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Agronomic management combining early-sowing on establishment opportunities, cultivar options and adequate nitrogen is critical for canola (*Brassica napus*) productivity and profit in low-rainfall environments

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Abstract. Sustaining diverse, yet productive crop sequences that integrate break crops such as canola (*Brassica napus* L.) remains a critical challenge for farming systems in low-rainfall cropping environments. Recent advances in canola productivity through early sowing, understanding of critical stress periods, hybrid cultivars and improved nitrogen (N) fertilisation offer promise under many conditions but require careful adaptation for risky, low-rainfall environments. A series of eight experiments was implemented over four growing seasons (2015–18) in the low-rainfall environments of southern Australia to test combinations of sowing date, cultivar selection and N-management strategies. Simulation modelling extended the field experiment results, enabling a simple, whole-farm profit–risk analysis across growing season deciles. The aim was to identify combinations of practices where the potential production and risk were understood, thereby assisting management decisions in low-rainfall cropping systems. Earlier sowing (April) was generally beneficial but only where seasonal conditions led to successful establishment, meaning that the best fit for canola in low-rainfall environments is as an opportunity crop. A hybrid cultivar (triazine tolerant) did not provide a yield advantage in an early experiment, but productivity increases were measured with a modern hybrid cultivar (Clearfield) in a later experiment. Profit-risk analysis suggested that a yield advantage of >20% over open-pollinated cultivars needs to be sustained across the full range of season deciles to generate economic advantage. Although there was relative insensitivity to the timing of N application, an adequate dose of N, either through fertiliser or legume crops, was critical to improve canola productivity. We conclude that opportunities exist to make significant gains in yield (by up to 110% compared with current standard practice) and profit–risk outcomes (~30% increased gross margins across all season types) for canola in low-rainfall environments by using a package of agronomic management decisions that includes early sowing on genuine establishment opportunities, hybrids that offer sustained yield benefits, and matching N dose from both fertiliser and legume crops to yield potential of the soil type and seasonal outlook.

Keywords: canola hybrids, establishment opportunity, rainfall limitation, risk management, sowing time, nitrogen application, yield gain.

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Introduction

Canola (*Brassica napus* L.) is Australia's third most important grain crop producing an average of 2.5 Mt per annum in the 5-year period 2014–18 valued at AU$1.25 billion per annum (ABARES 2019). In addition to providing producers with substantial income, canola provides benefits within the crop sequence, such as management of soil-borne diseases (particularly caused by *Rhizoctonia solani*) and grass weeds. Cereal crops following canola in the low-rainfall zone (<350 mm) consistently yield up to 0.4 t ha^{-1} more than continuous cereal crops (Kirkegaard *et al*. 2014; McBeath *et al*. 2015) and provide sequence-level gross-margin benefits (Browne *et al*. 2012). However, the average Australian canola yield is <1 t ha^{-1} (ABARES 2019) and is vulnerable to a range of production and price risks, particularly in the low-rainfall cropping region of southern Australia. This region is characterised by annual rainfall of <350 mm and sandy soils that are inherently lacking in fertility and constrained in nitrogen (N) supply (Sadras 2002; Sadras and Roget 2004; Monjardino *et al*. 2013). Sadras and Roget (2004) demonstrated increased productivity of cereals in the low-rainfall Mallee environment by including canola in the cropping sequence, but the profitability of this sequence compared with continuous cereal was largely dependent on canola being grown opportunistically when there was adequate early-season rainfall and reduced risk of poor yield (Whitbread *et al*. 2015). Thus, improving the stability of yield and profitability of canola in low-rainfall environments is necessary to ensure that it remains a viable option in these cropping systems.

The benefits of sowing canola early in the cropping season have been well demonstrated across the southern Australian cropping region (Hocking and Stapper 2001; Kirkegaard *et al*. 2016; Harries *et al*. 2018). In low-rainfall regions of southern Australia, time of sowing has had a far greater impact on canola productivity than sowing depth or cultivar choice. Experiments in South Australia indicate that for every day that canola is sown after 20 April there is an average grain yield loss of 25 kg grain ha^{-1} up to 24 May (Ware *et al*. 2017). In Western Australia, Fletcher *et al*. (2015) showed an average yield loss of 56 kg grain ha^{-1} for each day of delay in sowing after 29 April up to 10 June. Nevertheless, adequate plant establishment must follow early sowing to ensure the overall success of canola crops, and this is a challenge in low-rainfall environments, owing to inadequate moisture at the time of sowing. Management factors to ensure successful establishment include combinations of larger seed size, optimum sowing depth and hybrid cultivars (Brill *et al*. 2016).

Hybrid canola grows more vigorously and can offer higher yield potential than open-pollinated (OP) triazine-tolerant (TT) varieties; however, the cost of hybrid seed remains a key barrier to adoption in low-rainfall environments because the relative yield and profit advantage of hybrids is proportionate to rainfall (Zhang *et al*. 2016). Consequently, the proportion of hybrid cultivar use in Australia remains relatively low at <20% (DPIRD 2018) compared with other areas such as Canada or Europe. Hybrid cultivars released more recently may offer yield advantages and stability not previously observed in low-rainfall environments (Pan *et al*. 2016*b*), particularly given limited OP cultivar choices for low-rainfall environments (Zhang *et al*. 2016).

Nitrogen (N) inputs are another important driver of canola yield, especially given the potential for increased yield recently identified with optimum sowing date (Lilley *et al*. 2019). Canola has a relatively high demand for N, with 80 kg N t^{-1} grain commonly cited as the N-supply level required (Brennan and Bolland 2009; Norton 2016; Pan *et al*. 2016*a*), but in the low-rainfall zone, rates must be carefully managed to deliver profit at an acceptable level of risk. In southern Australia, canola was traditionally grown following legume pastures because of its high N demand and the ability to provide a disease break from diseases harboured by grass species in the pasture (Kirkegaard *et al*. 1997, 2016). As cropping systems have intensified, canola has increasingly been grown later in a crop sequence when levels of mineral N tend to be lower (Hocking *et al*. 2002) and inputs of N from fertiliser have become more important. Supplying appropriate amounts of N fertiliser while managing the risk of economic loss if crops subsequently fail is a challenge. In a review of N management, Norton (2016) identified options for adopting a more tactical approach to the amount of N applied as important future research targets in canola, including the ability to sense in-crop N status and optimise N timing later in the season, maintenance of oil content, and minimising N losses to the environment. Although the amount of N supplied to canola is known to be critical, there have been contradictory findings about the effect of N timing. For example, Seymour *et al*. (2016) suggest that N timing is not important and delaying decisions up to the start of flowering can be used as a risk-management tool, whereas Hocking *et al*. (1997) measured a yield penalty of 10–30% when N was delayed to the start of flowering.

In order to identify profitable, low-risk canola management options for low-rainfall environments, we combined field studies across contrasting soils in such environments in southern Australia, long-term simulation, and farm-level gross-margin analysis. We aimed to capture the effect of season type on canola management outcomes to understand the profit-risk implications.

Materials and methods

Site description

Eight field experiments were conducted during 2015–18 at sites in southern Australia, including South Australia and Victoria from Minnipa in the west to Ouyen in the east (Table 1). All sites are considered part of the low-rainfall cropping zone with average annual rainfall (and growing season rainfall) of 329 (211) mm at Ouyen, 267 (124) mm at Mildura, 338 (215) mm at Karoonda, and 324 (256) mm at Minnipa. The experiments covered a range of soils (described according to the Australian Soil Classification; Isbell 2002) and season types from decile 1 (2018) to decile 9 (2016) (Table 1). The experiments included a range of treatment factors thought to influence the risk and profit of canola production: time of sowing, cultivar choice, N dose, N timing, and N source.

