CSIRO PUBLISHING

Crop & Pasture Science, 2016, **67**, 450–466
http://dx.doi.org/10.1071/CP15224

Nitrogen responses of canola in low to medium rainfall environments of Western Australia

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Abstract. Canola (*Brassica napus* L.) is widely grown throughout all rainfall zones in south-western Australia. Yields are low by world standards, and variable in low-rainfall (<350 mm annual rainfall) and medium-rainfall (350–450 mm) zones, so that minimising production costs is a major consideration for growers in these areas. One of the major input costs is nitrogen (N) fertiliser. Fifteen N rate × application time × canola plant-type experiments were conducted in the low- and medium-rainfall zones between 2012 and 2014. In most experiments, five rates of N were tested, of ranges 0–75, 0–100, or 0–150 kg N/ha. Nitrogen was applied at four different times (seeding, or 4, 8 or 12 weeks after sowing) or split between these timings. Each experiment compared triazine-tolerant (TT), open-pollinated (OP) canola with Roundup Ready (RR) hybrid canola, and one experiment included TT hybrid and RR OP canola types. On average, RR hybrid produced 250 kg/ha, or 23% more seed and 2.2% more oil than TT OP canola, and the average gross margin of RR hybrid was AU$65/ha more than TT OP. However, seed yield and gross margin differences between RR hybrid and TT OP canola were reduced when seed yields were <1400 kg/ha.

Canola growth (dry matter) and seed yield responded positively to N fertiliser in most experiments, with 90% of maximum seed yield achieved at an average of 46 kg N/ha (s.e. 6). However, 90% of maximum gross margin was achieved at a lower average N rate of 17 kg N/ha, due primarily to the relatively small yield increase compared with the reduction in concentration of oil in the seed with N applied. Because canola growers of south-western Australia are now paid an uncapped premium for canola grain with oil concentration >42%, decreases in oil percentage have a significant financial effect, and recommended rates of N should be lower than those calculated to optimise seed yield. In 80% of cases, the first 10 kg N/ha applied provided a return on investment in N >$1.50 for every $1 invested. The next 20 kg N/ha applied provided a return on investment of $1.25 for every $1 invested 80% of the time, and further increases would most likely break even. The timing of N application had a minor effect on yield, oil and financial returns, but delaying N application would allow farmers to reduce risk under poor conditions by reducing or eliminating further inputs. Overall, our work demonstrates that a conservative approach to N supply mindful of the combined impacts of N on yield and oil is necessary in south-western Australia and that split and delayed applications are a viable risk-management strategy.

Additional keywords: canola, hybrid, nitrogen, open pollinated, timing, triazine tolerant, RoundupReady.

Received 7 July 2015, accepted 8 January 2016, published online 6 May 2016

Introduction

The area of canola (*Brassica napus* L.) sown in the grain growing regions of Western Australia (WA) has expanded from 106 000 ha in 1997 to 1.16 Mha in 2013 (ABARES 2014). During this time, the area sown has expanded 6-fold in high-rainfall regions (>450 mm annual rainfall), 13-fold in medium-rainfall regions (350 – 450 mm), and 19-fold in low-rainfall regions (<350 mm). In 2013, 81% of the canola area in WA was in low (19%, 226 000 ha) and medium (62%, 717 000 ha) rainfall regions.

Although the area of canola sown in WA is extensive, seed yields are inherently low. During the 1997–2013, the average canola yield in WA was 1.1 t/ha (ABARES 2014), with yields in the low-rainfall area averaging ~70% of the state's average. Despite these low yields, farmers persist with canola because of the high relative grain price and the break-crop value it provides for their cropping systems (Seymour *et al*. 2012; Kirk 2012).

While persisting with canola at these low yield levels, farmers seek to reduce their financial risk. One way to reduce risk is to reduce inputs. Some inputs such as weed and insect control are often mandatory, whereas fertiliser inputs, particularly nitrogen (N), are often considered optional, and at a cost of AU$1–1.50/kg, N is a major input cost. Throughout the world, canola is reputed to have a high requirement for N (Holmes 1980), and in south-west WA, the amount of N required for maximum seed yield production is usually more than supplied by soil (Mason and Brennan 1998; Brennan *et al*. 2000). Fertiliser N is often used to optimise the growth of canola and maximise seed yield (Mason and Brennan 1998). However, adequate to high levels of fertiliser N have been shown to decrease oil concentration in the seed of canola (Bhatty 1964; Brennan *et al*. 2000; Brennan and Bolland 2007*a*, 2007*b*). Therefore, it is important to match N inputs to anticipated yield levels and avoid reducing the concentration of oil in the seed.

Canola responds to fertiliser N at a wide range of growth stages (Norton 2016). For example, Ramsey and Callinan (1994) showed that canola grown in Victoria produced similar results when N was applied either at sowing or at early flowering bud stage. The capacity of canola to respond to late-applied N may allow growers to reduce their financial risk by delaying decisions on inputs until they have a good assessment of the yield potential of their crop and, if the seasonal outlook is poor, perhaps reduce inputs. To assist WA farmers in low- and medium-rainfall areas making decisions on N inputs, we conducted several experiments to assess the response of canola to N and to determine whether the timing of N could be delayed in WA until later in the growing season.

Materials and methods

Fifteen N experiments were conducted over 3 years from 2012 to 2014 in the low–medium rainfall zones in south-west WA (Tables 1 and 2). The rates of applied N in 2012 and 2013 were 0, 25, 50, 75, and 100 kg N/ha in five low-rainfall experiments, and 0, 25, 50, 75, and 150 kg/ha in five medium-rainfall experiments. In 2014, rates of applied N were 0, 10, 30, and 70 kg/ha in two low-rainfall and three medium-rainfall experiments. Nitrogen was applied as urea (46% N) in a single dose or applied over two to four doses/times, either directly in front of the seeding equipment at seeding by diverting fertiliser hoses to the front of the seed, and/or 4 weeks after seeding (WAS), 8WAS and/or 12WAS by hand (Table 3). In 2014 at Salmon Gums, the post-seeding treatments used liquid N (urea ammonium nitrate -UAN 42% N) applied with a handheld boom spray.

In 2012, the cultivars tested were CB Telfer (triazine-tolerant (TT) open-pollinated (OP), very early maturity), CB Tanami (TT OP, early maturity), CB Junee HT (TT hybrid, early maturity), GT Cobra (Roundup Ready® (RR) OP, early-mid maturity), Hyola 404RR (RR hybrid, early–early-mid maturity), and Pioneer 43Y23RR (RR hybrid, early maturity). In 2013, Hyola404RR and ATR-Stingray (TT OP, early–mid-maturity) were compared at medium-rainfall sites, and Hyola 404RR and CB Telfer were compared at low-rainfall sites. In 2014, 43Y23RR and Sturt TT (TT OP, early–mid-maturity) were tested at all sites.

The sites were selected in March of each year of experimentation. Rotation history was collated from the landholder. Soil samples from each site were collected before or at sowing by using a combination of 2.5-cm-diameter pogo samples from 50 random locations collected from a depth of 0–10 cm and five soil cores to a depth of 0.5–1.0 m, separated into 10-cm layers. Samples were sent to CSBP (Bibra Lake, WA) for soil chemical analysis (Tables 1 and 2) including pH

Table 1. Location, experimental series, rotation, sowing date and rainfall (mm) in the growing season (GSR, April–October) and the long-term average rainfall (LTA) of canola nitrogen experiments conducted in the south-west of Western Australia in 2012–14

W, Wheat; B, barley (*Hordeum vulgare* L.); L, lupin (*Lupinus angustifolius* L.); C, canola (*Brassica napus* L.); O, oats (*Avena sativa*); OH, oaten hay; P, subterranean-clover based (*Trifolium subterranean*) pasture; F, fallow with low pasture content; FP, field peas (*Pisum sativum* L.). Rainfall data from http://reg.bom.gov.au/climate/data/

No.	Location	Experimental series	Rotation and year	Sowing date	GSR (mm)	LTA GSR (mm)
			2012			
1	Grass Patch	Low	11 B, 10 W, 09 FP	30 Apr.	246	244
			2013			
2	Cunderdin	Medium	12 B, 11 W, 10 P	7 May	243	269
3	Eradu	Medium	12 W, 11 W, 10 L	6 May	280	294
4	Holt Rock	Low	12 B, 11B, 10 W	16 May	282	220
5	Katanning	Medium	12 O, 11 L, 10 OH	21 May	356	354
6	Merredin	Low	12 F 11 F 10 F	3 May	204	228
7	Salmon Gums	Low	12 W, 11 B, 10 C	16 Apr.	217	225
8	West Dalwallinu	Low	12 W, 11 W 10 L	9 May	204	222
9	Wittenoom Hills	Medium	12 B, 11 W, 10 FP	26 Apr.	305	300
10	Wongan Hills	Medium	12 W, 11 P, 10 P	13 May	227	297
			2014			
11	Chapman	Medium	13 W, 12 W, 11 W	29 Apr.	266	293
12	Cunderdin	Medium	13 W, 12 C, 11 W	7 May	321	269
13	Ogilvie	Low	13 W, 12 L, 11 W	29 Apr.	263	295
14	Salmon Gums	Low	13 B, 12 W, 11 W	6 May	244	225
15	Wongan Hills	Medium	13 W, 12 P, 11 P	13 May	242	297

Table 2. Soil classification and chemical properties of the <2 mm fraction of the soil surface (0–10 cm) measured on samples collected before seeding, and estimated mineral N supply from organic sources in the growing season at 15 nitrogen experimental sites in 2012–14

