and not simply extreme temperatures, dictate the optimum sowing dates for canola. Clearly, the magnitude of the frost-heat indices chosen (in Table 3) had a significant effect on the predicted yield outcomes for specific scenarios.

Discussion

The experimental series presented in this paper confirms previous studies on the significant impact of later sowing on the yield, oil and water-use efficiency of canola. The range in magnitude of the yield reductions falls within the general rule-of-thumb previously summarised by Robertson *et al*. (1999*b*) at ~3-6% per week delay in sowing after late April. In addition to the yield reductions, these experiments demonstrate a significant reduction in oil content, ranging from 0.5% to 1.5% reduction in oil content per week delay in sowing after mid-April, which is similar to that previously published by Hocking and Stapper (2001). Robertson and Kirkegaard (2005) predicted a decline in WUE for canola of ~3.3% per week from early April sowing, which also corresponds well with the levels reported here. Together, these results reinforce the message that timely sowing in canola is crucial to achieving high and reliable yield and oil content and improved WUE in south-eastern Australia.

The specific aim of this study was to investigate the potential to gain further improvements in yield and oil content by moving the sowing date back from late April (25 April) to mid or early April, to understand the risks associated with such a change to management and the strategies required for success. Overall, in the experiments where sowing was moved earlier than 25 April, the results were promising, with yield and oil either higher or unchanged compared with later sowing. The outcome was influenced in some cases by the cultivar phenology selected (e.g. Condobolin 2003, Trangie 2009, Tamworth 2012), although these interactions often related to the specific seasonal conditions prevailing at the sites. For example at Condobolin, mid-maturing varieties yielded best from early sowing in the more favourable year of 2003, but not under the hotter and drier conditions in 2002. Interestingly, one of the significant perceived risks of early sowing—frost damage—did not appear to be a major factor in the experimental results, despite frosts recorded at sensitive stages at some of the sites. Yield reductions in early-sown crops at Wagga Wagga were possibly the exception, where significant frost damage seems to have reduced yield, as evidenced by the improved yield prediction when frost was taken into account (Fig. 7*c, d*). At Canberra, yield impacts appeared to be related as much to water stress as to frost, while potentially damaging frosts on early-sown crops at Condobolin in 2003 and Trangie in 2012 do not appear to have had large impacts on grain yield. Under conditions of reasonable spring rainfall or significant stored water at those sites, it is possible that the indeterminate nature of canola allowed for compensation, especially in early-sown crops with higher potential biomass and yield. Although severe frost can cause damage at any reproductive stage, frost is thought to be most damaging on young water-filled pods in canola, when the seeds are vulnerable to freezing. However, the capacity of crops frosted during this early-pod stage to recover, especially when seasonal conditions favour recovery, makes the specific yield impacts difficult to predict. Recent grazing experiments in the high-rainfall zone have included spring canola cultivars sown much earlier than recommended, which have flowered early (from late-May) and been exposed to repeated frosts during the sensitive period, yet have achieved yields from 2.6 to 4.0 t/ha (Kirkegaard *et al*. 2008; Sprague *et al*. 2015). The harvest indices were somewhat lower than the later sown treatments (0.22-0.24 *v*. 0.27-0.35), which indicates that grain production had been constrained to some extent, presumably by frost. However, this demonstrates the capacity for canola to recover grain yield if sufficient time and suitable conditions occur after significant frost events. These data are consistent with those of Brill *et al*. (2015), where spring canola sown on 1 April and flowering from late July had similar grain yield (1.7-2.0 t/ha) to crops sown later in environments where significant frost events occurred during the sensitive stages. Thus, the low yield of early-sown crops at Canberra and Wagga Wagga in this experimental series may have been due to an inability to recover from frost damage because of severe water stress, whereas better recovery from apparent frost damage was possible in early-sown crops at Condobolin in 2003 and Trangie in 2012. Despite this uncertainty regarding the precise impacts of frost on canola yield, the improvements to the yield prediction by the inclusion of the frost-heat indices in the simulation across the sites reported here provides circumstantial evidence that both are having some effects on yield, and that ignoring them results in over-prediction of attainable yields. The improved prediction of observed yields provides further useful validation for the indices proposed by Lilley *et al*. (2015).