Experimental design and analyses

Canola was sown in experimental plots of 20–25 m length and each plot had six rows 0.28 m apart. Seeding rates were adjusted for seed size and germination to achieve a target population of ~40 plants m^{-2} and the seed was treated with Maxim XL (fludioxonil + metalaxyl-M; Syngenta Australia, Sydney) to minimise the potential effect of blackleg (*Leptosphaeria maculans*). All OP treatments were sown to the cultivar ATR Stingray. Establishment numbers were recorded ~3 weeks after sowing by counting established plants within an area of 1-m length across six rows in every plot. Optimal agronomy was used to ensure that weeds, fungal infection and insect pests were controlled at all sites, and no major incursions were recorded. Regular observations were

Table 1. Site and management details for the eight experiments measuring responses to the factors of sowing date, cultivar and N management as a combination of dose (kg N ha^{-1}) and timing
Growing season rainfall (GSR) from April to October, sowing plant-available water (SPAW, average ± s.e.), pre-sowing soil mineral N to 1 m depth (PSMN, average ± s.e.), and crop establishment are shown for each site and soil combination. B, Barley; FP, field pea; V, vetch; n.a., data not available

Experiment no. Year	1 2015	2 2015	3 2016	4 2016	5 2016	6 2017	7 2017	8 2018
Location	Ouyen	Minnipa	Ouyen	Minnipa	Karoonda	Mildura	Karoonda	Karoonda
State	Vic.	SA	Vic.	SA	SA	Vic.	SA	SA
Soil type (ASC)	Kandosol	Calcarosol	Kandosol	Calcarosol	Kandosol, Calcarosol, Chromosol	Kandosol	Kandosol, Calcarosol, Chromosol	Kandosol, Calcarosol, Chromosol
APSoil no.	640	909	640	909	387, 386, 385		387, 386, 385	387, 386, 385
SILO weather station	76047	18052	76047	18052	25039		25039	25039
Sowing date	22 Apr.,7 May	26 Apr, 15 May	22 Apr., 13 May	22 Apr.,11 May	10 May	15 May	3 May	4 May
Cultivar	ATR Stingray, TT Hyola 450	ATR Stingray, TT Hyola 450	ATR Stingray	ATR Stingray	ATR Stingray	ATR Stingray	ATR Stingray	ATR Stingray; 43Y92 CL
N dose rate (kg ha^{-1})	67.5	67.5	0, 80	0, 80	5, 30, 80	0, 30	5, 30, 80	5, 30, 60, 90, 120, 150
N-timing treatments	Sowing, 4–8 leaves, stem elongation, start of flowering	Sowing, 4–8 leaves, stem elongation, start of flowering	Sowing, 2–4 leaves, stem elongation, split sowing and 2–4 leaves, split 2–4 leaves and stem elongation, split sowing and stem elongation	Sowing, 2–4 leaves, stem elongation, split sowing and 2–4 leaves, split 2–4 leaves and stem elongation, split sowing and stem elongation	2 leaves, 4–8 leaves, stem elongation			
Crop type treatments						B, FP, FP–B mix, V–B mix, V–FP mix, V–FP–B mix, V	Lupins, wheat	
GSR (mm)	146	225	252	260	346	132	236	133
SPAW (mm)	13 ± n.a.	36–44 ± 1–3	20 ± n.a.	27–35 ± 4–6	41 ± 7, 114 ± 5, 90 ± 10	23 ± 2	57–63 ± 6–7, 104–114 ± 7–12, 92–114 ± 12–21	92 ± 13, 84 ± 12, 12 ± n.a.
PSMN (kg ha^{-1})	41 ± n.a.	57 ± n.a.	n.a.	26 ± n.a.	40 ± 7, 62 ± 5, 116 ± 10	39–85	40–59 ± 3–5, 51–107 ± 7–10, 85–150 ± 4–10	37 ± 2, 53 ± 4n.a.
Establishment (plants m^{-2})	20	30	43	20	14, 49, 58	#	45, 45, 41	39, 28, n.a.

made of phenological development in order to record the start of flowering where 50% of plants had one open flower. For harvest, the plots were desiccated with Weedmaster DST (glyphosate; Nufarm, Melbourne) at 2 L ha^{-1} when 70–80% of seeds showed colour change on both the whole shoot and main stem, and harvest was done 4–7 days later. Seed yield and harvest index (HI) were also measured in each plot from three quadrats (1.12 m^2 each) cut by hand at ground level before desiccation. The samples were dried, threshed and weighed to determine HI, and a subsample of seed was used to measure oil and protein using a near-infrared analyser (FOSS, Hillerød, Denmark).

Soils at the Karoonda and Minnipa sites were characterised for plant-available water capacity through measurement of bulk density, drained upper limit and crop lower limit before the initiation of the experiments, using the procedure outlined in Burk and Dalgliesh (2013). The Ouyen and Mildura characterisations were selected from the APSoil database (Dalgliesh *et al*. 2012) (Table 1).

For all experiments annotated with standard error (s.e.) in Table 2, two segmented soil cores to 1 m depth were taken in each plot or replicate block (depending on treatment design) before sowing in each year of the experiment. The cores were divided into depths of 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6 and 0.8–1.0 m and the samples from the two cores were bulked for analysis. For all sites, subsamples were weighed, then dried for 48 h at 105°C and re-weighed to calculate pre-sowing gravimetric water content. Gravimetric water content was converted to volumetric water content by using the bulk density from the site characterisations described. Volumetric water content was converted to mm water by using the depth increment, and the sowing plant-available water was calculated by subtracting the crop lower limit determined in the site characterisation procedure. Another set of subsamples was immediately dried at 40°C for 10 days. Samples were bulked at increments of 0–0.1, 0.1–0.6 and 0.6–1.0 m and then ground (mortar and pestle) and sieved (<2 mm) for nitrate-N and ammonium-N analysis. Soil nitrate-N and ammonium-N were analysed according to Method 7C2b of Rayment and Lyons (2011).

Although treatment factors varied year-to-year, all experiments were sown in a randomised complete block design with four replicates per treatment. All data were statistically analysed with Genstat 13th Edition software (VSN International, Hemel Hempstead, UK), using analysis of variance for all experiments. For sites with multiple soil types (e.g. Karoonda), each soil type was analysed as an independent experiment. Assumptions of normality of data distribution and additivity of treatment and replicate effects were tested for each analysis. For significant effects ($P < 0.05$), least significant difference (l.s.d.) was used for multiple comparison between treatments.

Experiments 1 and 2 (2015): effect of sowing date, cultivar and N fertiliser timing at Ouyen and Minnipa

At sites near Ouyen and Minnipa, the effect on canola production of the factorial combination of two times of sowing (April and May), two cultivars (ATR Stingray and the hybrid TT Hyola 450, both having the TT yield penalty), and four timings of N fertiliser application (67.5 kg N ha^{-1} topdressed at seeding, post-emergence (4–8 leaves), stem elongation (10 cm stem emergence) and start of flowering) was tested. Both sites received single superphosphate at 100 kg ha^{-1} to supply 8.8 kg phosphorus (P) and 11 kg sulfur (S) ha^{-1} at sowing. The aim of these experiments was to test the effect of combinations of time of sowing, cultivar and N timing on canola yield and production risk.