No.	Location	WA Soil Group[A]	Australian Soil Classification[B]	pH[C] ($CaCl_2$)	P[D] (mg/kg)	K[E] (mg/kg)	Org. C[F] (%)	Soil nitrate at sowing (0–10 cm) (kg N/ha)	N min. (kg N/ha)[G] Soil	N min. (kg N/ha)[G] Residues	Total N (kg/ha)
1	Grass Patch 2012	Alkaline grey shallow sandy duplex	Hypercalcic Subnatric Grey Sodosol	6.9	35	350	1.0	13	63	7	83
2	Cunderdin 2013	Yellow sandy earth	Yellow Kandosol	5.9	34	109	0.86	5	52	5	61
3	Eradu 2013	Yellow deep sand	Yellow-Orthic Tenosol	6.0	23	69	0.86	14	52	11	76
4	Holt Rock 2013	Deep sandy gravel	Ferric Dystrophic Yellow Kandosol	5.2	55	122	1.42	23	48	0	71
5	Katanning 2013	Duplex sandy gravel	Ferric-sodic Yellow Chromosol	4.7	54	112	2.9	14	23	11	48
6	Merredin 2013	Duplex sandy gravel	Ferric Yellow Kandosol	5	32	166	0.55	25	40	8	73
7	Salmon Gums 2013	Alkaline grey shallow loamy duplex	Hypercalcic Mesonatric Yellow Sodosol	5.4	44	313	0.8	7	51	0	58
8	West Dalwallinu 2013	Yellow deep sand	Yellow-Orthic Tenosol	4.7	24	76	0.47	8	29	8	45
9	Wittenoom Hills 2013	Alkaline grey shallow loamy duplex	Calcic Subnatric Grey Sodosol	7	26	387	1.8	41	114	11	41[H]
10	Wongan Hills 2013	Yellow deep sand	Yellow-Orthic Tenosol	5.8	26	95	1.01	71	66	15	152
11	Chapman 2014	Brown deep sand	Brown-Orthic Tenosol	5.9	36	100	0.72	6	43	0	49
12	Cunderdin 2014	Yellow-brown deep sandy duplex	Yellow Sodosol	5.2	24	76	1.49	4	35	7	46
13	Ogilvie 2014	Yellow sandy earth	Yellow Kandosol	5.4	22	57	0.57	13	45	0	58
14	Salmon Gums 2014	Alkaline grey shallow loamy duplex	Hypercalcic Mesonatric Yellow Sodosol	5.1	37	243	0.69	5	54	0	59
15	Wongan Hills 2014	Yellow deep sand	Yellow Orthic Tenosol	6.4	31	106	1.2	30	79	15	123

[A]Schoknecht (1997). [B]Isbell (2002). [C]1 : 5 soil : 0.01 $CaCl_2$ mol/L (w/v) (Rayment and Higginson 1992). [D]Bicarbonate-extractable P (Colwell 1963). [E]Bicarbonate-extractable K (Colwell and Esdaile 1968). [F]Organic carbon (Walkley and Black 1934). [G]Nitrogen from soil and plant fractions as calculated by the Select Your Nitrogen program (Diggle and Bowden 2003). [H]Inundation at Wittenoom Hills 2014 may have leached nitrogen, therefore soil samples from top 30 cm at sowing used to estimate N status.

Table 3. Nitrogen rates (kg N/ha) and timings for experiments conducted in 2012–14

WAS, Weeks after sowing

N	2012				2013 low rainfall				2013 medium rainfall				2014			
	Seeding	4WAS	8WAS	12WAS	Seeding	4WAS	8WAS	12WAS	Seeding	4WAS	8WAS	12WAS	Seeding	4WAS	8WAS	12WAS
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	–	–	–	–	–	–	–	–	–	–	–	–	10	0	0	0
25	25	0	0	0	25	0	0	0	25	0	0	0	–	–	–	–
25	–	–	–	–	0	25	0	0	12.5	12.5	0	0	–	–	–	–
25	–	–	–	–	0	0	25	0	8.3	8.3	8.3	0	–	–	–	–
25	–	–	–	–	0	0	0	25	6.3	6.3	6.3	6.3	–	–	–	–
30	–	–	–	–	–	–	–	–	–	–	–	–	10	0	20	0
30	–	–	–	–	–	–	–	–	–	–	–	–	10	0	0	20
40	–	–	–	–	–	–	–	–	–	–	–	–	10	0	20	10
50	0	50	0	0	50	0	0	0	50	0	0	0	–	–	–	–
50	25	25	0	0	0	50	0	0	25	25	0	0	–	–	–	–
50	–	–	–	–	0	0	50	0	16.7	16.7	16.7	0	–	–	–	–
50	–	–	–	–	0	0	0	50	12.5	12.5	12.5	12.5	–	–	–	–
50	–	–	–	–	25	25	0	0	–	–	–	–	–	–	–	–
50	–	–	–	–	25	0	25	0	–	–	–	–	–	–	–	–
50	–	–	–	–	25	0	0	25	–	–	–	–	–	–	–	–
50	–	–	–	–	–	–	–	–	–	–	–	–	10	0	40	0
50	–	–	–	–	–	–	–	–	–	–	–	–	10	0	0	40
50	–	–	–	–	–	–	–	–	–	–	–	–	10	0	20	20
70	–	–	–	–	–	–	–	–	–	–	–	–	10	0	60	0
70	–	–	–	–	–	–	–	–	–	–	–	–	10	0	0	60
70	–	–	–	–	–	–	–	–	–	–	–	–	10	0	20	40
75	25	50	0	0	–	–	–	–	75	0	0	0	–	–	–	–
75	–	–	–	–	0	50	25	0	37.5	37.5	0	0	–	–	–	–
75									25	25	25	0				
75									18.8	18.8	18.8	18.8				
100	25	50	25	0	25	50	25	0	–	–	–	–	–	–	–	–
100[A]	0	100	0	0	–	–	–	–	–	–	–	–	–	–	–	–
100[A]	0	0	100	0	–	–	–	–	–	–	–	–	–	–	–	–
100[A]	25	0	0	75	–	–	–	–	–	–	–	–	–	–	–	–
150	–	–	–	–	–	–	–	–	150	0	0	0	–	–	–	–
150	–	–	–	–	–	–	–	–	75	75	0	0	–	–	–	–
150	–	–	–	–	–	–	–	–	50	50	50	0	–	–	–	–
150	–	–	–	–	–	–	–	–	37.5	37.5	37.5	37.5	–	–	–	–

[A]CB Telfer and Hyola 404RR only.

(1 : 5 soil : 0.01 mol/L of $CaCl_2$(w/v); Rayment and Higginson 1992), bicarbonate-extractable phosphorus (P) (Colwell 1963), bicarbonate-extractable potassium (K) (Colwell and Esdaile 1968), organic carbon (Walkley and Black 1934), and extraction of nitrate-N and ammonium-N were measured by the methods of Reardon *et al*. (1966) and Searle (1984).

In order to consider relationships between total available N (TAN) and crop performance, some measure of N from organic sources was required. We used the Excel/web based program 'Select Your Nitrogen (SYN)' (Bowden and Burgess 1993; Diggle and Bowden 2003) to calculate N available from plant residues (residual organic N, RON), soil organic N (stable organic N, SON) and soil nitrate measured in the top 10 cm of soil at sowing at each site (Table 1). SYN uses information such as soil type, past rotations, tillage (no-till or not), organic carbon (%) in topsoil, and pre- and post-seeding rainfall including leaching rainfall to calculate available N. We calculated N availability at the end of each season to capture the actual rainfall effects on leaching and mineralisation. Our estimates of N available from organic sources were then combined with the rate of N applied to each treatment in order to estimate total available N (TAN, Table 2).

All experiments were sown using no-till machinery, principally knife-points followed by press-wheels. Canola was sown in plots 1.44–1.56 m wide at row spacing of 22–24 cm at depth of 2–3 cm. All plots were 20 m long, except at Salmon Gums in 2014, where they were 10 m. Seed weights per plot were adjusted for variety seed size, germination percentage and expected field establishment to establish 30 plants/m^2. The following basal fertilisers were applied to ensure that N was the only nutrient element limiting canola production. First, a range of different compound fertilisers was drilled below the seed while sowing. The products used to supply 9–11 kg P and 2–11 kg sulfur (S)/ha were Summit Pasture (18.2% P, 10% S) at 50–60 kg/ha, Bigphos + Mn (13.8%P, 6.8% S, 5.22% Mn) at 65 kg/ha, Bigphos (13.5% P, 7.5% S) at 65–80 kg/ha, Superphos (9% P, 10.5% S) at 80–100 kg/ha, or Double Phos (7.7% P, 3.6% S) at 50 kg/ha. Second, fertiliser was topdressed either before sowing or 0–6 weeks after sowing, with 300–400 kg/ha of gypsum (14% S, 18% calcium (Ca)) and 120–150 kg/ha of muriate of potash (50% K). Copper (Cu), zinc (Zn) and molybdenum (Mo) had been recently applied to the fields in which each experiment was located.

Experiments were sown from mid-April to mid-May (Table 1). Insect pests of the experiment were effectively controlled with post-emergent pesticides. Weeds were effectively controlled by the application of treatment herbicides. TT varieties had 1.1 kg/ha of Atradex (90% atrazine) applied at sowing and a further 1.1 kg/ha applied 4 weeks after sowing; and RR varieties had 0.9 kg/ha of Roundup Ready (69% glyphosate) applied at the 2-leaf stage and a further 0.9 kg/ha at the 6-leaf stage. When required, Lontrel (30% clopyralid) and/or grass herbicides such as Select (24% clethodim) were applied at 2–6-leaf stage to all herbicide blocks.

Measurements and analysis

At each site, we counted the number of plants per m^2 at ~4–6 weeks after sowing and at harvest. At most sites, we determined aboveground biomass at maturity from two randomly placed quadrats per plot of 4 rows by 0.5 m or three quadrats per plot of 2 rows by 1 m. All rows within plots were harvested with a self-propelled harvester, and harvested seed was collected and hand-cleaned and the oil and moisture percentages were measured by infrared reflectance spectrometer (Infratech; Foss, Hillerød, Denmark), using calibrations developed by CBH. Seed yield was calculated based on plot centres of 2 m, and both seed yield and the concentration of oil in seed were adjusted to a standard moisture content of 6%. We calculated gross margins (AU$/ha = gross returns minus all input costs) using the following values and assumptions:

(1) Oil bonus/discount of +/− 1.5% per unit of oil (%) with a base of 42% oil, with no oil ceiling.
(2) TT costs: hybrid seed $24/kg, OP seed $2/kg, which assumed cleaning, grading and storage costs as well as repurchase of new variety every 3 years. Herbicides $58/ha and grain price of $530/t minus any End Point Royalties for specific varieties such as CB Telfer. Oil in grain was valued at $1262/t.
(3) RR costs: hybrid seed $32/kg, OP seed $23/kg, herbicides $47/ha, grain price of $513/t, oil in seed price of $1221/t.

