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Impacts of retained wheat stubble on canola in southern New South Wales

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Abstract. Field experiments were conducted in southern New South Wales to determine the effect of surface-retained wheat stubble on the emergence, growth and yield of canola. The 5 experiments included treatments to investigate the impact of stubble load, stubble cultivar and level of decomposition as well as the impact of different environments on the crop response. Overall, 5 t/ha of surface-retained wheat stubble reduced the rate of emergence, plant establishment (mean reduction 33%), vegetative biomass (–56%) and yield (–23%), although the impact varied with site and season. Laboratory experiments assessing the phytoxicity of stubble revealed the possible role of allelopathy in the growth response at 1 site; however, there was no correlation between laboratory phytotoxicity of different stubble cultivars and their impact on canola growth at any other site. Wheat stubble comprising thinner stems (lower straw linear density) had a greater impact on emergence at 2 of the sites, indicating a possible role of reduced light penetration in the growth response. Colder temperatures on the surface of the stubble also reduced emergence and growth, and caused seedling death at the coldest sites. The experiments confirm the widely observed phenomenon of poor canola growth in surface-retained wheat stubble, and suggest several possible mechanisms for the effect, although further studies are required to determine their relative importance in different environments.

Additional keywords: stubble retention, canola, hypocotyl, direct drilling, phytotoxicity, allelopathy, phytotoxins, allelochemicals, leachates.

Introduction

Stubble retention was initially adopted in cropping systems to reduce the risk of erosion (Chan and Pratley 1998; Charman 1985), and more recently to maintain organic matter, increase water infiltration and reduce evaporation (Malinda 1995). However, in temperate Australia the rate of adoption for stubble retention has been slow, particularly in southern New South Wales (NSW) and Victoria (Bruce 2003; Steed *et al*. 1993). In these regions, yield increases of cereals have led to stubble loads of 7–10 t/ha which cause physical problems during the sowing operation as low summer rainfall limits the rate of stubble decomposition (Chan and Pratley 1998).

Other constraints have also slowed the adoption of stubble retention. Several studies in the United States of America and Australia show that retained crop stubbles can reduce the yield of subsequent crops (Guenzi and McCalla 1962; McCalla and Army 1961; Purvis 1990; Putman and Tang 1986). A review by Kirkegaard (1995) established that wheat yields in southern NSW were consistently reduced by 0.3 t/ha in stubble-retained compared with stubble-burnt systems. More recently, there has been mounting anecdotal evidence in the same region for poor growth and reduced yield of canola when sown into surface-retained wheat stubble (I. J. Packer pers. comm.).

Several factors associated with stubble retention have been shown to cause growth and yield depression in other species and may also be responsible for the poor growth of canola in wheat stubble. These include: (i) poor seed–soil contact; (ii) ineffective pre-sowing herbicide incorporation resulting in increased weed competition; (iii) nitrogen immobilisation (Fenster 1977; Thompson 1992); (iv) reductions in soil and air temperature (Ball *et al*. 1991, 1997; Unger 1988; Van Wijk *et al*. 1959); (v) increased incidence of root disease (Cook and Haglund 1991); (vi) phytotoxins liberated from the stubble (Bruce *et al*. 1999; Guenzi and McCalla 1962; Kimber 1967); and (vii) increased insect and slug damage.

Increasing reports of poor early growth and unsatisfactory yields of canola crops sown into wheat stubble in the south-eastern wheatbelt of NSW prompted more detailed investigations of the impacts of wheat stubble on the growth and yield of canola. This study examined the general impacts of stubble on growth and yield of canola in replicated field experiments. The experiments aimed to assess the magnitude of the effects of retained wheat stubble on canola growth and yield and to investigate possible causes. The impact of stubble amount, cultivar and decomposition as well as the impact of different environments were also considered. Laboratory experiments to assess the phytotoxicity of stubble collected from some of

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the field sites were used to seek evidence for allelopathic influence in the growth effects of the stubble.

Materials and methods

Five field experiments were conducted in 1999 and 2000 in southern NSW and the Australian Capital Territorty (Table 1). In 1999, a stubble-retained treatment within a long-term tillage experiment at Harden was used to investigate the impact of stubble quantity on crop growth. In 2000, the experiments included 3 sites [Ginninnderra Experiment Station 1 (GES 1), Gundibindyal and Moombooldool] where canola was sown over areas previously used for wheat cultivar experiments and an experimental field site [Ginninnderra Experiment Station 2 (GES 2)] where stubble cultivar and quantity, and level of decomposition were manipulated. All experiments used stubble grown on the site during the previous season and retained on-site over summer. The stubble was either burnt or removed before sowing, and for stubble-retained treatments was replaced after the sowing operation. At 2 sites (Harden and GES 2), plots were irrigated immediately after sowing to ensure even germination and to simulate post-sowing rainfall likely to release allelochemicals from the stubble (Table 2). Weeds were controlled to the same extent on all treatments in all experiments.