Experiments 3, 4 and 5 (2016): effect of sowing date, N fertiliser dose and timing at Ouyen, Minnipa and Karoonda

At sites near Ouyen and Minnipa, the effect on canola production of the factorial combination of two times of sowing (April and May), and seven N treatments supplying 0 or 83 kg N ha^{-1} (nil N, all N at sowing, all N post-emergence, all N at stem elongation, N split seeding and early post-emergence, N split post-emergence and stem elongation, N split seeding and stem elongation) was tested by using cv. ATR Stingray. Both sites received single superphosphate at

Table 2. Key characteristics of the Mallee and Upper Eyre Peninsula (UEP) case-study farms
Currency is AU$

	Mallee	Upper Eyre Peninsula (UEP)
Soil type	60% Kandosol (sand), 30% Calcarosol (sand over loam), 10% Chromosol (loam)	20% Kandosol (sand), 40% Calcarosol (sand over loam), 40% Calcarosol (clay loam)
Annual variable costs ($ ha^{-1})	171 wheat, 146 peas, 169–225 canola	204 wheat, 166 peas, 200–256 canola
Canola cost breakdown (excludes cultivar) ($)	Fertiliser N 1.20 kg^{-1}; sowing fertiliser 18 ha^{-1}; pesticides 41 ha^{-1}; freight 25.4 t^{-1}; repairs, maintenance and contracting 61 ha^{-1}; insurance and levies 6% of income	Fertiliser N 1.20 kg^{-1}; sowing fertiliser 18 ha^{-1}; pesticides 52 ha^{-1}; freight 18.6 t^{-1}; repairs, maintenance and contracting 68 ha^{-1}; insurance and levies 6% of income
Canola cultivar costs ($ ha^{-1})	Open-pollinated seed 10, hybrid seed 60	Open-pollinated seed 10, hybrid seed 60
Commodity price ($ t^{-1})	253 wheat, 167 peas, 500 canola	253 wheat, 167 peas, 500 canola
Variable nitrogen input (kg N ha^{-1})	Sands: decile 1, 5; decile 3, 50; decile 5–9, 80. Loam: decile 1, 5; decile 3–9, 50	Sand and clay loam: decile 1, 5; decile 3, 50; decile 5–9, 80
Establishment rules	10 mm in 7 days (sands),15 mm in 7 days (loams)	10 mm in 7 days (sands), 15 mm in 7 days (loams)
Yield penalty for time-of-sowing delay	44% for June establishment, 85% for July establishment	44% for June establishment, 85% for July establishment

100 kg ha^{-1} to supply 8.8 kg P and 11 kg S ha^{-1}. At a site near Karoonda, two rates of N input (30 and 80 kg N ha^{-1}) were tested when applied at three growth stages (early post-emergence (2-leaf), post-emergence (4–8-leaf) and stem elongation) on three soil types (Kandosol, Calcarosol and Chromosol). All plots received 50 kg zinc (Zn)-coated mono-ammonium phosphate (MAP) at sowing (5 kg N and 11 kg P ha^{-1}). Refining treatments based on results from Experiments 1 and 2, the aim of these experiments was to test whether combinations of sowing date, N fertiliser dose and timing offered further benefits to canola yield and production risk.

Experiments 6 and 7 (2017): effect of residual legume N and fertiliser N on canola production at Mildura and Karoonda

At a site near Mildura plots of barley, field pea, field pea–barley mix, vetch–barley mix, vetch–field pea mix, vetch–field pea–barley mix, and vetch were established in 2016. Barley and vetch were fallowed in spring in order to brown manure; field peas were grown to maturity. Canola cv. ATR Stingray was sown on 15 May 2017 (re-sown after failed establishment for April sowing) with single superphosphate at 100 kg ha^{-1}. On 13 July, 32 kg N ha^{-1} was applied as urea to one-half of each plot. There was no follow-up rain to incorporate the urea until 3 August. Seed yield, harvest index and oil content were measured on all plots.

At a site near Karoonda, plots of lupin and wheat were established in 2016 in a completely randomised block design with four replicates. In 2017, all plots were sown with canola cv. ATR Stingray and received 11 kg P, 11 kg S and 27 kg potassium (K) ha^{-1}, and foliar Zn, copper (Cu) and manganese (Mn) to ensure that other nutrients were non-limiting. Fertiliser was applied as 50 kg MAP + 1% Zn ha^{-1} at sowing (5 kg N ha^{-1}), and any additional fertiliser was applied after the crop emerged (2–4 leaves) by topdressing with two doses of N as urea (30 or 80 kg N ha^{-1}) on 21 June. Given the demonstrated importance of canola N supply in Experiments 1–5, the aim of these experiments was to test whether combinations of legume crops and fertiliser N offered any further benefits to canola yield and production risk.

Experiment 8 (2018): effect of cultivar and N fertiliser rate at Karoonda

At a site near Karoonda, plots were sown with canola and received 11 kg P, 11 kg S and 27 kg K ha^{-1}, and foliar Zn, Cu and Mn to ensure that other nutrients were non-limiting. Fertiliser was applied as 50 kg MAP + 1% Zn ha^{-1} at sowing (5 kg N ha^{-1}), and any additional fertiliser was applied after the crop emerged (2–4 leaves) by topdressing with urea to create N-dose treatments of 5, 30, 60, 90, 120 and 150 kg N ha^{-1} for cv. ATR Stingray, and 5 and 90 kg N ha^{-1} for hybrid cv. 43Y92 CL on 7 June. With the importance of N dose highlighted in Experiments 1–7 and emerging data demonstrating the potential fit of new hybrid cultivars (with no TT yield penalty) in low-rainfall environments, the aim of Experiment 8 was to compare the optimal dose of N in the most widely grown TT canola cultivar, and a newly released hybrid cultivar with matched phenology.

Simulation analysis

The results obtained from field experiments were complemented with long-term (50-year) simulations for the main experimental sites (Karoonda, Minnipa and Ouyen), with the sites validated for flowering time in Lilley *et al*. (2019). The systems model APSIM has been validated and used extensively to simulate canola production in Australian environments (Robertson and Lilley 2016; Lilley *et al*. 2019; Meier *et al*. 2020). A factorial combination of management practices that had been investigated in the field experiments were simulated with APSIM version 7.9 (Holzworth *et al*. 2014), configured with modules for canola (Robertson and Lilley 2016), and crop residue (SurfaceOM), soil N (SoilN) and soil water dynamics (SoilWat) (Probert *et al*. 1998). Canola yield was reduced according to frost- and heat-damage functions described by Lilley *et al*. (2019). Simulated soils were obtained from the APSoil database on the basis of previous characterisation activities (Table 1). Crops and management were simulated in response to the SILO weather record (https://www.longpaddock.qld.gov.au/silo/) from the locations for the years 1956–2016 (Table 1).

All canola crops were simulated in response to a factorial of sowing dates, target N-fertiliser rates, cultivar types, rates of cultivar development and planting densities. Sowing dates consisted of 16 dates from 15 March to 12 July in weekly time-steps. In order to evaluate yield in response to time of sowing, the germination of simulated crops was promoted by increasing plant-available water to 50% in the top 0.3 m of the soil; crops that did not germinate within 14 days of sowing were terminated. The N fertiliser was applied as 5 kg urea-N ha^{-1} to all crops at sowing, and an additional in-crop adjustment (at 50 days after sowing) was made to achieve 5, 10, 20, 30, 40, 50, 70, 100 kg N ha^{-1} in the surface 0.3 m of soil. Generic cultivar types representing either hybrid or TT, OP cultivars were simulated with a fast, medium or slow rate of development. Crops were simulated in response to three planting densities: 15, 30 and 45 plants m^{-2}.

Profit–risk analysis

Objectives for profit–risk analysis

The analyses undertaken utilising the case-study farms included investigations of (*i*) the amount of yield advantage required for hybrid-cultivar gross margins to match OP gross margins; (*ii*) the effect of dry sowing compared with sowing on a genuine establishment opportunity; and (*iii*) the effect of altering N-management options (fertiliser and use of legumes) on the canola gross margin.