The longer term simulation study was more definitive in predicting optimal sowing windows, and in general, the results are compatible with the experimental data presented here, given the seasonal conditions encountered. In the absence of frost or heat stress, the highest potential yields were predicted from early-mid-April sowing at all sites, with a clear advantage over late-April sowing. When the frost-heat indices nominated by Lilley *et al*. (2015) were imposed, there were clear penalties for sowing too early in April, especially for the early-maturing cultivars. The clear sowing date optima that increased mean yield and reduced risks tended to move into mid-April for the southern sites, and to late April at Tamworth. The effect of moving sowing back to 1 April was tested experimentally at only two of the sites: Canberra in 2007 (March 25 and April 5), where frost and water stress in an unusually dry winter reduced the relative yield of the early-sown crop; and Condobolin in 2003 (sown April 3), which was indeed the highest yielding treatment at that site. The wide range in potential outcomes simulated across the 50 years of weather data (Fig. 9) demonstrates that these experimental outcomes are certainly not at odds with longer term predictions, and suggests that sowing in the early-April window is no worse than the current recommendation of late April. This suggests that if farm operational issues, or the timing of rainfall, dictate that earlier sowing of canola is warranted, there seems little risk associated with moving to earlier April sowing, with care to select an appropriate phenology type.

The significant effect of the frost-heat indices on yield prediction (as depicted in Figs 8 and 10) demonstrates the importance of having accurate estimates of the yield impacts to develop the indices. For example, an index that overestimates the impact of frost compared with heat will inevitably suggest later sowing optima, whereas the opposite will occur where heat effects are overestimated. The indices used by Lilley *et al*. (2015) are based on the physiological literature for known impacts of temperature stress and were developed to reproduce similar relationships between yield reduction and temperature stress observed for heat by Morrison and Stewart (2002) and for frost by Takashima *et al*. (2013). Such data to improve the accuracy and reliability of these stress indices will be important and will be a worthy area for new research. Only by simulation can we appreciate the overall seasonal risks in canola production; however, reliable estimates of heat and frost effects are crucial if we are to have faith in the predicted outcomes. The capacity for canola to recover from frost events, and the impacts of heat on the sudden termination of pod growth and crop senescence under different levels of water stress are two areas worthy of further investigation.

Conclusion

The experimental and simulation studies reported here suggest that the yield, oil content and WUE of spring canola can be significantly improved with no increase in risk by moving recommended sowing dates of canola in south-eastern Australia 10-14 days earlier than the current late-April-early May recommendations. Cultivars with appropriate phenology will need to be selected for specific regions; however, there appeared little difference in the response of hybrid, conventional and TT varieties to earlier sowing. Further validation of frost and heat indices applied in simulation studies are warranted to refine recommendations further; however, it appears that earlier sowing strategies are a sensible and safe response to the recent changes in farming system and climate in the region.

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References

ABARES (2014) Agricultural commodity statistics 2014.

AOF (2015) Australian Oilseeds Federation Crop Reports. www.australianoilseeds.com/oilseeds_industry/crop_report_assets

Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. *Crop & Pasture Science* **66**, 523-552. doi:10.1071/CP14252

Brill R, Kirkegaard JA, Lilley JM, Menz I, McCaffery D, McMaster C (2015) Early sowing of canola in southern NSW. In 'GRDC-sponsored Grains Research Update'. Wagga Wagga, NSW, 17-18 February 2015. (Eds J Crane, C James) pp. 197-204. (ORM Communications: Bendigo, Vic.)

Cai W, Cowan T, Thatcher M (2012) Rainfall reductions over Southern Hemisphere semi-arid regions: the role of subtropical dry zone expansion. *Scientific Reports* **2**, 702. doi:10.1038/srep00702

Christy B, O'Leary G, Riffkin P, Acuna T, Potter T, Clough A (2013) Long-season canola *Brassica napus* L.: cultivars offer potential to substantially increase grain yield production in south-eastern Australia compared with current spring cultivars. *Crop & Pasture Science* **64**, 901-913. doi:10.1071/CP13241

Colton RT, Sykes JD (1992) Canola. Agfact P5.2.1. 4th edn. NSW Agriculture, Orange, NSW.