The rate of seedling emergence was measured in the field experiments by regular counts of 3–4 m of row in each plot. Seedlings were considered to have emerged when the cotyledons were visible above the stubble. Plant number, leaf area and shoot dry weight and, in some instances, hypocotyl length were measured at stem extension (Harden, Gundibindyal and Moombooldool) or flowering (GES 1 and GES 2) from 0.32 m^2 bordered quadrat cuts excluding the border rows. Plants from a 0.32 m^2 quadrat were removed from each plot at maturity, and seed yield and harvest index (HI) were determined at all sites except Harden where plots were too small at maturity for meaningful samples. The incidence of plants infected with sclerotinia stem rot (*Sclerotinia sclerotiorum*) and blackleg (*Leptosphaeria maculans*) were assessed. Stem cankering was considered symptomatic of blackleg and areas of whitened stem containing black sclerotia were considered symptomatic of sclerotinia stem rot. Although these diseases were observed in the experiments, treatment differences were not apparent and results are not presented.

1999 Harden field experiment

This experiment was established within a long-term field site established in 1990, near Harden (described by Kirkegaard *et al*. 1994), which included stubble-retained and burnt treatments with 4 replicates each measuring 30 by 2 m. The experiment was established within the stubble-retained plots, using the existing wheat stubble (cv. Janz) that had been on the plots since harvest in December 1998. The plots were divided into 6 treatments: a burn of stubble immediately before sowing (burn, 0 t/ha) and 2, 4, 6, 8 and 10 t/ha of stubble retained.

The rate of seedling emergence, shoot dry weight and leaf area were measured as described previously. Due to the small size of the plots (1.7 by 2 m), insufficient bordered plants remained for meaningful seed yield estimates. However, as the long-term experimental site included additional stubble-burn and stubble-retained treatments also sown to canola, the impacts of about 5 t/ha of retained wheat stubble on canola yield at the site were recorded (J. A. Kirkegaard pers. comm.).

2000 field experiments

GES 1, Gundibindyal and Moombooldool: impact of wheat stubble cultivar and environment on canola growth and yield. Each of the 3 sites had grown 23 wheat cultivars in 1999, including Janz, Swift, Worrakatta, Eradu, Corella, Lillimur, Sunvale, Dollarbird, Egret, Excalibur, C306, Baviacora, Yecora, 950, Chuan Mai, Vulcan, Nainari, Wollaroi, Kulin, Westonia, Havik, Krichauf, Compass 88 and a triticale cultivar, Currency. GES 1 and Moombooldool had 2 replicates and Gundibindyal had 3 replicates of each cultivar arranged randomly in blocks. Two treatments were established immediately before sowing in a split-plot design, superimposed on the wheat cultivar stubbles. The bare treatment had the stubble raked off before sowing while the stubble treatment had stubble raked off the plots before sowing and 5 t/ha replaced and distributed evenly immediately after sowing. Rates of seedling emergence, plant number, shoot dry weight, seed yield and HI were measured as described previously.

Table 1. Management details for the five experimental sites investigating the impacts of wheat stubble on the growth of canola during 1999 and 2000

Site	Harden	GES 1	Gundibindyal	Moombooldool	GES 2
Date of experiment	1999	2000	2000	2000	2000
Latitude and longitude	148°17′E, 34°30′S	149°06′E, 35°12′S	147°47′E, 34°29′S	146°49′E, 34°11′S	149°06′E, 35°12′S
Elevation (m.a.s.l.)	497	600	300	200	600
Soil type[A]	Gradational red earth (Gn 4.12)	Yellow podzolic (Gn 3.85)	Gradational red earth (Gn 4.12)	Gradational red earth (Gn 4.12)	Yellow podzolic (Gn 3.85)
Quantity of stubble (t/ha)	2, 4, 6, 8, 10	5	5	5	3,6
Canola cultivar	Pinnacle	Oscar	Oscar	Oscar	Oscar
Quantity of seed (kg/ha)	5	5	5	5	5
Fertiliser at sowing (kg/ha) (kg N;P;S/ha)	Starter15 143 (20N;18P;16S)	Starter15 160 (22N;20P;18S) Urea40 (18N)	Starter15 160 (22N;20P;18S) Urea40 (18N)	Starter15 160 (22N;20P;18S) Urea40 (18N)	Starter15 160 (22N;20P;18S) Urea40 (18N)
Fertiliser at stem extension (kg/ha) (kg N/ha)	Urea 125 (57.5N)	Urea 50 (23N)	Urea 36 (17N)	Urea 36 (17N)	Urea 50 (23N)
Sowing date	18 May	2 June	12 May	11 May	14 June
Row spacing (cm)	18	18	18	18	18
Date of initial emergence counts	27 May	21 June	23 May	23 May	29 June
Harvest date (vegetative)	28 July, 9 Sept.	4 Oct.	1 Aug.	1 Aug.	27 Sept.
Harvest date (seed)	—	18 Dec.	20 Nov. (bare) 4 Dec. (stubble)	20 Nov.	18 Dec.
Treatment plot size (m)	1.7 by 2	3 by 2	3 by 2	3 by 2	3 by 2

[A] Northcote (1971).