Division of results into deciles

Presenting the gross-margin outcome across a range of season deciles (or terciles) is a technique that allows the potential risk to be presented and considered in the context of practice change (Rodriguez *et al*. 2018; Meier *et al*. 2020). The analysis of gross margins across season deciles using hypothetical case-study farms allowed for integration of field and modelling experimentation and an evaluation of the key processes as they relate to decisions that will be made on-farm.

The profit–risk scenarios analysed in this study have capitalised on the process used by Meier *et al*. (2020) to identify the key levers that influenced the gross margin and consider them as decision points, for which management rules might be useful. Seasons were divided into deciles based on the growing-season rainfall plus 0.25 fallow rainfall, as per average fallow efficiency reported by Robinson and Freebairn (2017) with analyses produced for decile 1, 3, 5, 7 and 9 seasons. The gross margin analysis presented here is designed to inform a farm cash-flow analysis for providing better support for decisions around practice change.

Case-study description

The potential profit–risk outcomes of different canola management scenarios were analysed by developing two case-study farms: Mallee (region including Karoonda, Ouyen and Mildura), and Upper Eyre Peninsula (UEP, region including Minnipa) (Table 2). Although the soil types for the two farms classify as the same groups (Kandosol (sand), Calcarosol (sand over loam) and Chromosol (loam), there are some important differences in the distribution of these soils for the case-study farms, with a higher proportion of the loam soil types for UEP. The UEP farm also had a slightly higher level of uniform N input (40 kg N ha^{-1}) than the Mallee farm

Table 3. Estimated canola yield (t ha^{-1}) in response to soil type (where Kandosols and Calcarosols are sands and Chromosols are loam), season type (decile), establishment date, fertiliser regime, and legume break effect for Mallee and Upper Eyre Peninsula (UEP) case-study farms

Establishment (% of years on sands, loams) for Mallee: May (60%, 40%), June (28%, 40%), July (10%, 10%); and for UEP: May (48%, 23%), June (30%, 30%), July (15%, 25%)

	Decile 1	Decile 3	Decile 5	Decile 7	Decile 9
Mallee and UEP, May establishment yield					
Kandosol	0.20	0.50	0.80	1.30	1.30
Calcarosol	0.20	0.70	1.00	1.50	2.00
Chromosol	0.20	0.50	1.00	1.30	2.00
Mallee and UEP, June establishment yield					
Kandosol	0.19	0.47	0.75	1.21	1.21
Calcarosol	0.19	0.65	0.93	1.40	1.87
Chromosol	0.19	0.47	0.93	1.21	1.87
Mallee and UEP, July establishment yield					
Kandosol	0.03	0.08	0.75	0.20	0.20
Calcarosol	0.03	0.11	0.93	0.23	0.30
Chromosol	0.03	0.08	0.93	0.20	0.30
Mallee, dry-sowing yield combining establishment-date effect					
Kandosol	0.18	0.44	0.12	1.14	1.14
Calcarosol	0.18	0.62	0.15	1.32	1.76
Chromosol	0.15	0.38	0.15	1.00	1.54
Mallee, blanket N-application (30 kg N ha^{-1}) yield (only sown on opportunity)					
Kandosol	0.20	0.30	0.50	0.80	0.80
Calcarosol	0.20	0.40	0.50	1.00	1.50
Chromosol	0.20	0.50	1.00	1.30	1.80
UEP, dry-sowing yield combining establishment-date effect					
Kandosol	0.11	0.26	0.42	0.69	0.69
Calcarosol	0.06	0.20	0.29	0.44	0.59
Chromosol	0.06	0.15	0.29	0.38	0.59
UEP, blanket N-application (40 kg N ha^{-1}) yield (only sown on opportunity)					
Kandosol	0.20	0.50	0.50	0.80	0.80
Calcarosol	0.20	0.70	0.50	1.00	1.50
Chromosol	0.20	0.50	0.50	0.80	1.50
Mallee and UEP, aggregated practices: establishment on opportunity, variable N, canola following wheat					
Kandosol	0.20	0.50	0.80	1.30	1.30
Calcarosol	0.20	0.70	1.00	1.50	2.00
Chromosol	0.20	0.50	1.00	1.30	2.00
Mallee and UEP, aggregated practices: as above but canola following legume yield					
Kandosol	0.26	0.65	1.04	1.69	1.69
Calcarosol	0.24	0.84	1.20	1.80	2.40
Chromosol	0.22	0.55	1.10	1.43	2.20

(30 kg N ha^{-1}) based on farm data accessed in the process of the analysis (Table 2). Further to this, the distribution of rainfall influences the outcomes for the different management scenarios despite the yields for crops sown on an establishment opportunity in the window 15 April–15 May being the same for the two farms (more detail below).

Yield estimation and costs used for profit–risk analysis

Yield estimates (Table 3) were derived from data sourced from a combination of plot experimental yields gained in this study, supplemented with other published data (e.g. McBeath *et al*. 2015; Roberts *et al*. 2017; Ware *et al*. 2017), and model-based estimates were used to identify management penalty or benefits to yield for the factors time of establishment, fertiliser-N response and crop-sequence effects.

Limited published data are available comparing different canola herbicide-tolerance types, which presented a challenge when evaluating the hybrid gross margin outcome. The range in percentage yield benefit we identified was 10–25% (e.g. Zhang *et al*. 2016). For this reason, we provided an evaluation of the percentage yield benefit required to generate a gross-margin benefit on the two case-study farms at the current differences in pricing between hybrid and OP varieties rather than a direct assessment of the canola cultivar effect on profit–risk.

The estimate of establishment date was used to predict the yield outcome for a dry-sown canola crop by combining yields of crops establishing in each month, based on the chance of an appropriate rainfall trigger. The establishment opportunity was predicted based on a requirement for 10 mm in 7 days on sand (Kandosol and Calcarosol) and 15 mm in 7 days on loam (Chromosol) (rules developed by Ware *et al*. 2017) and using climate analyses from the CliMate weather app (https://climateapp.net.au/) to predict the probability of an establishment opportunity in each month. Modelling with APSIM generated predictions of the penalty for delay in time of sowing, which were applied to the yield estimates to generate the dry-sowing yield estimate (Fig. 1) with a 44% yield penalty applied to crops establishing in June and an 85% yield penalty applied to crops establishing in July (based on modelling in Fig. 1).

Case-study yields in response to aggregated practices were based on only sowing ATR Stingray canola on an establishment opportunity, sowing using the variable N-input rules as described in Table 2 for canola sown after a wheat crop.

Price and cost data were sourced from a combination of published information (PIRSA 2019) and local expert input (Table 2). Gross margins were calculated as total income (AU$ ha^{-1}) minus variable costs, which included seed, fertiliser, chemicals, freight, insurance, levies, labour and machinery operations, and interest payable on seed purchase for each enterprise. The gross margins were aggregated across the three key soil types for each case-study farm. For example, if a farm was 0.33 sand, 0.33 loam and 0.33 clay, then a gross margin ($ ha^{-1}) is made up of 0.33 sand gross margin, 0.33 loam gross margin and 0.33 clay gross margin.

Results

Rainfall for establishment and in-season N topdressing

In the environments under consideration, canola requires $\geq$10 mm rainfall in a 7-day period to establish successfully (Ware *et al*. 2017). An evaluation of climate data (1957–2019) indicates a significant risk of a lack of rainfall to establish canola through April and May at all sites, but particularly at Minnipa and Ouyen. The proportion of years with adequate rainfall to establish canola increases as time progresses into May but it remains at $\leq$30% (Fig. 2). Analysis of the years in which there has been $\geq$10 mm rainfall in winter also provides an indication of the chance of topdressed urea being incorporated into soil by rainfall. This presents a significant risk for the management of in-crop N-fertiliser application to canola at the low-rainfall sites, particularly at Ouyen and Karoonda (Fig. 2).