We calculated non-treatment costs of $100–205/ha for individual experiments, largely dependent on costs of controlling insects and diseases. Nitrogen costs of $1/kg for solid N sources, $1.50/kg of N for liquid N sources, and N application costs of $8/ha were used.

The probability of obtaining an economic response to N was calculated by fitting quadratic models ($y = a + bx + cx^2$) to oil yield data. We used the fitted curves to calculate oil yield and the rate of change in oil yield for each 10 kg/ha increment in N. The rate of change in oil yield was divided by the ratio of N cost to oil in seed value (equivalent to $1000/1262 = 0.79 for TT canola and $1000/1221 = 0.82 for RR canola) to calculate the return on investment in N. We then calculated the frequency of returning at least (*i*) $1 for $1 invested (referred to as 1 : 1), (*ii*) $0.75 for $1 invested (0.75 : 1), (*iii*) $1.25 for $1 invested (1.25 : 1), (*iv*) $1.50 for $1 invested (1.5 : 1), (*v*) $2 for $1 invested (2 : 1) or (*vi*) $3 for $1 invested (3 : 1). The range in rates of returns was selected to cover expectations indicated to us by private consultants (Garren Knell and Richard Quinlan) and farmers at field days, and it allows for some interpretation of scenarios such as fluctuations in grain and fertiliser prices. For example, 1.25 : 1 could be used for a 25% increase in grain price or decrease in fertiliser price and 0.75 : 1 for a 25% decrease in grain price or increase in fertiliser price. Similarly, comparisons could be made between fertiliser type such as liquid (1.5 : 1) *v.* solid (1 : 1).

Experimental design and statistical analyses

All experiments were arranged as split plot designs with herbicide (TT or RR) as the main plot treatment and variety × N combinations (rate × timing) as subplots. There were three replications arranged in separate blocks.

Statistical analysis of plot data included analysis of variance (ANOVA) or restricted maximum likelihood (REML) in GENSTAT for Windows Edition 16.0 (GENSTAT 2013). Regression analysis and curve fitting occurred in either GENSTAT or SigmaPlot 12 (Systat Software, San Jose, CA, USA). Least significant differences (l.s.d.) are presented at $P = 0.05$. Multi-environment trial (MET) analysis of plot and mean data was conducted using REML in Genstat. Fixed models included Trial*Variety (or Type)*Napplied (or Napplied/Timing), with random model of Rep/Herbicide used in all plot data analysis.

Results

Seasonal conditions

Growing-season rainfall (April–October) was similar to long-term averages at Grass Patch in 2012, and Salmon Gums, Wittenoom Hills, Eradu and Katanning in 2013, and was higher than the long-term average at Holt Rock in 2013 and Cunderdin and Salmon Gums in 2014 (Table 1). At Merredin, West Dalwallinu, Cunderdin and Wongan Hills, 2013 growing-season rainfall was less than the long-term average by 24–50 mm. At these sites, there was an extended dry period after seeding in May until the second week of July, after which each site received >120 mm of rainfall during the reproductive phase of July–September. In 2014, the sites in the northern wheatbelt, at Ogilvie, Chapman, and Wongan Hills, received 27–55 mm less rainfall than the long-term average and experienced hot weather during the reproductive phase. Wongan Hills had 8 days with maximum temperatures ≥26°C, and Ogilvie and Chapman had 19 days with maximum temperatures ≥26°C during the same period (data not shown).

Seed yield

Seed yield without applied N ranged from 480 to 1730 kg/ha and averaged 940 kg/ha (Figs 1, 2, 3 and 4). RR hybrid canola consistently achieved higher seed yield than TT OP canola. When no N was applied, RR hybrid canola averaged 1050 kg/ha and TT OP 850 kg/ha (l.s.d. = 190). Averaged over all N treatments, RR hybrid canola produced an average seed yield of 1310 kg/ha compared with 1060 t/ha for TT OP canola (l.s.d. = 180 kg/ha).

Seed yield increased with applied N in all experiments (Figs 1–4); however, in many instances the responses were small. For example, across all experiments the average yield increase to the first 25–30 kg N/ha was 4.2 kg/kg N (standard error (s.e.) = 0.6), ranging from –0.9 for CB Telfer at Grass Patch in 2012 (Fig. 1*a*) to 15.8 for 43Y23RR at Chapman in 2014 (Fig. 4*b*). The average yield increase for the next 20–25 kg N/ha was 3.7 kg/kg N (s.e. = 0.5), ranging from –2.1 for Sturt TT at Cunderdin in 2014 (Fig. 4*c*) to 11.4 for 43Y23RR at Chapman in 2014, and the average yield increase for the third increment of 20–25 kg N/ha was 2.8 kg/kg N (s.e. = 0.4), ranging from –0.8 for 43Y23RR at Cunderdin in 2014 (Fig. 4*d*)

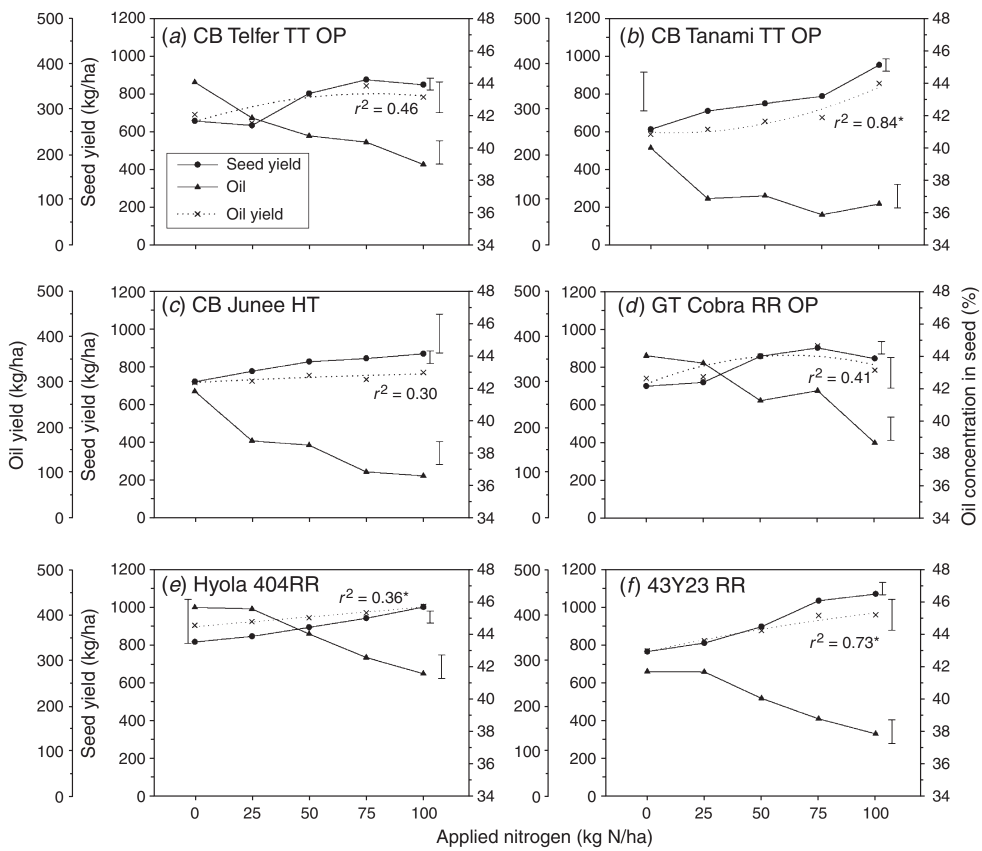

Fig. 1. Seed yield, oil concentration in seed and oil yield response of canola varieties to applied nitrogen (N) at Grass Patch in 2012. Quadratic models were fitted through oil yield data for all N × timing treatments, but for clarity of presentation only the mean of each N rate is shown. Vertical bars indicate l.s.d. at $P = 0.05$.