Stubble samples from 6 wheat cultivars were collected during canola emergence at Gundibindyal and Moombooldool for straw linear density (SLD) measurements. The cultivars were C306, Chuan Mai, Compass 88, Diamondbird, Egret and Kulin, and were chosen based on observed differences in canola seedling growth response in the field experiments. Mean SLD (g/m) was determined from 5 lengths of straw for each cultivar collected from the plots.

Temperature was measured on the surface of 1 stubble and 1 bare treatment at each site using Testostar 175 loggers (which have thermistors encased in boxes). The location of the probe was about 1 cm above the surface of the treatments (1 cm above the soil surface in the bare treatment and 1 cm above the surface of the stubble in the stubble treatment). Temperature was recorded during the months of June and July 2000.

GES 2: impact of wheat stubble cultivar, decomposition and quantity on canola growth. In May 1999, 14 cultivars of wheat were sown in a randomised block design with 4 blocks. The cultivars included Currawong, Sunbri, Diamondbird, Snipe, Vulcan, Gabo, Janz, Hybrid Mercury, Corella, Swift, Krichauf, Sunbrook, Whistler and Gordon. Immediately after harvest, samples of stubble were collected from each plot and stored to provide undecomposed stubble for subsequent treatments. Four treatments were superimposed on the wheat stubble cultivars in a split-plot design just before sowing in 2000. The treatments were: (i) a burn of 6 t/ha of stubble just before sowing (burn); (ii) 3 t/ha of decomposed stubble spread evenly across the plot (decomp3t); (iii) 6 t/ha of decomposed stubble spread evenly across the plot (decomp6); and (iv) 6 t/ha of undecomposed stubble spread evenly across the plot (undecomp6t). The decomposed stubble treatments used stubble existing on the plots from harvest until sowing, which was removed just before sowing and then replaced and redistributed immediately following sowing. The undecomposed stubble treatment used stored stubble (stored in plastic garbage bins in a barn) that was spread evenly across the plot following sowing. Both decomposed and undecomposed stubble was weighed just before distribution on the plots.

The rate of seedling emergence, plant number, shoot dry weight and hypocotyl length were measured as described previously. Seed yield and HI were determined for 6 of the 14 cultivars only (Corella, Diamondbird, Gabo, Snipe, Sunbri and Vulcan), which were chosen to represent a wide range of growth responses to the presence of wheat stubble.

Laboratory experiments

Germination and radicle length bioassays were used to determine the phytotoxic effect of stubble leachates from selected field experiments. Crop stubbles were collected at harvest for all wheat cultivars used in the experiments in 2000 and stored in the dark before evaluation. A subset of cultivars from the GES 1, Gundibindyal and Moombooldool experiments (Chuan Mai, Egret, C306, Sunvale, Diamondbird and Compass 88) was chosen for laboratory phytotoxicity experiments. Cultivar choice was based on the observed differences in canola response to the stubble cultivars in the field experiments, such that a full range of responses was represented. Stubble from all wheat cultivars in GES 2 was used for laboratory phytotoxicity experiments and 2 stubbles cultivars (Diamondbird and Snipe) collected in 1998 were included to test the consistency of the phytotoxicity effect between years.

Stubble was air-dried and chopped into 3 cm lengths. Stubble leachates were extracted from stubble using a modification of the method reported by Guenzi and McCalla (1962), which in other experiments was able to separate the allelopathic potential of a range of stubble species (Bruce 2003). Stubble leachates were prepared by agitating 20 g of stubble in 250 mL of distilled water for 2 h at 22°C. The leachate was decanted, centrifuged to remove particulate matter, passed through a 0.45 µm filter (Millipore) to remove microorganisms and stored at 4°C. Canola (cv. Oscar) seeds were surface-sterilised by immersion in a 3% calcium hypochlorite solution for 3 min and then rinsed 8 times in sterile distilled water. Twenty seeds were placed in sterile petri dishes on Whatman filter paper no. 42. Four millilitres of leachate were added to separate sterile petri dishes. Sterile distilled water was used for control treatments. The seeds were germinated in a growth cabinet in the dark, in a randomised block design at a constant temperature of 15°C. Germination was measured at 48 and 120 h after the start of the experiment, by which time at least 90–95% of the controls had germinated. A seed was considered to have germinated when radicle length was >2 mm. Radicle elongation was measured on pre-germinated seeds to avoid confounding germination time with radicle elongation rate. Other conditions were as described for the germination bioassay. After 48 or 72 h, the lengths of radicles were measured.

Statistical analyses

Data were subjected to analysis of variance (ANOVA) using Genstat 5 and are presented as means with the standard error of differences (s.e.d.).