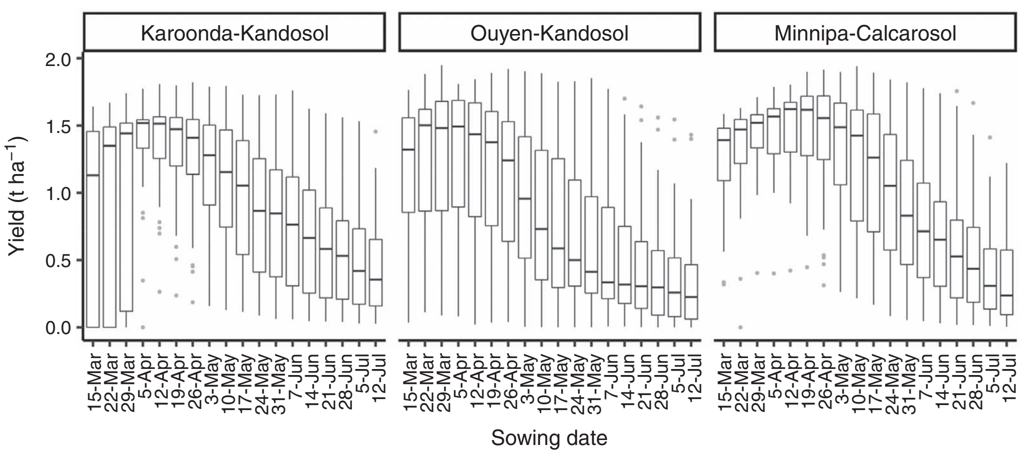

Fig. 1. Box plots for predicted yield of crops in response to progressively later sowing dates for three combinations of field trial location and soil type. Predicted yields were simulated using climate files at each location for the 50-year period 1967–2016. In plots, boxes depict the median and adjacent upper and lower quartiles of yield values; whiskers are 1.5 times the interquartile range; outlier points are values occurring beyond the range of the whisker fences.

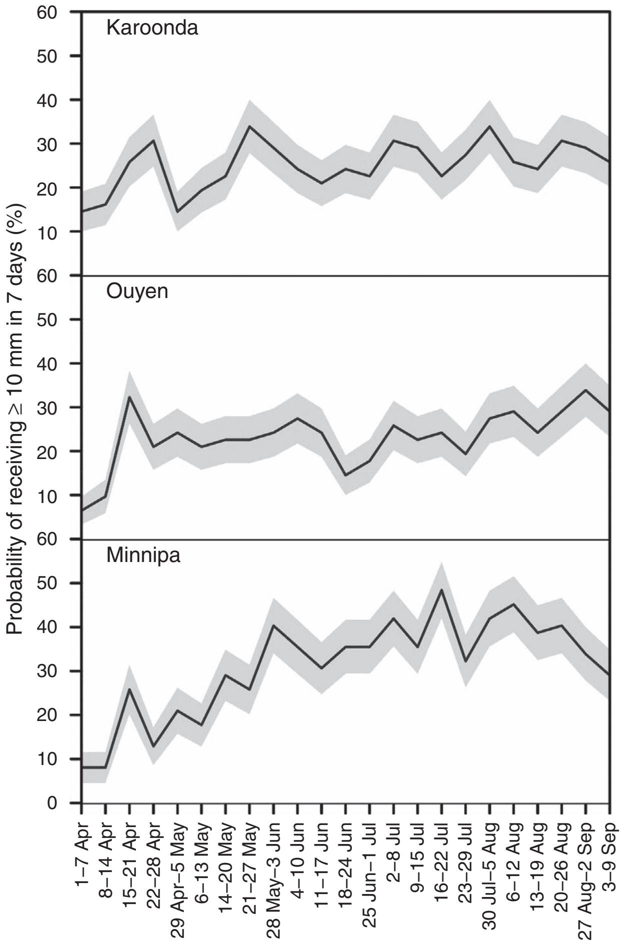

Fig. 2. The proportion of years in which ≥10 mm of rain falls over a 7-day period across the sowing window (April–May) and the window for topdressing of nitrogen (June–August) at the three key sites Minnipa, Ouyen and Karoonda for the period 1957–2018. Shading represents ± 1 standard error.

Summary of field-experiment seasonal conditions, yield and oil responses

The 2015 growing-season rainfall was below average at both Ouyen and Minnipa; 2016 rainfall was above average for Ouyen, Minnipa and Karoonda; 2017 rainfall was average for Karoonda and Mildura; and 2018 rainfall was well below average at Karoonda (Table 1). The effect of key treatment factors on yield and oil content are described in detail in the following subsections, but in summary:

(1) There was a significant sowing date × N timing interaction effect on yield at Minnipa in 2015 and 2016, but this interaction was not reproduced at other sites (Table 3). Sowing date significantly affected yield in three of the four instances, but affected oil content in only two of the four instances.
(2) Cultivar was a significant factor for yield and oil content only in the 2018 experiment when testing the newer cultivar 43Y92 CL.
(3) Nitrogen dose had a significant effect on yield in almost all instances where it was tested, but an effect on oil content in only two instances.
(4) Nitrogen timing showed some significant effects on yield, limited to the lighter textured Kandosols and Calcarosols, and affected oil content only in 2015.
(5) The previous crop type (cereal vs legume) had a significant effect on yield in all cases, and influenced oil content on lighter textured soils (Table 4).

Effect of sowing date

Early sowing increased yield and oil content of crops when good establishment occurred. There was a significant benefit of earlier sowing at Minnipa in 2015, with an extra yield of 0.27 t ha^{-1} from April sowing. However, in 2016 crop establishment was poor due to surface sealing; at Minnipa, April-sown plots had 7 plants m^{-2} compared with 33 plants m^{-2} for May-sown plots (l.s.d. 5.4 at $P = 0.05$), and the poor establishment of April-sown plots reduced yield by 0.3 t ha^{-1}. At Ouyen in 2015, there was no time-of-sowing response, whereas in 2016, the yield impact was +0.14 t ha^{-1} for May sowing (Table 5). There were only small differences in plant establishment number in both years (~5 plants m^{-2}, data not shown), but average plant numbers were very low across both treatments in 2015, at 20 plants m^{-2} (Table 1). The oil-content response mirrored the grain-yield response, whereby April sowing resulted in higher oil content at Minnipa in 2015 and May sowing resulted in higher oil content at Ouyen in 2016 (Table 5). Simulation analysis predicted that on balance, April sowing was a higher yielding option, with a penalty of 0.2–0.5 t ha^{-1} for May compared with April sowing for these sites (Fig. 1).

The case-study farm analysis, which compared sowing by the calendar (sown on 15 April) with sowing canola only when there is a genuine canola establishment opportunity, showed a gross margin benefit of \$46–348 ha^{-1} in deciles ≥3 when sowing on an opportunity (Fig. 3). This was particularly the case for UEP (benefit range \$108–348 ha^{-1}) where the soils are heavier and there is a higher probability of establishment failure.