Degenhardt DF, Kondra ZP (1981) The influence of seeding date and seeding rate on seed yield and yield components of five genotypes of *Brassica napus*. *Canadian Journal of Plant Science* **61**, 175-183. doi:10.4141/cjps81-027

Farré I, Roberston 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

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

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

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S, Keating BA (2014) APSIM—Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**, 327-350. doi:10.1016/j.envsoft.2014.07.009

Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop & Pasture Science* **62**, 915-929. doi:10.1071/CP11268

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**, 309-330. doi:10.1016/S1364-8152(01)00008-1

Kirkegaard JA, Sprague S, Robertson M, Hamblin P (2006) Effect of blackleg and sclerotinia stem rot on canola yield in the high rainfall zone, southern New South Wales, Australia. *Australian Journal of Agricultural Research* **57**, 201-212. doi:10.1071/AR05179

Kirkegaard JA, Sprague SJ, Dove H, Kelman W, Marcroft SJ, Lieschke A, Howe GN, Graham JM (2008) Dual-purpose canola—a new opportunity for mixed farming systems. *Australian Journal of Agricultural Research* **59**, 291-302. doi:10.1071/AR07285

Kirkegaard JA, Sprague SJ, Hamblin PJ, Graham JM, Lilley JM (2012) Refining crop and livestock management for dual-purpose spring canola (*Brassica napus*). *Crop & Pasture Science* **63**, 429-443. doi:10.1071/CP12163

Kirkegaard JA, Lilley JM, Morrison MJ (2016) Foreword: Drivers of trends in Australian canola productivity and future prospects. *Crop & Pasture Science* **67**, in press.

Lilley JM, Kirkegaard JA, Robertson MJ, Probert ME, Angus JF, Howe G (2003). Simulating crop and soil processes in crop sequences in southern NSW. In 'Proceedings of the 11th Australian Agronomy Conference 2003'. Geelong, Vic. (Australian Society of Agronomy/Regional Institute: Gosford, NSW) Available at: www.regional.org.au/au/asa/2003/c/12/lilley.htm

Lilley JM, Bell LW, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 2. Canola. *Crop & Pasture Science* **66**, 349-364. doi:10.1071/CP14240

Lisson SN, Kirkegaard JA, Robertson MJ, Zwart A (2007) Canola yield decline in southern NSW: a diagnosis of causal factors. *Australian Journal of Experimental Agriculture* **47**, 1435-1445. doi:10.1071/EA07041

Matthews P, McCaffery D, Jenkins L (2015) 'Winter crop variety sowing guide 2015.' (NSW Department of Primary Industries: Orange, NSW) Available at: www.dpi.nsw.gov.au

McCormick JI, Virgona JM, Lilley JM, Kirkegaard JA (2015) Evaluating the feasibility of dual-purpose canola in a medium rainfall zone of south-eastern Australia—a simulation approach. *Crop & Pasture Science* **66**, 318-331. doi:10.1071/CP13421

Morrison MJ, Stewart DW (2002) Heat stress during flowering in summer brassica. *Crop Science* **42**, 797-803. doi:10.2135/cropsci2002.0797

Ozer H (2003) Sowing date and nitrogen rate effects on growth, yield and yield components of two summer rapeseed cultivars. *European Journal of Agronomy* **19**, 453-463. doi:10.1016/S1161-0301(02)00136-3

Payne RW, Harding SA, Murray DA, Soutar DM, Baird DB, Welham SJ, Kane AF, Gilmour AR, Thompson R, Webster R, Tunnicliffe Wilson G (2007) 'GENSTAT Release 10 Reference Manual.' (VSN International: Hemel Hempstead, UK)