Field experiments. The emergence data were analysed using 2 methods. For the first analysis, the measurements of final emergence

Table 2. Monthly rainfall (mm), supplementary irrigation (mm; GES 2 and Harden, supplied at 10 mm/h), growing season rainfall (GSR) during 1999 at Harden and during 2000 at Ginninnderra Experiment Station (GES), Gundibindyal and Moombooldool and the long-term mean (LTM)

Data were collected from Bureau of Meteorology stations close to the location of experiments

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	GSR	Total
							Harden							
1999	65	7	87	41	36 (20)[A]	53	26	56	57	206	33	135	475	802
LTM	51	42	52	47	48	58	53	53	52	59	47	50	371	609
							GES							
2000	38	14	40	74	70	35 (10)[A]	37	106	85	75	152	29	480	753
LTM	51	42	52	47	48	58	53	53	52	59	47	50	371	609
							Gundibindyal							
2000	0	78	29	15	19	26	55	87	33	79	80	13	313	514
LTM	48	36	41	44	44	43	47	46	43	55	45	41	320	530
							Moombooldool							
2000	41	27	31	27	64	38	31	73	22	60	67	3	315	484
LTM	44	38	38	38	42	42	43	44	39	46	39	36	292	490

[A] Supplementary irrigation.

were subjected to ANOVA. The second analysis was conducted on the estimated emergence rate of the common response curves of the data from each experimental plot (see below). For the Harden field experiment, exponential decay models were fitted to the emergence data from each plot. For the other field experiments, linear growth curves were fitted to the data as exploratory data analyses showed that exponential growth curves did not fit the data.

The growth curve fitted to the Harden field experiment emergence data was the Mitschlerlich curve that has the following form:

$$y_i = \alpha + \beta e^{-\kappa xi} + \varepsilon_i.$$

For numerical reasons, Genstat fits the curve using the following form:

$$y_i = \alpha + \beta\rho^{xi} + \varepsilon_I,$$

where $\rho = e^{-\kappa}$ and is the emergence rate (when the value of the regression coefficient ρ increases, the rate of emergence declines), α is the asymptote, and β is the range of the curve between the value $x = 0$ and the asymptote. α is not reported as in all instances, when the growth curves had naturally asymptoted, the final emergence was similar to the α values. β is not reported as it has no biological meaning.

Where exponential growth did not fit the data, linear growth curves were fitted using the following form:

$$y_i = \alpha + \beta x_1 + \varepsilon_I,$$

where β is the emergence rate and α is the intersect. α is not reported as it has no biological significance.

Laboratory experiment. Data were analysed using Genstat 5. Initial and final germination data were analysed using Generalised Linear Models (GLMs) on a logit scale. Radicle elongation was subjected to ANOVA.

Straw linear density measurements and petri dish phytotoxicity measurements for the selected wheat cultivars were regressed against the growth responses of the same wheat cultivars in the field experiments where significant cultivar effects were apparent. In this way, evidence for correlations between growth suppression in the field with either SLD or phytotoxic effects of the stubble was sought. Plant growth responses to stubble in the field were presented as the percentage change in growth from the bare treatments, and petri dish data (or stubble phytoxicity data) were presented as the percentage change from the control treatments as follows:

$$\%\text{reduction} = \frac{\text{Bare} - \text{Stubble}}{\text{Bare}} \times 100 \text{ and } \frac{\text{Control} - \text{Leachate}}{\text{Leachate}} \times 100.$$

Results

Rainfall

The monthly rainfall and long-term mean for each experiment are presented in Table 2. Rainfall was above average for the growing season in 1999 at Harden, although conditions were dry at the time of sowing in April–May. At GES 1 and GES 2, rainfall was below average from sowing (June) until the end of July, but above average thereafter. The monthly rainfall in 2000 for Gundibindyal was average for the growing season but there was a dry period in September during the flowering period. The monthly rainfall at Moombooldool was below average before May but average or above average thereafter with the exception of September. Average annual rainfall declines from east to west with GES having the highest growing season rainfall and Moombooldool the least.

1999 Harden field experiment

In the Harden field experiment, increasing the quantity of stubble reduced plant establishment although there was no effect at levels less than 6 t/ha (Table 3). At stem extension, an increase in stubble load led to a reduction in plant number and plant biomass (Table 3). Stubble at 10 t/ha led to an 81% reduction in leaf area and in total dry weight. However, at flowering there were no differences in biomass between the treatments indicating that the plants growing in the presence of higher quantities of stubble were able to compensate for the slower early growth at this site (possibly due to quadrat cuts being taken in small plots leading to less competition for light and nutrients). In the main long-term field experiment at this site, stubble retention (about 5 t/ha) reduced yield by 26% compared with the stubble-burn treatment [stubble 3.22 t/ha; burn 4.35 t/ha (J. A. Kirkegaard unpublished data)], suggesting that the compensation in vegetative biomass apparent in the small plots at flowering was not evident in the yield response of the long-term field experiment at the site.

Table 3. Impact of increasing quantity of stubble on canola growth at Harden field experiment in 1999

The value for the rate of exponential increase $\rho(e^{-\kappa})$ is the emergence rate; when the value of the regression coefficient ρ increases, the rate of emergence declines

Stubble quantity (t/ha):	0	2	4	6	8	10	s.e.d.
			Emergence				
Plant establishment/m^2	90	107	90	71	64	47	19
Variate ρ	0.8329	0.8629	0.8510	0.8613	0.9011	0.9107	0.0309
			Stem extension				
No. of plants/m^2	79	90	94	84	57	39	21
Shoot biomass (g/m^2)	14.7	12.8	10.7	9.95	3.68	2.83	3.10
Leaf area index	0.19	0.18	0.17	0.15	0.05	0.04	0.06
			Flowering				
No. of plants/m^2	79	79	65	63	48	61	n.s.
Shoot biomass (g/m^2)	253	184	127	187	182	159	n.s.
Leaf area index	1.66	1.27	0.98	1.33	1.30	1.23	n.s.

n.s., not significant at $P = 0.05$.