Effect of cultivar

The effect of cultivar on yield and oil content varied according to the hybrid cultivar available for low-rainfall environments. The first comparison of a hybrid cultivar (TT Hyola 450) with the most used OP cultivar at the time (ATR Stingray) did not reveal a significant advantage (Table 6). However, the possibility of using a hybrid cultivar was reassessed in 2018 with the increased availability of cv. 43Y92 CL, which better matched the flowering time of the existing TT varieties (ATR Stingray still being the most commonly used OP variety in the low-rainfall environment). There were indications of a more substantial difference between the OP (TT) and hybrid (non-TT) varieties in this instance, with a yield gain of up to 0.26 t ha^{-1} (41%) (Table 6). Although the hybrid TT Hyola 450 had a higher oil content in 2015, the higher yielding 43Y92 CL had a lower oil content in 2018.

Table 4. Summary showing main effects and interactions of sowing date, cultivar and nitrogen effects on yield and oil content across eight different experiments

*$P < 0.05$; **$P < 0.001$; n.s., not significant ($P > 0.05$). Grey shading, not applicable

Expt. no.:	1	2	3	4	5	6	7	8
Year	2015	2015	2016	2016	2016	2017	2017	2018
Location	Ouyen	Minnipa	Ouyen	Minnipa	Karoonda	Mildura	Karoonda	Karoonda
Soil Type	Kandosol	Calcarosol	Kandosol	Calcarosol	Kandosol, Calcarosol, Chromosol	Kandosol	Kandosol, Calcarosol, Chromosol	Kandosol, Calcarosol, Chromosol
				Yield (t ha^{-1})				
Sowing date	n.s.	**	*	*				
Cultivar	n.s.	n.s.						n.s., *, **
N dose			**	**	**, **, **	*	**, *, n.s.	**, *, *
N timing	*	**	**	**	*, n.s., n.s.			
Prior crop type						**	**, **, *	
Interaction	n.s.	Sow date × N* Cultivar × N*	n.s.	Sow date × N**		n.s.	n.s., n.s., n.s.	n.s., n.s., n.s.
				Oil content (%, w/w)				
Sowing date	n.s.	*	**	n.s.				
Cultivar	**	*						**, **, n.s.
N dose			n.s.	n.s.	n.s., n.s., n.s.		n.s., n.s., n.s.	n.s., **, **
N timing	*	**	n.s.	n.s.	n.s., n.s., n.s.			
Prior crop type							n.s., **, *	
Interaction	n.s.	Cultivar × N*	n.s.	n.s.			n.s., n.s., n.s.	n.s., n.s., n.s.

Table 5. Canola grain yield and oil content response to time of sowing (April or May) at Ouyen and Minnipa in 2015 and 2016

n.s., Not significant ($P > 0.05$)

	Grain yield (t ha^{-1})			Grain oil (%, w/w)		
	April sowing	May sowing	l.s.d. (P = 0.05)	April sowing	May sowing	l.s.d. (P = 0.05)
			2015			
Ouyen	0.28	0.38	n.s.	37.6	39.7	n.s.
Minnipa	1.69	1.42	0.24	44.4	42.3	1.04
			2016			
Ouyen	1.04	1.18	0.07	44.3	45.6	0.47
Minnipa	0.64	0.94	0.16	44.2	44.1	n.s.

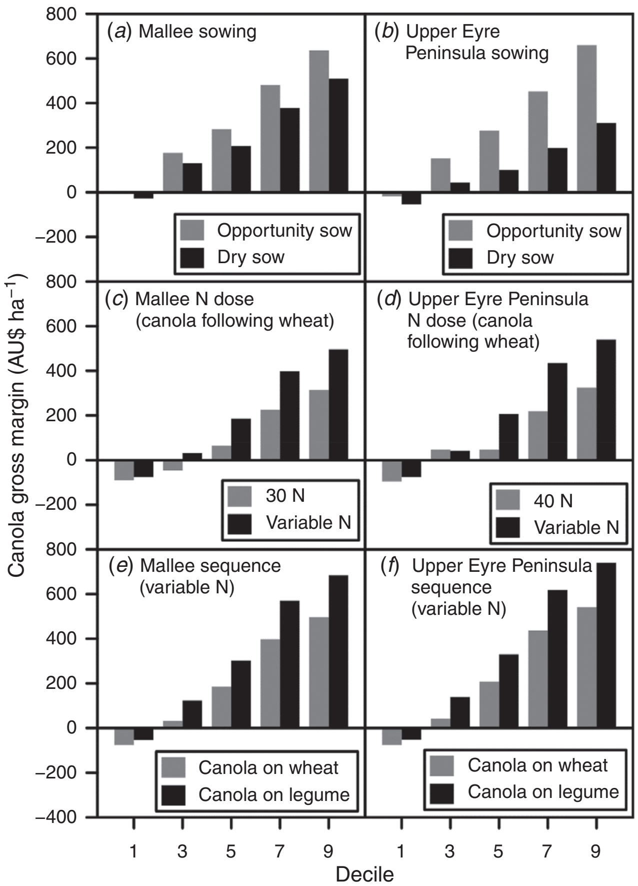

Fig. 3. Predicted canola gross-margin effect of: sowing on an establishment opportunity (10 mm rainfall for sands and 15 mm rainfall for clay and loams) compared with dry sowing on 15 April in response to season decile for (*a*) Mallee and (*b*) Upper Eyre Peninsula (UEP) case-study farms; blanket application of fertiliser N at compared with variable inputs of N according to soil and season, all applied after crop establishment for (*c*) Mallee and (*d*) UEP for canola sown on an establishment opportunity; and sowing canola following legume vs wheat crops on a variable fertiliser N system for (*e*) Mallee and (*f*) UEP for canola sown on an establishment opportunity.

The average yield benefit that needs to be sustained with the hybrid option in order to cover the extra cost of the hybrid seed was analysed (oil effects were not considered). The yield advantage needed to be >20% and season type of decile ≥5 for the hybrid seed to offer a gross-margin advantage (Table 7).

Effect of N dose

The grain-yield response to fertiliser N was consistently greater on the sandy soil types, with significant responses in all season types (Table 8). However, the rate of responsiveness (kg grain kg^{-1} fertiliser N) varied according to site and season. Higher levels of responsiveness were recorded in the wet growing season of 2016, and in most cases (except Minnipa), the sites yielded close to their estimated potential (Table 8). In 2017 the yields were well below potential despite rainfall sums being close to average, and as a result the rate of N response was lower. In 2018, despite a dry season, yields were close to potential but with a wider range of rates tested; the rate of response was lower where there was a significant yield response to fertiliser N (e.g. at 60–90 kg N ha^{-1}, Table 7).

Effect of N from preceding legume crops

Nitrogen supply from the previous crop had a significant effect on canola grain yield at both Mildura and Karoonda in 2017. At Mildura, the pre-sowing mineral N derived from the prior crop was a primary driver of the canola yield response, with a relationship of 13.3 kg grain kg^{-1} pre-sowing mineral N (data not shown). Canola grain yield also responded to fertiliser N input, but this response was independent of the prior crop type and had a lower efficiency (5.3 kg grain kg^{-1} N).

At Karoonda, the 2016 lupin crop provided an additional 19–62 kg pre-sowing mineral N ha^{-1} depending on the soil type, with the greatest benefit on the clay loam (Table 1). However, there was a grain yield response to previous crop type only when lupin was compared with wheat on the sandy Kandosol and Calcarosol, with a 40–60% yield benefit. The grain-yield benefit did not directly relate to pre-sowing mineral N or to the change in mineral N provided by the legume (e.g. the canola on the Chromosol had the highest mineral-N boost from the legume but there was no yield benefit of legume vs wheat). The previous crop type did not interact with fertiliser-N input for grain yield response. Both sandy soil types (Kandosol and Calcarosol) showed significant yield benefit at the input level of 80 kg N ha^{-1} compared with 5 kg N ha^{-1}. There was a wide variation in the extra grain produced from this additional 75 kg N ha^{-1} supplied as fertiliser, with 4.4–10.6 kg grain kg^{-1} N (Table 9).