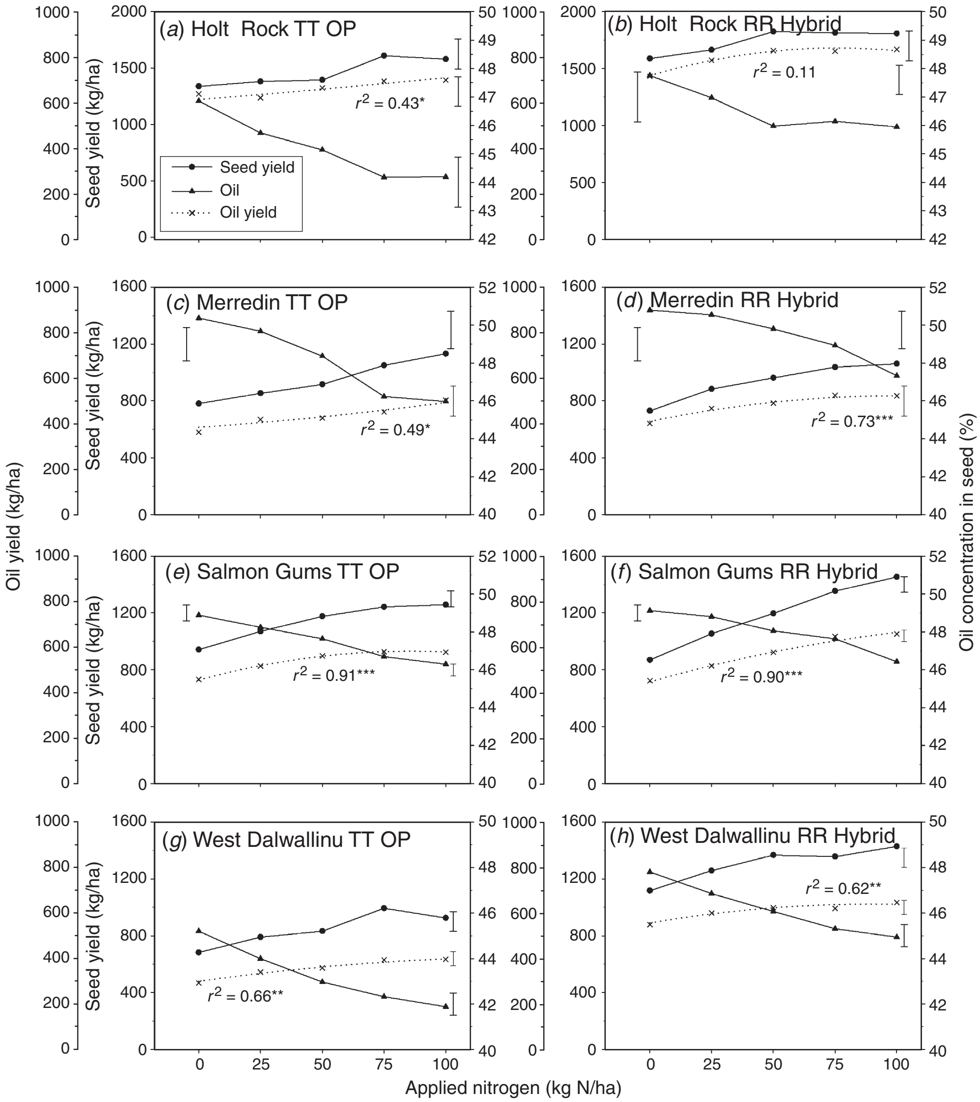

Fig. 2. Seed yield, oil concentration in seed and oil yield response of triazine-tolerant open-pollinated (TT OP) and Roundup Ready (RR) hybrid canola to applied nitrogen (N) at four sites in 2013 where maximum applied N was 100 kg/ha. Quadratic models were fitted through oil yield data for all N × timing treatments, but for clarity of presentation only the mean of each N rate is shown. Vertical bars indicate l.s.d. at $P = 0.05$.

to 8.6 for CB Telfer at Holt Rock in 2013 (Fig. 2*a*). On average, 90% of maximum seed yield was obtained following the application of 46 kg N/ha (s.e. = 6). There was no difference between RR hybrid and TT OP canola for the rate of applied N at which 90% of maximum seed yield was obtained. RR hybrid produced 90% maximum yield at 45 kg N/ha (s.e. = 6) and TT OP at 49 kg N/ha (s.e. = 6). The average difference between 90% maximum seed yield and seed yield with no applied N was 210 kg/ha (s.e. = 40).

An exponential curve described the relationship between total available N and seed yield as a percentage of maximum seed yield (Fig. 5, $P < 0.001$). On average, 90% of maximum seed yield was achieved at 110 kg TAN/ha (s.e. = 37 kg TAN/ha), and we found no difference between TT or RR canola (data not shown). A higher level of TAN of 200 kg/ha was required to encapsulate all points ≥90% maximum seed yield.

Although we have described differences in the scale of the response to N, there were very few interactions between variety and N in this study. The only significant interactions were at Grass Patch in 2012, which had a wider range of canola varieties including hybrid TT and OP RR varieties, and at Salmon Gums in 2013. As mentioned earlier, at Grass Patch in 2012 the TT hybrid variety CB Junee HT had a relatively flat response to N compared with other TT varieties (Fig. 1*c*) and the OP RR variety GT Cobra had a yield decrease at the highest rate of applied N (100 kg/ha), whereas other RR varieties maintained or increased yield (Fig. 1*e–f*). At Salmon Gums in 2013, the TT OP variety CB Telfer produced yields equal to or higher than the RR hybrid variety Hyola 404RR at rates of applied N below 50 kg/ha. At higher rates of applied N, the seed yield of the RR hybrid variety continued to respond, while the seed yield of the TT OP variety flattened out (Fig. 2*e–f*).

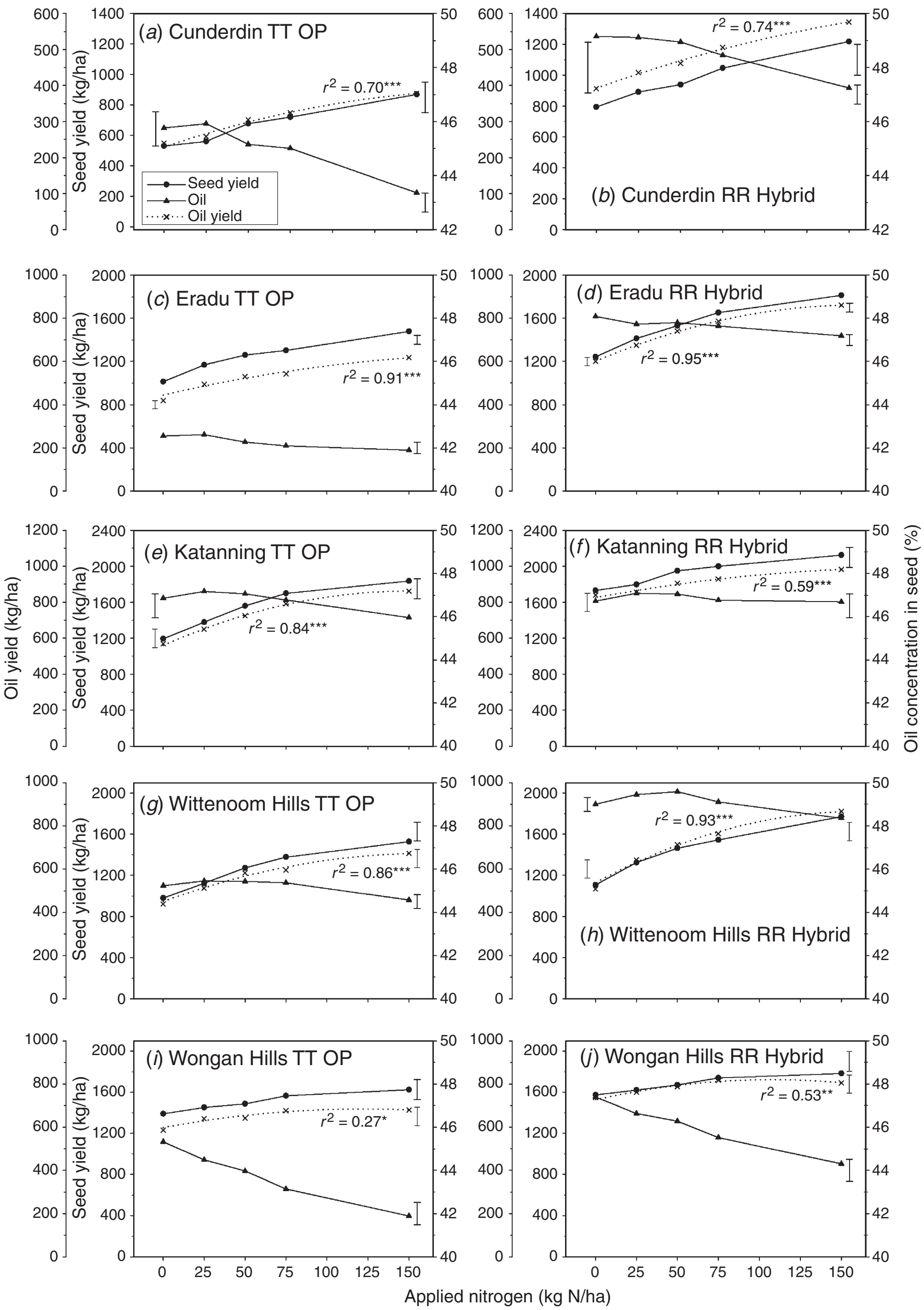

Fig. 3. Seed yield, oil concentration in seed and oil yield response of triazine-tolerant open-pollinated (TT OP) and Roundup Ready (RR) hybrid canola to applied nitrogen (N) at five sites in 2013 where maximum applied N was 150 kg/ha. Quadratic models were fitted through oil yield data for all N × timing treatments, but for clarity of presentation only the mean of each N rate is shown. Vertical bars indicate l.s.d. at $P = 0.05$.

The time of N application had no effect on the seed yield of canola at Grass Patch in 2012 (Table 4), at eight of the nine sites in 2013 and four of the five sites in 2014. MET analysis of the low-rainfall sites in 2013 indicated that when 25–50 kg N/ha was applied, it made no difference to seed yield whether it was applied at seeding, 4WAS, 8WAS or 12WAS (Fig. 6*a*). Split applications of 25 kg N/ha at seeding followed by 25 kg N/ha at 4WAS or 8WAS produced similar yields to applying 50 kg N/ha in one application, whereas splitting the application at seeding and 12WAS produced higher yields in 2013.