2000 field experiments

GES 1, Gundibindyal and Moombooldool: impact of wheat stubble cultivar and environment on canola growth and yield. There was no effect of and no interaction between wheat stubble cultivar on the rate of canola emergence or on plant establishment at any of the sites, so only main effects of stubble treatments are considered. Seedlings in the bare treatments emerged faster than in the stubble treatments at all sites (Table 4). Canola seedlings emerged faster through stubble at Moombooldool than at Gundibindyal, and GES 1 had the slowest rate of emergence (Table 4). Final plant establishment was reduced in the presence of stubble at all sites (Table 4). Stubble treatments reduced establishment to 90, 79 and 30% of the bare treatments at the Moombooldool, Gundibindyal and GES 1 sites, respectively.

At stem extension, canola at Moombooldool had a higher plant density than at Gundibindyal (Moombooldool 121; Gundibindyal 84; s.e.d. 5). There was an interaction between stubble and cultivar; however, the response of cultivars to stubble treatments was similar at both sites. The mean across sites of the interaction between stubble and cultivar is presented in Figure 1. In general stubble had little effect on plant density, although Corella, Egret and Sunvale stubbles reduced plant density by 47, 50 and 40%, respectively, relative to the bare treatments. However, Compass 88 had 91% more plants/m^2 in the stubble treatment than the corresponding bare treatment. At GES 1, there was no effect of wheat cultivar on plant density at flowering and no interaction between stubble and cultivar (data not shown), although overall, stubble reduced plant density by 80% (bare 128; stubble 25; s.e.d. 7).

At stem extension, there was more shoot biomass at Moombooldool than Gundibindyal but stubble reduced biomass by 33% at Moombooldool and by 27% at Gundibindyal (Table 4). There was a site × cultivar × stubble interaction, with some cultivars of wheat stubble having no effect on shoot biomass. However, there was no consistent effect of stubble cultivars on shoot biomass between the sites (data not shown). It is probable that growth at Moombooldool was faster than at Gundibindyal because the mean temperature at Moombooldool was higher (17.8 *v.* 18.6°C). At GES 1, stubble reduced biomass by 86% at flowering.

At final harvest, the effect of the stubble on plant density persisted and was consistent between sites (Table 4). Stubble at GES 1 reduced final plant density by 86%, while stubble at Gundibindyal and Moombooldool reduced plant density by only 23 and 9%, respectively. Stem biomass was reduced in the presence of stubble at GES 1, was increased at Gundibindyal but did not differ between treatments at Moombooldool. There was no difference in the HI between stubble and bare treatments at Gundibindyal and Moombooldool; however, HI was lower in the presence of stubble at GES 1.

Overall, seed yield was reduced substantially (66%) by stubble at GES 1 (Table 4), but there were cultivar differences. For example, yield in the presence of Janz wheat stubble was increased by 166%, which is possibly a result of unusually low germination in the bare treatment in some replicates caused by crusting of the soil surface. This response is unlikely to be caused by the stubble treatment. Excalibur stubble had no effect (data not shown). Overall, seed yield at Gundibindyal was increased in the presence of

Table 4. Characteristics of plants in two treatments, stubble and bare, across three sites, Ginninnderra Experiment Station (GES 1), Gundibindyal and Moombooldool

There were no effects of wheat stubble cultivar or any interactions with wheat stubble cultivar
Variate β is the regression coefficient for the rate of emergence
s.e.d. values are reported; the min. rep s.e.d. is used for differences between the treatments of minimum replication (GES 1 and Moombooldool); the max-min s.e.d. is used for differences between the treatments of maximum and minimum replication (Gundibindyal and either GES 1 or Moombooldool); and the max. rep s.e.d. is used for differences between treatments of maximum replication (within Gundibindyal)

	GES 1 (2 reps)		Gundibindyal (3 reps)		Moombooldool (2 reps)		s.e.d.	s.e.d.	s.e.d.
	Bare	Stubble	Bare	Stubble	Bare	Stubble	min. rep	max-min	max. rep
				Emergence					
Plant establishment/m^2	144	43	119	94	148	133	7	7	6
Variate β	4.81	1.36	5.13	4.12	5.90	5.44	0.298	0.272	0.243
				Stem extension					
Plant biomass (g/m^2)	—	—	41	30	130	87	5	4	3
				Flowering					
Plant biomass (g/m^2)	234	34	—	—	—	—	10	—	—
				Seed harvest					
No. of plants/m^2	110	15	69	53	108	98	7	6	6
Stem biomass (t/ha)	5.13	1.70	4.79	5.01	5.05	5.16	0.46	0.42	0.38
Harvest index	0.37	0.27	0.33	0.32	0.26	0.25	0.02	0.02	0.02
Yield (t/ha)	3.21	1.14	2.47	2.88	1.78	1.81	0.17	0.15	0.14

stubble (Table 4), although for most of the cultivars there was no difference between the stubble and the bare treatments (data not shown). Yield at Moombooldool was not different between the stubble and bare treatments (Table 4).