Effect of N timing

Comparison of N applications at stem elongation and early post-emergence suggests that the responses to N timing can vary (Table 4). In the wetter growing season of 2016 at Karoonda, which included a wet spring, there was an advantage of delaying the application of N fertiliser. In many cases there was no effect of the timing of N fertiliser application, and there was an example of a yield penalty from delaying N input in the lower growing season rainfall of 2015 at Ouyen (Table 4).

Effect of N-management strategy on profit–risk

The effect of N-management strategy on the canola gross margin was explored for canola that had satisfactory establishment (>40 plants m^{-2}). Because the dose of N in the system was considered a key driver of yield (Tables 4 and 8), the effect of flat-rate inputs of N (30–40 kg N ha^{-1}) to target a low yield was compared with opportunistic inputs of N that were soil- and season-specific. These adjustments for soil and seasonal conditions were relatively simple so that management complexity would not be a burden. Thus, the rates could be adjusted manually by soil type if required (sand vs loam or clay loam), and by season for decile 1 (low) vs decile 3–5 (average) vs decile 7–9 (above average) (Fig. 3). Considerable gains were made with the variable-input system by avoiding investment in N fertiliser after sowing in a decile 1 season (adding only 5 kg N ha^{-1} with starter fertiliser), by using higher N rates on sandy than on heavy soils, and by increasing inputs at deciles $\geq$5. With variable fertiliser inputs gross margin losses were reduced by \$14–20 ha^{-1} in decile 1, whereas gains of up to \$159 ha^{-1} were possible in deciles 3–5 and \$173–216 ha^{-1} in deciles 7–9.

As was the case in the field experiments, the effects of legumes on canola productivity and profit were considered for the case-study farms. Based on the yield gains and N savings predicted for incorporating a legume in the sequence before canola production, gains in the canola gross margin were made across all season types. The loss in decile 1 was reduced by \$22–24 ha^{-1}, whereas the gain in deciles 3–9 increased by \$99–181 ha^{-1} and \$97–199 ha^{-1} across the season deciles for the Mallee and UEP case study farms, respectively (Fig. 3).

Table 6. Canola grain yield and oil content for hybrid and open-pollinated (OP) varieties at Ouyen and Minnipa in 2015 and Karoonda in 2018

Hybrid varieties were TT Hyola 450 in 2015, and 43Y92 CL in 2018; ATR Stingray was the OP variety in all cases. n.s., Not significant (P > 0.05)

	Grain yield (t ha^{-1})			Oil content (% w/w)		
	Hybrid	OP	l.s.d. (P = 0.05)	Hybrid	OP	l.s.d. (P = 0.05)
			2015			
Ouyen	0.33	0.33	n.s.	39.7	37.6	0.3
Minnipa	1.57	1.53	n.s.	43.6	43.2	0.3
			2018, Karoonda			
Kandosol	0.84	0.68	0.16	43.7	46.0	0.6
Calcarosol	0.86	0.76	0.10	43.5	44.2	0.7
Chromosol	0.88	0.62	0.10	40.1	39.7	n.s.

Discussion

Early establishment, not early sowing, drives success

It is widely accepted that sowing and establishment of spring canola should be targeted in April for southern Australian cropping systems in order to optimise grain yield (Hocking and Stapper 2001; Kirkegaard *et al*. 2016). Modelling of low-rainfall sites showed that the average yield of canola is predicted to drop significantly after mid-April, with a 44% yield penalty for crops established in June and 85% penalty for crops established in July across the three sites analysed (Fig. 1). The ability to achieve an adequate plant stand following sowing at the optimal time has been identified as a key issue limiting productivity (Brill *et al*. 2016; Ware *et al*. 2017). Field experiments in the 2015–16 growing seasons revealed that the requirement for a genuine April–May crop-establishment opportunity is especially important in low-rainfall environments. Although there was a significant benefit of April sowing (+0.27 t ha^{-1}) in 2015, the establishing rains did not occur until May (51 mm May rainfall) in 2016

Table 7. Canola gross margin (AU\$ ha^{-1}) for farm-retained open-pollinated (OP) seed at a cost of \$3.5 kg^{-1} and sown at 3 kg ha^{-1} compared with hybrid seed at a cost of \$30 kg^{-1} and sown at 2 kg ha^{-1} and offering a yield advantage of 10–25% on the Mallee and Upper Eyre Peninsula (UEP) case-study farms

Values in bold for hybrids have a higher gross margin than the OP seed option

Season	OP seed	Hybrid seed with yield gain:				OP seed	Hybrid seed with yield gain:			
		10%	15%	20%	25%		10%	15%	20%	25%
		Mallee farm					*UEP farm*			
Decile 1	–15	–80	–76	–71	–66	–12	–62	–58	–53	–48
Decile 3	173	127	140	154	168	159	126	142	154	**169**
Decile 5	267	235	256	**277**	**298**	234	**279**	**302**	**325**	**343**
Decile 7	469	458	**492**	**522**	**554**	418	**460**	**499**	**530**	**564**
Decile 9	622	**629**	**669**	**709**	**749**	668	**686**	**739**	**782**	**826**

Table 8. Canola grain yield (t ha^{-1}) responses to N fertiliser across all sites and seasons where a dose effect was tested

The grain response per kg fertiliser N is presented for treatments that are significantly different from each other, along with estimates of canola yield potential (calculated according the method outlined by Robertson and Kirkegaard 2005) and N requirement (according to Norton 2016). n.s., Not significant (P > 0.05)

Year	Site and soil	Fertiliser N (kg N ha^{-1}) applied: 0[A]	30	60	80[B]	120	150	l.s.d. (P = 0.05)	Response (kg grain kg^{-1} fertiliser N)	Yield potential (t ha^{-1})	N requirement (kg N ha^{-1})
2016	Ouyen	0.83			1.22			0.08	4.9	1.5	120
	Minnipa	0.53			0.95			0.11	5.3	2.2	176
	Karoonda										
	Kandosol		1.04		1.50			0.23	9.2	1.8	144
	Calcarosol		1.85		2.39			0.14	10.8	2.6	208
	Chromosol		2.24		2.76			0.14	10.4	2.3	184
2017	Mildura	1.05	1.22					0.17	5.7	0.6	46
	Karoonda										
	Kandosol	0.38	0.58		0.82			0.08	4.8–8.0	1.9	152
	Calcarosol	0.40	0.50		0.54			0.11	4.1	2.4	192
	Chromosol	0.36	0.42		0.40			n.s.	n.s.	2.3	184
2018	Karoonda										
	Kandosol	0.39	0.60	0.64	0.88	0.85	1.04	0.25	2.6–8.4	1.2	96
	Calcarosol	0.61	0.59	0.75	0.84	0.91	1.02	0.17	3.1	1.1	88
	Chromosol	0.64	0.50	0.62	0.76	0.80	0.74	0.16	1.4	0.3	24

[A]5 kg N at Karoonda in 2017, 2018. [B]90 kg N at Karoonda in 2018.