In 2013, we tested split applications more thoroughly at sites in the medium-rainfall region. MET analysis of these

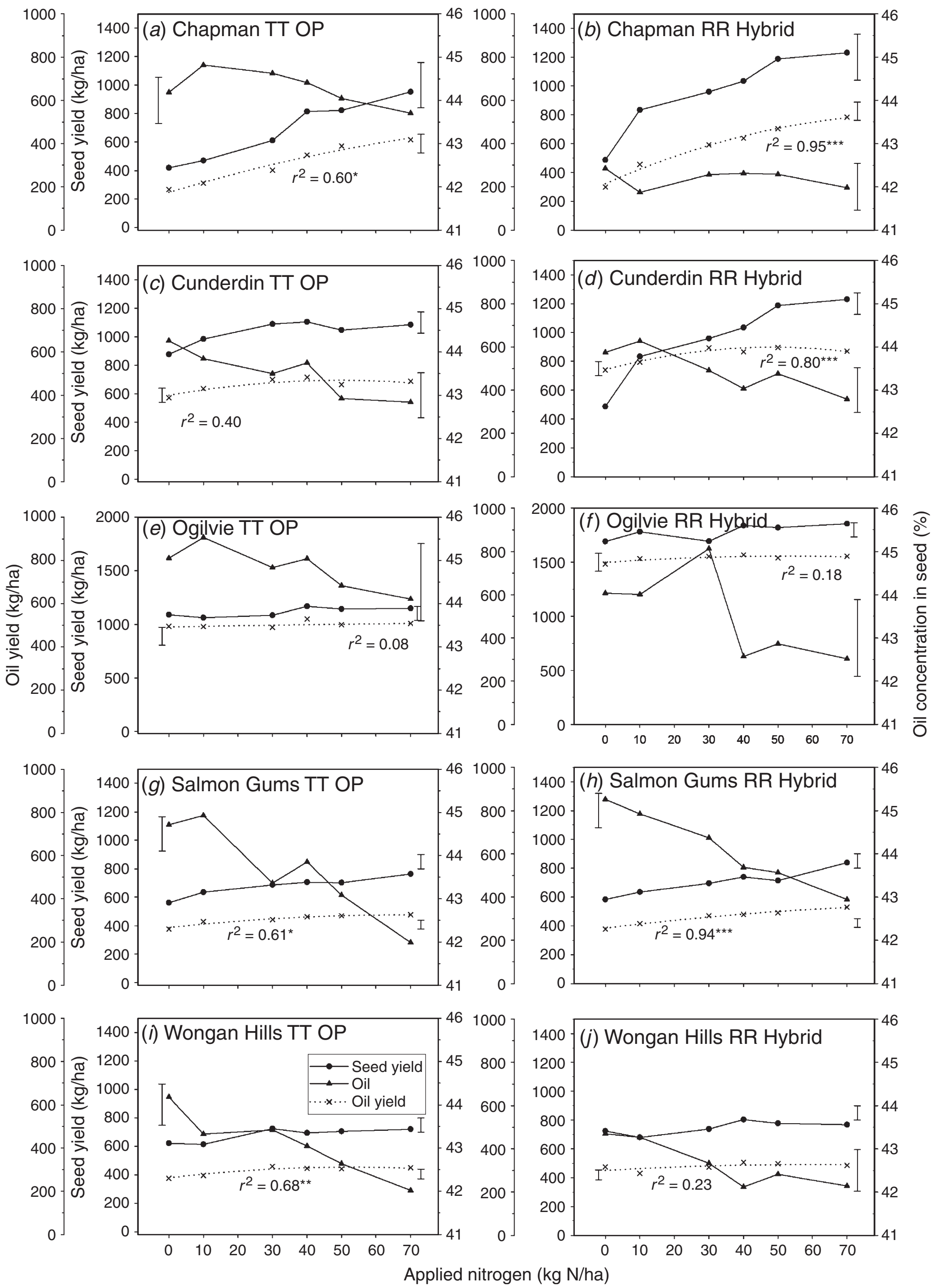

Fig. 4. Seed yield, oil concentration in seed and oil yield response of triazine-tolerant open-pollinated (TT OP) and Roundup Ready (RR) hybrid canola to applied nitrogen (N) at five sites in 2014. Quadratic models were fitted through oil yield data for all N × timing treatments, but for clarity of presentation only the mean of each N rate is shown. Vertical bars indicate l.s.d. at $P = 0.05$.

experiments indicated that at a total application rate of 25 kg N/ha as split applications produced similar yields to 25 kg N/ha applied all at seeding (Fig. 7*a*). Similarly, treatments totalling 50 and 75 kg N/ha applied at seeding or in split applications produced comparable yields. At the highest N rate of 150 kg N/ha, applying all N at seeding reduced yield. At Wongan Hills in 2013, this may have been the result of reduced plant density with only 11 plants/m^2 being established following 150 kg N/ha applied at seeding compared with 69 plants/m^2 in nil-N plots.

Multi-site analysis of 2014 experiments indicated that delaying top-up N application until 12 weeks reduced yield by 7% compared with the same rate applied at 8 weeks, and 8% compared with the same rate split over 8 and 12 weeks (Fig. 8*a*).

As indicated earlier, across all sites and years, RR hybrids outyielded TT OP canola by an average of 250 kg/ha or 23% (l.s.d. = 180 kg/ha). The difference between RR hybrid and TT OP increased as site mean yield increased (Fig. 9*c*). At lower yielding sites, the mean differences between the yield of RR hybrid and TT OP decreased to ~20% or 133 kg/h, and at higher yielding sites the difference widened to 25% or 392 kg/ha.

Oil concentration in the seed of canola

Applied N had a significant negative effect on the concentration of oil in the seed of canola at 14 of 15 sites (Figs 1–4). The average decrease in oil% due to applied N was 0.02 per kg N/ha, with steeper decreases at low-rainfall sites (0.04) compared with medium-rainfall sites (0.01). In general, we found that sites with a seed yield response to N >200 kg/ha had lower rates of change in oil% per kg of applied N (data not shown).

At Chapman in 2014, N had no effect on oil (Fig. 4*a, b*). Chapman experienced 19 days with maximum temperatures >26° in July–September, and 69 days with daily average temperature >15°C. It was also the site with the largest seed-yield response to applied N of ~500 kg/ha.

The MET analysis indicated that RR hybrid canola produced average oil of 46.5% compared with 44.3% for OP TT canola (l.s.d. = 0.2%), with the differences remaining similar at sites that produced high oil concentration (Fig. 9*b*). In 13 of 15 experiments, there was no interaction between variety or type and applied N, with RR hybrid producing higher oil concentration than TT OP canola at all rates of available N (Figs 1–4). The two exceptions were (*i*) at Grass Patch in 2012, where GT Cobra (RR OP) had a larger decrease in oil% at the highest rate of applied N than other varieties, similar to the seed-yield response mentioned earlier; and (*ii*) at Merredin in 2013, where the TT OP variety CB Telfer maintained oil% with 100 kg N/ha compared with 75 kg N/ha, whereas the oil% of RR hybrid variety Hyola 404RR decreased.

Although N rate had an effect on oil%, the timing of N application had no significant effect on oil% in 2012 (Table 4), at medium-rainfall sites in 2013 (Fig. 7*b*) or in 2014 experiments (Fig. 8*b*). MET analysis of low-rainfall sites in 2013 indicated that the timing of 25 kg N/ha had no overall effect on oil% (Fig. 6*b*). However, at a higher rate of total applied N of 50 kg N/ha, the split application of 25 kg N/ha at seeding plus 25 kg N/ha at 12 weeks reduced oil% in low-rainfall sites in 2013.

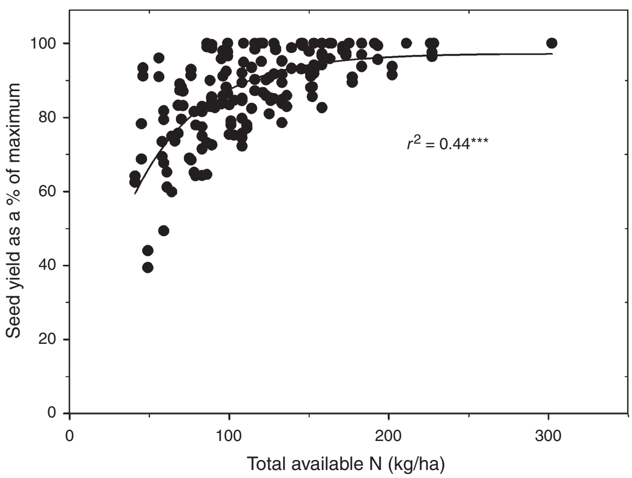

Fig. 5. Relationship between total available nitrogen and the seed yield (% of maximum of individual variety at each site) of canola WA. Data collated for 2012–14 nitrogen experiments. Fitted curve: Seed yield % = $a(1 - \exp(-b^*x))$.

Oil yield and economic analysis

Nitrogen application had a significant effect on the oil yield of canola in 14 of 15 experiments. The exception was at Ogilvie in 2014 (Fig. 4*e, f*), where oil yield did not respond to N application. The average maximum increase in oil yield compared with oil yield of the nil-N treatments was 129 kg oil/ha (s.e. = 15). In no experiment was a variety × N interaction observed. The combination of higher average seed yield and oil% resulted in RR hybrid canola averaging 567 kg oil/ha (s.e. = 21), compared with 446 kg oil/ha for TT OP canola (s.e. = 17).

Nitrogen application reduced gross margins at Grass Patch in 2012 and at Wongan Hills in 2013 and 2014; had no effect at four sites in 2013 (Cunderdin, Holt Rock, Merredin and West Dalwallinu) and at Ogilvie and Salmon Gums in 2014; and increased gross margins at Salmon Gums, Katanning, Wittenoom Hills and Eradu in 2013 and Cunderdin and Chapman in 2014. Salmon Gums 2013 was the only experiment with a significant variety × N interaction, with Hyola 404RR continuing to respond up to 75 kg N/ha whereas CB Telfer's gross margin reached a peak at 25 kg N/ha (data not shown).