Straw linear density varied between the 6 wheat cultivars, from 1.2 g/m for Sunvale to 2.7 g/m for Chuan Mai. The mean canola plant density at stem extension for each stubble cultivar treatment (as a percentage of the bare treatments) at the sites was regressed against the mean SLD for each of those wheat cultivars (Fig. 2). For the 6 wheat cultivars selected from Gundibindyal and Moombooldool, the linear regression could account for 53% ($P = 0.04$) of the variation in the number of canola plants/m^2 in the stubble treatment compared with the bare treatment. As SLD decreased (i.e. the wheat straw became thinner) canola plant density was reduced. Wheat straw linear densities above 2 g/m were associated with an increase in the number of canola plants/m^2 relative to the bare treatment. It is probable that this was a result of either crusting of the soil surface in the bare treatment that reduced plant emergence in this treatment, or that the presence of stubble reduced the loss of soil moisture leading to increased water availability for germinating seedlings in the stubble and hence higher plant establishment.

One cultivar had significant leverage on the regressions, Compass 88 (Fig. 2). The cultivar had an intermediate SLD, but had less of an impact on plant density than other cultivars with higher SLDs. Unevenly spread stubble, due to movement by wind, may explain the higher plant population found in the Compass 88 stubble.

Since canola shoot biomass at stem extension also varied with site, cultivar and stubble treatment, the canola shoot biomass for 6 stubble cultivar treatments (as a percentage of the bare treatments) was regressed against SLD for each stubble cultivar. At Moombooldool and Gundibindyal, there was no relationship between the SLD and shoot biomass in the stubble treatments. There was no relationship between SLD and any of the other plant growth measurements in the field.

Temperature data for 2 days, 9 and 10 July, considered representative of the treatment and site differences during the

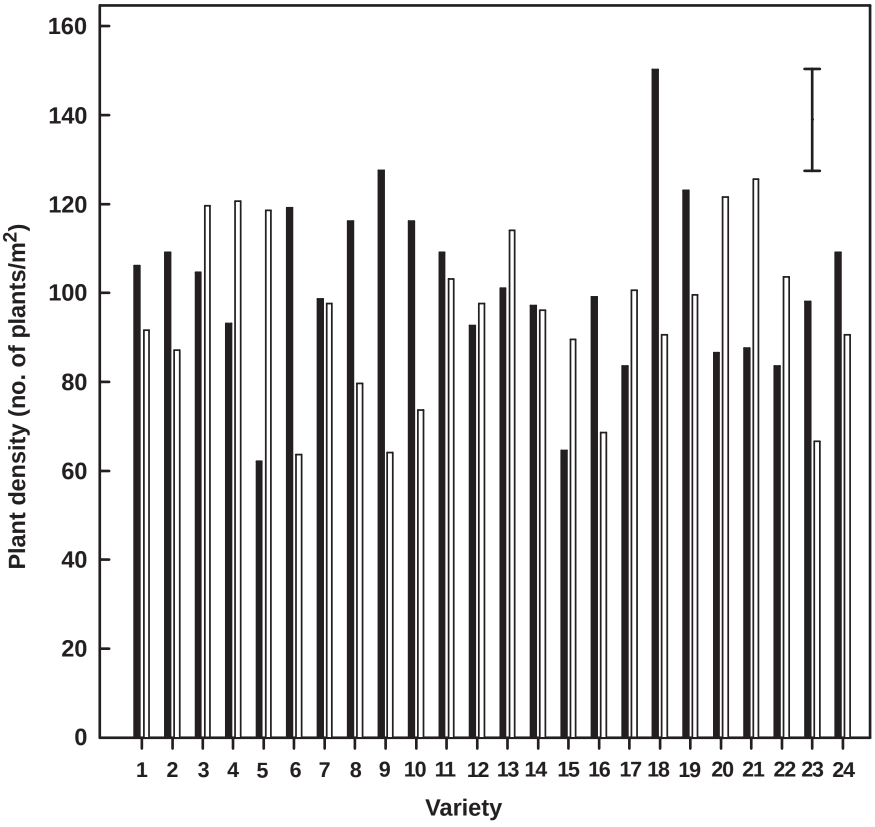

Figure 1. The effect of wheat stubble (bare, solid bars; stubble, open bars) and cultivar on plant density (no. of plants/m^2) at stem extension. Data are the mean of the Gundibindyal and Moombooldool sites. Codes for the stubble cultivars are as follows: 1, 950; 2, Baviacora; 3, C306; 4, Chuan Mai; 5, Compass 88; 6, Corella; 7, Currency; 8, Dollarbird; 9, Egret; 10, Eradu; 11, Excalibur; 12, Havik; 13, Janz; 14, Krichauf; 15, Kulin; 16, Lillimur; 17, Nainari 60; 18, Sunvale; 19, Swift; 20, Vulcan; 21, Westonia; 22, Wollaroi 18; 23, Worrakatta; and 24, Yecora. The vertical bar indicates the s.e.d.