Table 9. Canola yield (t ha^{-1}) response to the prior crop type and fertiliser input at Mildura and Karoonda in 2017

n.s., Not significant (P > 0.05)

	Karoonda Kandosol	Karoonda Calcarosol	Karoonda Chromosol	Mildura Kandosol
Prior crop effect				
Wheat	0.79	0.70	0.78	0.79
Legumes	1.29	0.98	0.86	1.26
l.s.d. (P = 0.05)	0.11	0.09	n.s.	0.34
Fertiliser effect				
5 kg N ha^{-1}	0.70	0.74	0.79	1.05
30 kg N ha^{-1}	0.92	0.71	0.79	1.22
80 kg N ha^{-1}	1.50	1.07	0.88	
l.s.d. (P = 0.05)	0.24	0.11	n.s.	0.17

with a yield penalty of 0.14–0.30 t ha^{-1} for April sowing (3 mm April rainfall) in that year (Table 5). The case-study analysis allowed a clear demonstration of the potential impact of combining optimal time of sowing with a rule for sowing only with a genuine establishment opportunity (10 mm rainfall over 7 days in sand and 15 mm over 7 days in loam) with benefits of up to \$348 ha^{-1} (Fig. 3). There was a bigger advantage of using the establishment rule on the UEP farm, and this is because the farm had a higher proportion of heavier clay loam soils, which are more prone to establishment failure. However, the logistics around opportunistic sowing (e.g. cost associated with retaining seed if not sown) are critical issues not considered in this analysis (Fletcher *et al*. 2019). Although we have analysed the rules around an establishment opportunity at the beginning of the growing season, the value of knowing the amount of stored soil-water at the time of sowing to inform the canola-sowing opportunity requires thorough exploration beyond the scope of this study.

The case for varieties with better adaptation to low-rainfall environments

Previous research has suggested that the hybrid yield advantage is related to growing-season rainfall and the case for hybrid varieties in low-rainfall environments has not been well supported owing to a lack of gross-margin gain related to higher seed and licence costs (Zhang *et al*. 2016). In 2018 (decile 1) the production of a canola crop of up to 1.0 t ha^{-1} with 225 mm water (~100 mm of which was stored soil water), compared with a potential yield of 1.2 t ha^{-1} based on the benchmark of 11 kg ha^{-1} mm^{-1} and a 120 mm evaporation intercept (Table 7) (Robertson and Kirkegaard 2005), suggests that recent developments in hybrid varieties that offer yield advantages of 11–20% in low-rainfall environments (NVT 2020) provide promise (Seymour *et al*. 2016; Seymour and Brennan 2017). The additional seed cost of hybrids combined with the possibility of either not being able to sow the seed through unfavourable weather or failed crop establishment carries a significant upfront risk. These factors combine to require a consistent and substantial yield advantage (at least 20%, Table 7) over current OP varieties. The risk reduction that might be offered through the availability of higher yielding and well-adapted OP varieties cannot be ignored (Zhang *et al*. 2016).

Management of N through fertiliser and prior legume crop inputs

For crops that had enough seedbed soil-water to establish, N availability was a key driver of yield on the sandy soil types. Extra pre-sowing mineral N derived from a preceding legume crop proved directly beneficial to canola yield (0.3–0.5 t ha^{-1}, up to 70% yield gain). In addition, fertiliser N provided yield gains (0.3–0.8 t ha^{-1}, up to 110% yield gain) (Table 9). The lack of interaction between previous crop and fertiliser N demonstrates the responsiveness of canola on sands to extra N in the system, because even with extra N from a prior legume crop, canola responded to fertiliser N inputs. This mirrors the system responses observed in wheat grown on low-rainfall sands (Muschietti-Piana *et al*. 2020). By contrast, in higher rainfall, higher fertility systems, there is an interaction whereby the use of legumes or fallows in sequence management for canola production can reduce the N fertiliser requirement (St. Luce *et al*. 2015, 2016; Pan *et al*. 2016*a*).

The range of N-fertiliser doses selected was based on yield potential with adjustment for pre-sowing mineral N, anticipated N mineralisation and yields previously observed in the systems being tested, except in 2018 where a full N-response curve was attempted. The response to N was generally in excess of break-even (2 kg grain kg^{-1} N) except in the more fertile Chromosol from Karoonda, and a 2 : 1 return at 4 kg grain kg^{-1} N was achieved in most of the sandy soil scenarios except the very low-rainfall season of 2018. There was no clear effect of N dose on oil content, which suggests no dilution effect within the range tested as is commonly observed (Ramsey and Callinan 1994; Mason and Brennan 1998; Hocking *et al*. 2002; Seymour *et al*. 2016; Seymour and Brennan 2017) and that optimal N nutrition was not reached. The responsiveness (1.4–10.1 kg grain kg^{-1} N) was often lower than reported elsewhere (Mason and Brennan 1998; Ma *et al*. 2015; Pan *et al*. 2016*a*) but within the range reported by Seymour and Brennan (2017). This suggests that N supply was likely to have been limited by co-existing constraints, which in this environment were most likely soil-water, soil compaction, soil chemical constraints and/or soil biological constraints (Sadras 2002, 2005). Seymour and Brennan (2017) did not find a clear interaction between cultivar (including hybrid vs OP) and responsiveness, and we did not have enough data to explore whether this was a significant factor influencing the level of response measured.

The reported effects of the timing of fertiliser N application have been variable and reflect an interaction between the base soil N supply, the distribution of rainfall and the canola yield potential (Hocking *et al*. 1997; Ma *et al*. 2015; Seymour *et al*. 2016). The relative insensitivity to the timing of N application before stem elongation offers some flexibility for N application across different farm logistics. However, the continued decline of soil organic N in low-fertility environments (Angus and Grace 2017) means that shortfalls in N supply very early in the growing season are increasingly likely to need closer management.

The responsiveness to fertiliser N input was consistently higher on sand, and not closely related to growing-season rainfall (Table 8). The soil-specific response when used in combination with some simple rules about the effect of season on yield potential could generate significant canola gross-margin benefits (\$120–159 ha^{-1} in decile 5). Importantly, gross-margin benefits were available across all season types, indicating that this variable approach to N management on sands is both more profitable and less risky, which supports findings for wheat in the same environment (Monjardino *et al*. 2013). Even when using the variable approach to N management, growing the canola on a prior legume crop resulted in a prediction of increased gross margins (up to \$199 ha^{-1}) at both case-study sites, and profit gains were across all season types. However, depending on price and season it is possible that other crop sequences outside of the scope of this study may have resulted in higher total gross margins than those represented by the canola-focused sequences discussed in this paper. The N doses used in the gross-margin analysis were based on data from the field experiments, meaning they were conservative and not yield-maximising. Identifying the economic optimum dose remains a gap in some canola-producing environments (Norton 2016).

Pan *et al*. (2016*b*) make the case for the exploration of combinations of practices that will allow the expansion of canola production into low-rainfall environments not previously considered suitable for canola. The maximum gain in a decile 5 season occurred in this study from combining sowing with establishment opportunity, variable N management and sowing on a preceding legume, and was \$202–230 ha^{-1}, compared with a baseline gross margin of just \$100 ha^{-1} for dry-sown canola sown after a wheat crop. The review of Assefa *et al*. (2018) found that very similar combinations of practices were key to closing canola yield gaps in North American environments. This is a clear example of how the aggregation of improved practices can generate systems that are substantively more productive than baseline practice (Kirkegaard 2019).

Conclusions

Management practices that are currently available and can increase productivity and profit of canola while managing risk in low-rainfall environments include: adjusting time-of-sowing rules to ensure that a genuine crop-establishment opportunity is available within a sowing window that closes in the second week of May, increasing the supply of N to the canola crop through combinations of legume crops before canola and fertiliser N with the optimal dose yet to be defined, and simple adjustments to N-fertiliser input in response to soil type and yield potential as determined by seasonal conditions. For economic integration of the genetic gains in yield potential from hybrid canola into low-rainfall systems, the hybrids need either to offer a substantial and sustained yield advantage of >20% compared with OP varieties currently used or to have lower seed costs.

Conflict of interest

The authors declare no conflicts of interest.

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