In 7 of the 15 experiments, the gross margins of RR hybrid and TT OP varieties were the same. Multi-site analysis found that RR hybrid canola produced gross margins of $329/ha,

Table 4. Seed yield, oil concentration in seed and gross margin of two canola varieties in response to time of nitrogen application of two rates of total applied nitrogen (50 and 100 kg N/ha) at Grass Patch in 2012

WAS, Weeks after sowing. Values followed by the same letter are not significantly different ($P = 0.05$)

Total applied N	Time and rate of N application (kg/ha)				Seed yield (t/ha)		Oil in seed (%)		Gross margin ($/ha)	
(kg N/ha)	Seeding	4WAS	8WAS	12WAS	CB Telfer	Hyola 404RR	CB Telfer	Hyola 404RR	CB Telfer	Hyola 404RR
50	0	50	0	0	0.80a	0.89a	42.9c	42.0bc	149b	107ab
50	25	25	0	0	0.79a	0.90a	41.7bc	42.8c	136b	125ab
100	25	50	25	0	0.85ab	1.07b	40.6ab	40.4ab	76ab	115ab
100	0	100	0	0	0.85ab	0.99ab	39.8ab	40.5ab	91ab	97ab
100	0	0	100	0	0.88ab	0.93ab	41.1a	39.8a	112ab	56a
100	25	0	0	75	0.77a	1.01ab	40.1ab	40.0ab	51a	103ab

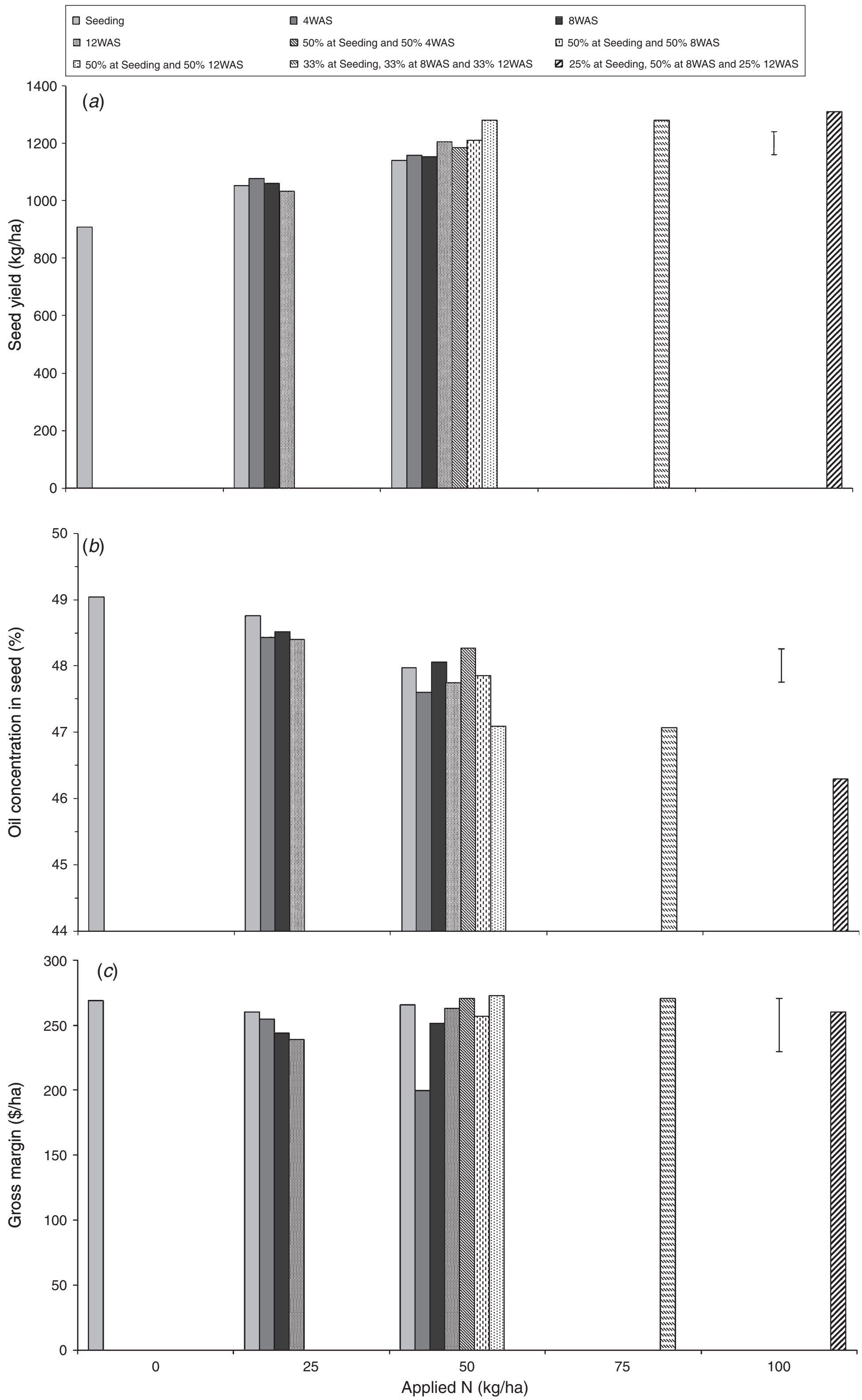

Fig. 6. Responses to single and split applications of nitrogen (N) in 2013 low-rainfall experiments where the highest rate was 100 kg N/ha (MET analysis of Holt Rock, Merredin, Salmon Gums and West Dalwallinu): (*a*) seed yield, (*b*) oil concentration in seed, and (*c*) gross margin. Legend indicates timing of split applications of N. WAS, Weeks after sowing. Vertical bars indicate l.s.d. at $P = 0.05$.

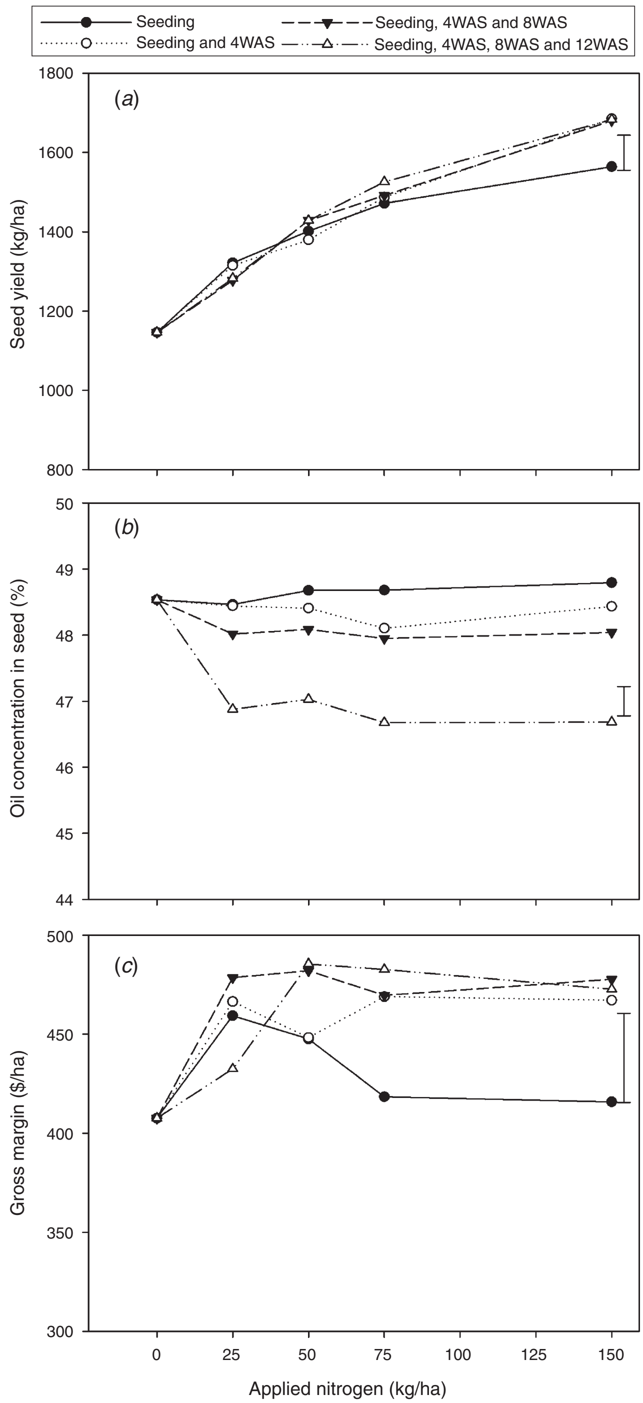

Fig. 7. Responses of (*a*) seed yield, (*b*) oil concentration in seed, and (*c*) gross margin to split applications of nitrogen in 2013 medium-rainfall experiments where highest rate was 150 kg N/ha (MET analysis of Cunderdin, Eradu, Katanning, Wittenoom Hills and Wongan Hills). Legend indicates timing of split applications of N. WAS, Weeks after sowing. Vertical bars indicate l.s.d. at $P = 0.05$.

compared with $264/ha for TT OP canola (l.s.d. = $28/ha). There was a trend at low-grossing sites for TT OP to produce similar gross margins to RR hybrid canola (Fig. 9*a*, *d*).

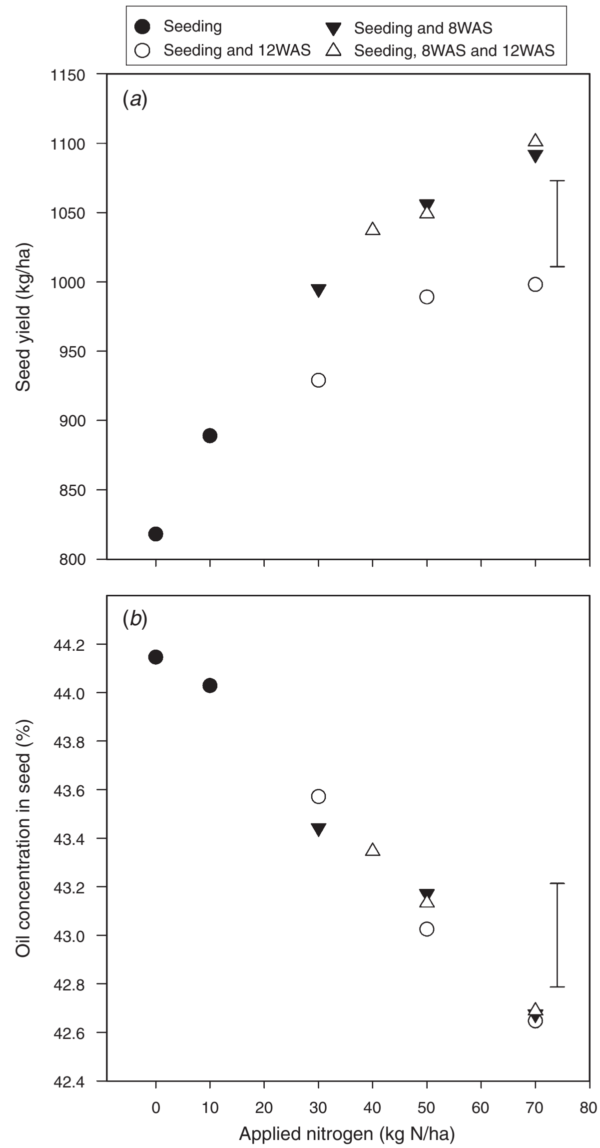

Fig. 8. Seed yield and concentration of oil in seed in relation to rate and time of nitrogen application in 2014 (MET analysis of Chapman, Cunderdin, Ogilvie, Salmon Gums and Wongan Hills). Vertical bars indicate l.s.d. at $P = 0.05$.