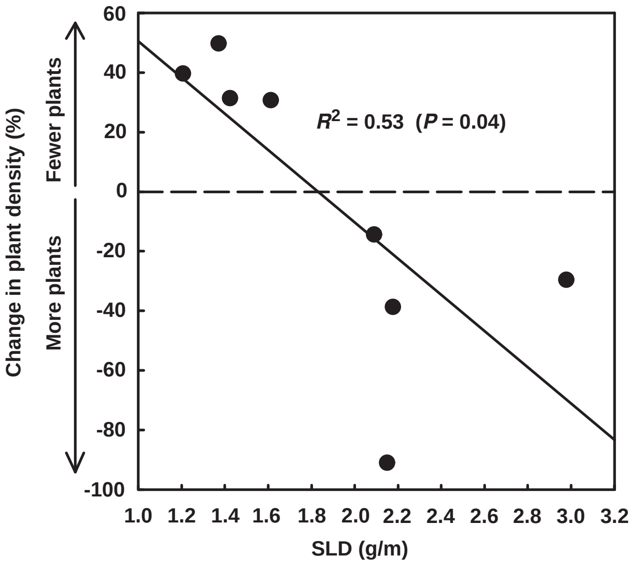

Figure 2. The relationship between straw linear density [SLD (g/m)] of stubble and the percentage reduction in plant density/m^2. Plant population data are the mean of the Gundibindyal and Moombooldool sites and are presented as the percentage reduction compared with the bare treatments. The R^2 and P values for the linear regression are presented. Arrows on the *y*-axis indicate either a decrease (fewer plants) or an increase (more plants) in plant population. An increase indicates that in the presence of stubble, the plant population was higher than the bare treatments.

early growth period are presented. The presence of stubble at GES 1 on both days and at Moombooldool and Gundibindyal on 10 July led to greater diurnal variation in temperature on the surface of the stubble compared with the soil surface in the bare treatment (Fig. 3*a, d–f*), while diurnal variation in temperature at Moombooldool and Gundibindyal on 9 July was similar between treatments (Fig. 3*b* and *c*). The difference in temperature between the treatments and the extent of diurnal variation was greatest at GES 1 (Fig. 3*a* and *d*). At GES 1, temperatures as low as –6.8°C were recorded on the surface of the stubble near dawn, 3.8°C cooler than the bare treatment on the same day (Fig. 3*a*). During the same period, the temperature on the surface of the stubble was 7.1°C at Moombooldool and 7.0°C at Gundibindyal (Fig. 3*b* and *c*).

GES 2: impact of wheat stubble decomposition and quantity on canola growth and yield. Increasing the quantity of stubble reduced canola establishment, although 3 t/ha of stubble was not statistically different from the burn treatments (Table 5). Plants emerged more slowly in the 6 t/ha stubble treatments regardless of decomposition and fastest in the burn and decomp3t treatments. More plants were established in the burn and decomp3t treatments than the decomp6t and undecomp6t treatments. Stubble cultivar had no impact on emergence.

At flowering, plant numbers were higher in the burn and decomp3t treatments and least in the undecomp6t treatment, while the decomp6t treatment was intermediate between these extremes (Table 5). Shoot biomass followed a similar trend; however the decomp3t treatment reduced shoot biomass compared with the burn treatment. Hypocotyls were shortest in the burn treatment and increased in length as stubble quantity increased. In contrast, the cultivar of wheat stubble had no impact on plant density, hypocotyl length or shoot biomass and there was no interaction between cultivar and stubble quantity (data not shown).

At seed harvest, stubble treatments influenced both plant density and seed yield (Table 5). Overall, plant density had declined since flowering in all but the burn treatment, a possible result of sampling differences, or of blackleg infection as plants fall over when infected and so may not have been collected. Plant density was highest in the burn treatment and decreased with increasing levels of stubble. The undecomp6t treatment had fewer plants then the decomp6t treatment (Table 5). Yield followed the same trend with the undecomp6t treatment suffering a 60% reduction in yield relative to the burn treatment, the decomp6t treatment a 38% reduction and the decomp3t treatment a 25% reduction compared with the burn treatment. There was no effect of wheat stubble cultivar on yield or plant density at harvest.

Laboratory experiments

Impact of wheat stubble cultivar and environment on leachate phytotoxicity. Leachates obtained from the wheat cultivars collected from GES 1, Gundibindyal and Moombooldool reduced germination relative to the control at 48 h (Fig. 4*a*). Stubble from Moombooldool reduced germination the most, and those from GES 1 reduced germination the least. Toxicity of the cultivars varied between the sites. For example, at GES 1, C306 reduced germination the most, while at Gundibindyal and Moombooldool it was the least toxic of the wheat cultivars. However, Compass 88 and Dollarbird had a similar toxicity at all sites.

At 120 h, there was a main effect of site and of cultivar on germination but no interaction. Leachates from Moombooldool remained toxic, while stubbles from GES 1 and Gundibindyal had no effect on germination relative to the control (control, 2.54; GES 1, 2.35; Gundibindyal, 2.29; Moombooldool, 1.01; s.e.d. 0.3 at $P<0.05$; logit scale). Compass 88 was the most toxic of the cultivars at 120 h and Sunvale the least toxic (control, 2.54; C306, 2.27; Chuan Mai, 1.78; Compass 88, 1.30; Diamondbird, 1.83; Egret, 1.63; Sunvale, 2.5; s.e.d., 0.4 at $P<0.05$; logit scale).