Pook M, Lisson S, Risbey J, Ummenhofer CC, McIntosh P, Rebbeck M (2009) The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield. *International Journal of Climatology* **29**, 2012-2026. doi:10.1002/joc.1833

Robertson MJ, Holland JF (2004) Production risk of canola in the semi-arid subtropics of Australia. *Australian Journal of Agricultural Research* **55**, 525-538. doi:10.1071/AR03219

Robertson MJ, Kirkegaard JA (2005) Water-use efficiency of dryland canola. *Australian Journal of Agricultural Research* **56**, 1373-1386. doi:10.1071/AR05030

Robertson MJ, Lilley JM (2016) Simulation of growth, development and yield of canola (*Brassica napus*) in APSIM. *Crop & Pasture Science* **67**, in press.

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

Robertson MJ, Holland JF, Bambach R, Cawthray S (1999*b*) Response of canola and Indian mustard to sowing date in risky Australian environments. In 'Proceedings of the 10th International Rapeseed Congress'. Canberra, ACT. (The Regional Institute: Gosford, NSW) Available at: www.regional.org.au/au/gcirc/index.htm

Robertson MJ, Watkinson AR, Kirkegaard JA, Holland JF, Potter TD, Burton W, Walton GH, Moot DJ, Farre I (2002) Environmental and genotypic control of time to flowering in canola and Indian mustard. Australian Journal of Agricultural Research. *Australian Journal of Agricultural Research* **53**, 793-809. doi:10.1071/AR01182

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, Lawes RA, Bathgate A, Byrne F, White P, Sands R (2010) Determinants of the proportion of break crops on Western Australian broadacre farms. *Crop & Pasture Science* **61**, 203-213. doi:10.1071/CP09207

Sprague SJ, Kirkegaard JA, Marcroft SJ, Graham JM (2010) Defoliation of *Brassica napus* increases severity of blackleg caused by *Leptosphaeria maculans*: implications for dual-purpose cropping. *Annals of Applied Biology* **157**, 71-80. doi:10.1111/j.1744-7348.2010.00410.x

Sprague SJ, Kirkegaard JA, Graham JM, Dove H, Kelman WM (2014) Crop and livestock production for dual-purpose winter canola (*Brassica napus*) in the high-rainfall zone of south-eastern Australia. *Field Crops Research* **156**, 30-39.

Sprague SJ, Kirkegaard JA, Graham JM, Bell LW, Seymour M, Ryan M (2015) Forage and grain yield of diverse canola (*Brassica napus*) maturity types in the high rainfall zone of Australia. *Crop & Pasture Science* **66**, 260-274. doi:10.1071/CP14319

Sylvester-Bradley R, Makepeace RJ (1984) A code for stages of development in oilseed rape (*Brassica napus*). *Aspects of Applied Biology* **6**, 399-419.

Takashima NE, Rondanini DP, Puhl LE, Miralles DJ (2013) Environmental factors affecting yield variability in spring and winter rapeseed genotypes cultivated in the southeastern Argentine Pampas. *European Journal of Agronomy* **48**, 88-100. doi:10.1016/j.eja.2013.01.008

Taylor AJ, Smith CJ (1992) Effect of sowing date and seeding rate on yield and yield components of irrigated canola (*Brassica napus* L.) grown on a red-brown earth in south eastern Australia. *Australian Journal of Agricultural Research* **43**, 1629-1641. doi:10.1071/AR9921629

Verdon-Kidd DC, Kiem AS, Moran R (2014) Links between the Big Dry in Australia and hemispheric multi-decadal climate variability—implications for water resource management. *Hydrology and Earth System Sciences* **18**, 2235-2256. doi:10.5194/hess-18-2235-2014

Wallach D, Goffinet B (1989) Mean square error of prediction as a criterion for evaluating and comparing system models. *Ecological Modelling* **44**, 299-306. doi:10.1016/0304-3800(89)90035-5

Wang S, Wang E, Wang F, Tang L (2012) Phenological development and grain yield of canola as affected by sowing date and climate variation in the Yangtze River Basin of China. *Crop & Pasture Science* **63**, 478-488. doi:10.1071/CP11332