For the same rate of total applied N, the timing of N application had no effect on gross margins at Grass Patch in 2012 (Table 4), in the low-rainfall zone in 2013 (Fig. 6*c*) or in any experiment conducted in 2014 (data not shown). However, multi-site analysis of 2013 experiments conducted in the medium-rainfall zone indicated that owing to the costs of split application there was a trend for split applications to decrease gross margins when the total N applied was 25 kg/ha, but not significantly ($P > 0.05$). Similarly in 2013, the reduced yield following 150 kg N/ha at seeding resulted in lower gross margins for medium-rainfall sites compared with split applications (Fig. 7*c*).

We evaluated the probability of obtaining an economic response to applied N and TAN at a wide range of expected

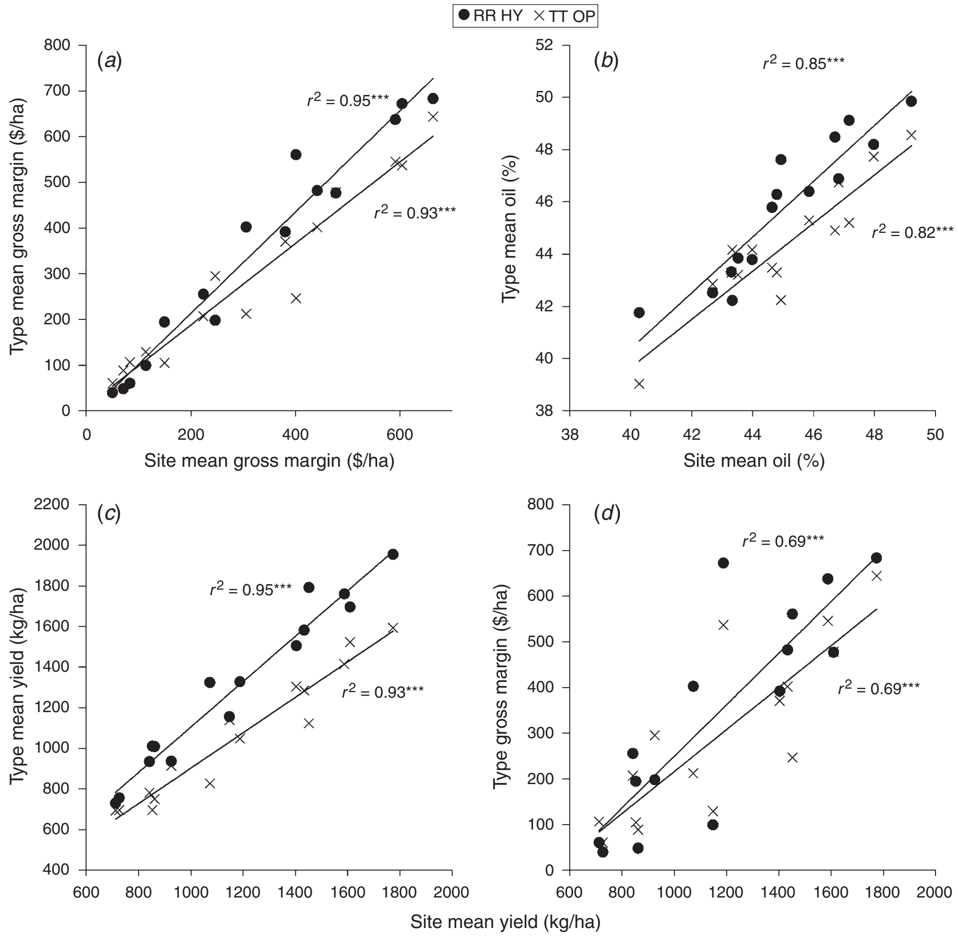

Fig. 9. Regressions of site means *v.* type (RR HY or TT OP) means for the traits: (*a*) site mean gross margin *v.* type mean gross margins ($/ha, lines have different slopes, $P < 0.05$), (*b*) site mean oil *v.* type mean oil concentration in seed (%, same lines, $P > 0.05$), (*c*) site mean seed yield *v.* type mean seed yield (kg/ha, lines have different slopes, $P < 0.05$), and (*d*) site mean seed yield *v.* type mean gross margins ($/ha, same lines, $P > 0.05$). Data collated from 2012 to 2014 nitrogen experiments.

returns. We found that the frequency of obtaining a $3 return on the investment in applied N was <40% for RR canola and <30% for TT canola (Fig. 10). Similarly, the frequency of obtaining a 2 : 1 return on the investment in applied N was <70%. We found that the frequency at which the first 10 kg N/ha applied would give a return on investment in N >1.50 : 1 was 80%. The next 20 kg N/ha applied would give a return on investment of 1.25 : 1 at a frequency of 80% of the time, and further increases would most likely breakeven.

Rates of applied N >50 kg/ha provided expected rates of return ≤1.50 : 1 at a frequency of 50% of the time. If higher degrees of certainty were required then rates of applied N decreased. For example, rates of applied N had to be ≤20 kg/ha in order to obtain a return greater than 1 : 1 on the investment in N on 90% of occasions. Similar results were found when analysing gross margins, wherein 90% of maximum gross margin was achieved at an average N rate of 17 kg N/ha (s.e. = 5).

The probability of achieving an economic response to all sources of N was also evaluated (Fig. 11). This indicated that the frequency of obtaining a 3 : 1 return from TAN was <50% and 2 : 1 return <70%. The probability increased at lower rates of return. For example, the probability was ≥70% for rates of return of 1.50 : 1, 1.25 : 1, 1 : 1 and 0.75 : 1 at TAN of 60–90, 60–120, 60–140 and 60–170 kg/ha. The dataset was too small to consider the effect of yield potential (low *v.* high yielding sites) or canola type (RR hybrid *v.* TT OP) on the probability of a response to TAN.

Dry matter at maturity

Dry matter production increased with applied N in all experiments (data not shown). There were no significant variety × N interactions in any experiment. Ninety per cent of maximum dry matter ranged from 3.8 to 6.8 t/ha (mean = 5.5 t/ha, se = 0.3) and was produced at a wide range of applied N from 6 to 88 kg N/ha (mean = 42 kg N/ha, s.e. = 7).

In each experiment, RR canola produced more dry matter than TT canola, averaging 6.1 t/ha (s.e. = 0.4) compared with 4.7 t/ha (s.e. = 0.2). TT canola had a higher concentration of N at maturity, averaging 1.3% (s.e. = 0.1) across all sites compared

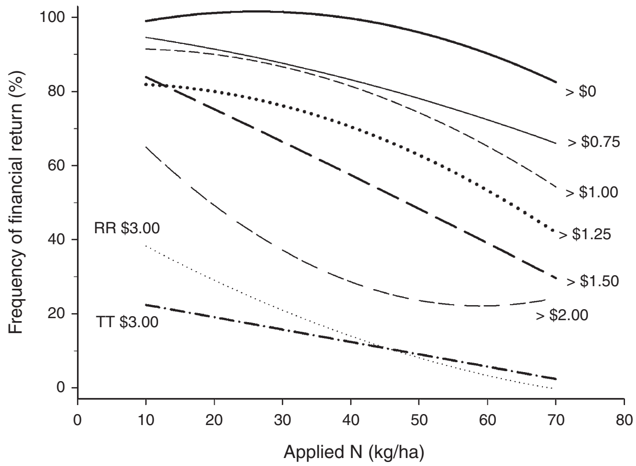

Fig. 10. Frequency of obtaining a range of financial returns by supplying nitrogen from fertiliser sources to canola. Lines represent the frequency of returning at least $0 for $1, $0.75 for $1, $1 for $1, $1.25 for $1, $1.50 for $1, $2 for $1, or $3 for $1 invested. Separate lines are shown for Roundup Ready (RR) and triazine-tolerant (TT) canola at the $3 rate of return as the only comparison between TT and RR that was significantly different ($P < 0.001$).

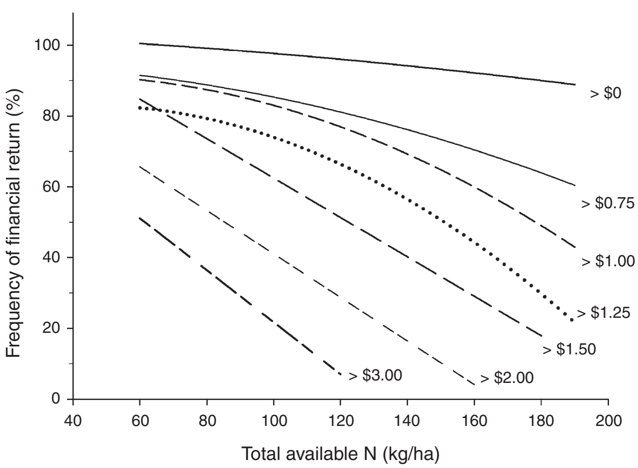

Fig. 11. Frequency of obtaining a range of financial returns by supplying nitrogen from soil, plant residue and fertiliser sources to canola. Lines represent the frequency of returning at least $0 for $1, $0.75 for $1, $1 for $1, $1.25 for $1, $1.50 for $1, $2 for $1 or $3 for $1 invested.

with 1.1% (s.e. = 0.1) for RR. In six experiments, RR had higher total N uptake than TT canola, and in four experiments RR had lower intake than TT canola.

Discussion

In this study, the growth and seed yield of canola responded positively to applied N. The average seed yield responses to applied N were ~130 kg/ha in low-rainfall sites and 280 kg/ha in medium-rainfall sites. The scale of this response to N is less than reported from experiments conducted in higher rainfall environments both in WA (Brennan and Bolland 2007*a*, 2007*b*, 2008) and in eastern Australia (Hocking and Stapper 2001; Norton 2016), but comparable to medium-rainfall sites reported by Hocking *et al*. (1997). We found little evidence of an interaction between genotype and N for either seed yield or oil%. Instead, we found that RR hybrid canola consistently produced higher yields (250 kg/ha or 25%) and oil% (2.2% higher) than TT canola at all levels of applied N. RR hybrids were also more likely to respond to improved growing conditions than OP TT canola, with RR hybrids producing consistently higher yields and gross margins when site yields were >1400 kg/ha. Zhang *et al*. (2016) demonstrated similar differences between RR hybrid and TT OP varieties, and improvements in seed yield have been shown between near-isogenic TT and non-TT lines (Robertson *et al*. 2002) and between OP and hybrid canola (Brandt *et al*. 2007).

Although we demonstrated genotype × environment interactions throughout this study, we found in most instances that interactions between canola genotypes (G) and management (M) did not occur. A similar lack of G × M interactions has been reported in Australia by Brill *et al*. (2014), Norton (1993, 2002), Riffkin (2011) and Riar *et al*. (2014). In our study, the lack of G × M interactions could be attributed to careful selection of RR hybrid and TT OP cultivars suited to their target environment; or perhaps the rather narrow genetic background from which Australian cultivars are generated (Cowling 2007) limited the scope for interactions to occur. It may also be a reflection of WA's growing conditions and low yield potential, curtailing the expression of genetics. We believe that on the rare occasion that significant G × M interactions occurred, it might have been the result of choosing cultivars less suited to WA conditions such as the TT hybrid variety CB Junee HT and the RR OP variety GT Cobra at Grass Patch in 2012, when alternative options to these cultivars were limited.

As found in many previous studies, N fertiliser decreased the concentration of oil in the seed of canola (Bhatty 1964; Allen and Morgan 1972; Ramsey and Callinan 1994; Brennan and Bolland 2007*a*). In this series, oil concentration decreased following N fertilisation at a rate of 0.01–0.04% oil per kg N/ha, which is comparable to results reported for WA conditions by Brennan and Bolland (2007*b*, 2008) but less than reported by Brennan and Bolland (2007*a*). We found that the rate of decrease in oil concentration was greater in low-rainfall regions and in experiments where the seed yield response to N was small. For example, the site where N had no effect on oil was Chapman in 2014, which may due to this site having the largest seed yield response to applied N of ~500 kg/ha and high temperatures during the reproductive phase (Canvin 1965; Si *et al*. 2003), with 19 days >26° in July–September, and 69 days with a daily average temperature >15°C. Similarly at Merredin in 2013, the TT OP variety CB Telfer maintained oil% with 100 kg N/ha compared with 75 kg N/ha whereas the RR hybrid variety Hyola 404RR showed the more 'normal' decreasing response as N rate increased, and we attribute this to the earliness of CB Telfer allowing it to fill under milder conditions than Hyola 404RR. It has been well documented that high temperatures during the reproductive phase can reduce the concentration of oil in the seed of oilseeds (Canvin 1965; Pritchard *et al*. 2000; Si *et al*. 2003).

Marketers of canola in Australia now reward growers for high oil%, imposing an uncapped 1.5% premium or discount to the price for every 1% oil concentration above or below 42%. Therefore, gains from increased seed yield following N fertilisation may be offset by reductions in the value of the grain as oil% decreases. In effect, oil yield is now the aim rather than seed yield. In this study, we found that the relatively small increase in seed yield and reduction in oil% following N application led to economic optimum N rates being markedly lower than N rates required for optimum seed yield. For example, maximum seed yield in this study was achieved at a rate of applied N equivalent to 89% of the top rate applied in each experiment, whereas 47% of the top rate was required to produce maximum gross margins. It was evident, therefore, that a conservative economic approach was required.

We calculated the probability of obtaining a range of economic returns from the investment in N fertiliser. We found that when N rates were <40 kg/ha, expected rates of return were in 50% of occurrences \$1.00–1.50 for each \$1 spent on N, with slightly better rates of return (2 : 1) at lower N rates (<20 kg/ha). We also calculated the probability of obtaining economic returns from all sources of N, which we referred to as total available N (TAN). As expected, as the level of TAN increased, the probability of obtaining economic returns from further N inputs decreased. For example, when TAN was 90 kg/ha the frequency of achieving a 2 : 1 return was 50%, and at a level of TAN of 120 kg/ha the frequency reduced to 30%. Similarly, if TAN was >180 kg/ha the frequency of breaking even was $\leq$50%. When conducting these experiments, we asked growers at field days and a limited number of private consultants what their expected rates of return were and we found those to be around 1 : 1 for compound fertiliser applied at seeding and 2 : 1 to 3 : 1 for 'top-up' fertiliser. Therefore, if we assumed a starting N status of 60 kg N/ha and 10 kg N/ha was added with compound fertiliser at seeding, a top-up of 20 kg N/ha would provide a 2 : 1 rate of return with a frequency of 50%. The frequency curves produced in this study can also be used to evaluate readily how changes in grain pricing, fertiliser pricing or fertiliser form would influence the likelihood of an economic return.

We were unable to assess whether the potential yield level alters the frequency of returning an economic response. To do this may require a larger dataset, or perhaps modelling of our data in a mechanistic model such as APSIM (Keating *et al*. 2003) would allow for multi-year scenarios with varying conditions to be evaluated. We were able to determine that a single frequency curve could be used for rates of return between \$0 and \$2 irrespective of whether the variety under investigation was RR hybrid or TT OP.

Currently, growers have access to tools such as SYN (Diggle and Bowden 2003), which can provide some insight into likely seed yield, oil% and returns, provided information on rotation, soil type, rainfall, and organic carbon/soil N are provided and realistic target yields are set. It may prove useful to update such models with information gathered in this study to optimise the model for lower rainfall conditions and apparent shifts in crop efficiency if RR hybrids instead of TT OPs are grown.

The rates of applied N found to provide reliable economic returns were lower than crop removal rates. For example, N rates of 25 kg/ha produced reliable economic returns and an average amount of N in aboveground dry matter at maturity of 69 kg N/ha, of which 33 kg N/ha was removed in the seed. Although we can assume some additional residual N from harvest losses (estimated to be ~1–3 kg N/ha) and from leaf drop before maturity and belowground dry matter (both of which were not assessed in this study), it appears likely that economic N rates will be reducing soil N. Additionally, nine of the experimental sites had organic carbon levels <1%, and further reductions may be difficult to address. It is feasible for growers to increase N rates in the canola year in order to undertake a more balanced approach to fertilising their crop. However, there appear to be several options to address reductions in soil N without increasing the financial risk in the year in which canola is grown. These include adding a legume species to the rotation (Blair and Crocker 2000), increasing N inputs in more reliable cereal crops (Carter *et al*. 1993), and reducing the frequency in which canola is grown. Other more novel approaches being evaluated in the farm system may also assist growers to manage soil N and organic carbon. These include the use of biochar (Blackwell *et al*. 2010), animal manures and green manure crops to increase organic carbon (Edmeades 2003), and claying sandy soils to protect organic carbon (Baldock and Skjemstad 2000).

Surveys of farmers throughout WA over recent years indicated that the majority of farmers apply a proportion of their N at seeding and then apply extra ('top-up') N at 6–8 weeks after sowing. We found that applying N at seeding, during the early vegetative stage (4WAS) and about the time of stem elongation (8WAS) produced similar seed yields. We also found that, in the majority of instances, applying top-up N around the time of the commencement of flowering (12WAS) produced seed-yield responses similar to earlier timings. On occasion, delaying N until 12 weeks reduced seed yield or reduced oil levels; however, we found that these reductions were not large enough to reduce gross margins. Reduced oil and seed yield levels with application of N at 12 weeks were more likely if low or no N was applied at seeding and then a high rate of N ($\geq$50 kg N/ha) was applied in a single application. Ramsey and Callinan (1994) in north-central Victoria and Motley *et al*. (2001) in central-west New South Wales also found that N applied at a wide range of timings up to and including early flowering at 13 weeks produced similar results. Therefore, we suggest that growers continue to aim to apply top-up N at 8 weeks, but if conditions are uncertain, applying top-up N at 12 weeks may be a viable strategy. The extra time would allow farmers to be better informed about the likely performance of their crop, and in poor conditions allow them to reduce or eliminate further inputs.

Conclusions

Canola yields in low- and medium-rainfall regions of south-western Australia are inherently low and variable. We have shown that although N fertilisation increases the yield of canola, the yield increases are often relatively low. Nitrogen also reduces the concentration of oil in the seed of canola and the rate of decrease can be rapid in low-rainfall areas. The combined effect of N on yield and oil, along with the current payment structure for high-oil canola, results in uncertain economic returns from N fertilisation in low–medium-rainfall areas. We found that 90% of maximum gross margin was achieved at an average N rate of 17 kg N/ha, and the first 10 kg N/ha gave a return on investment in N of >$1.50 per $1 in 80% of occurrences (experiments × variety combinations). The next 20 kg N/ha applied gave a return on investment in N of $1.25 for every $1 spent on N in 80% of occurrences, and further increases were most likely to break even. We have shown that although farmers should continue to plan to apply N onto canola within the first 8 weeks, delaying top-up N until 12 weeks after sowing, when the canola crop is near flowering, is a viable second option that provides some level of risk management for canola growers in low- and medium-rainfall areas in the south of WA.

Acknowledgements

This work was supported financially by the Department of Agriculture and Food Western Australia (DAFWA) and the Grains Research and Development Corporation (GRDC) of Australia. DAFWA research officers Paul Galloway and Andrew van Burgel assisted with soil classification and statistical analysis and economic optimisation. DAFWA technical officers Pam Burgess, Laurie Maiolo, Andy Sutherland, Allen Randell, Jo Walker and Stephanie Boyce ensured treatments were imposed correctly and data collected in a timely fashion. We thank all of the farmers and farming groups who hosted the experiments and to the DAFWA technical services teams, who sowed, managed and harvested the experiments. Journal reviewers provided useful advice and guidance, which helped the authors to improve the final version.

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