Radicle elongation was reduced most by leachates derived from the Moombooldool site (Fig. 4*b*). Chuan Mai was consistently toxic to radicle growth at each of the sites; however, other cultivars differed in their toxicity between the sites. For example, Sunvale reduced radicle growth at Moombooldool but had no effect at GES 1 and Gundibindyal.

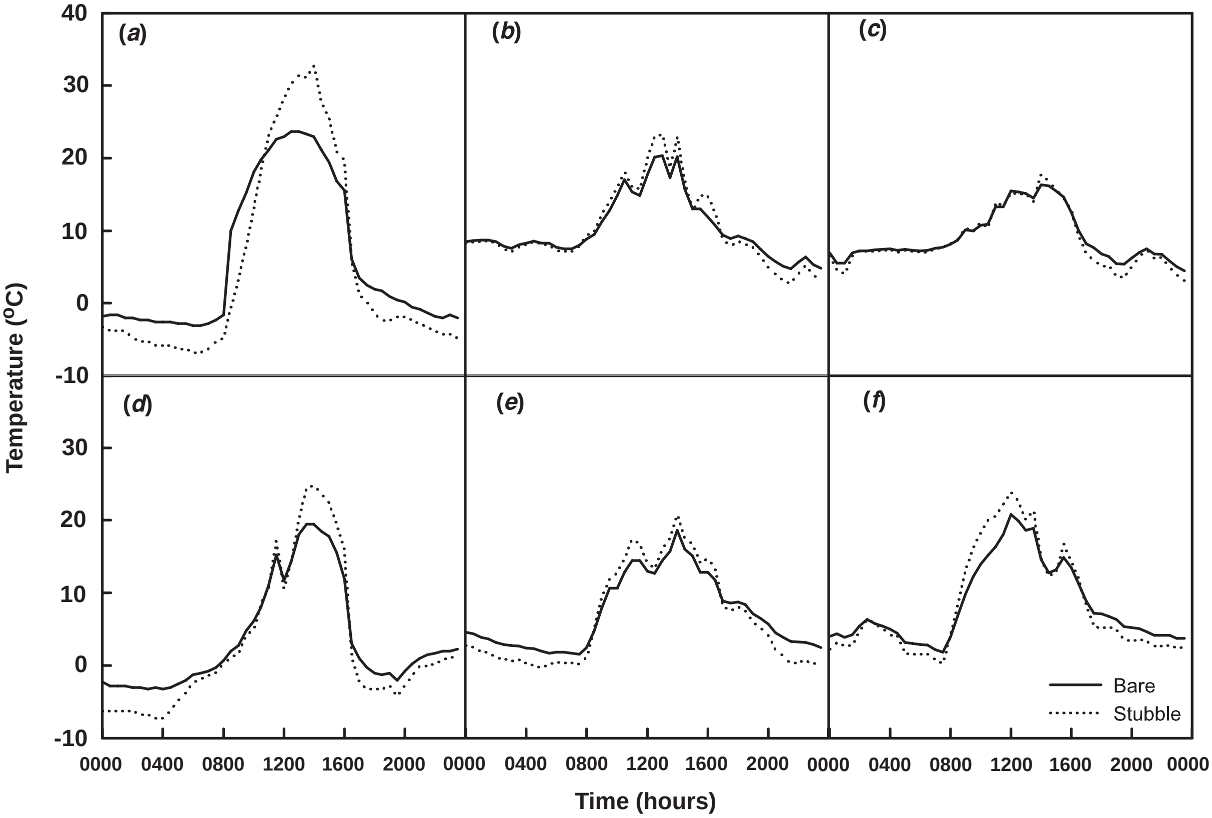

Figure 3. Air temperatures recorded for the surface of bare and stubble treatments for (*a*) GES 1, (*b*) Moombooldool and (*c*) Gundibindyal on 9 July 2000, and (*d*) GES 1, (*e*) Moombooldool and (*f*) Gundibindyal on 10 July 2000. Air temperatures were measured about 1 cm above the soil surface.

Impact of wheat stubble cultivar, decomposition and quantity on leachate phytotoxicity. Leachates obtained from GES 2 reduced germination of canola (cv. Oscar) at 48 h (Fig. 5*a*). This trend continued until 120 h (Fig. 5*b*). There was a trend for Diamondbird to be less toxic than Snipe to germination at 48 and 120 h, consistent with the leachates derived from the same cultivars from 1998 (Fig. 5*a* and *b*). The ranking of the cultivars differed between 48 and 120 h, with Krichauf the most toxic cultivar at 48 h and Sunvale the most toxic at 120 h.

Radicle elongation was reduced by the leachates and the extent of the reduction varied between the wheat cultivars (Fig. 5*c*). Diamondbird and Diamondbird-1998 were among

Table 5. Characteristics of plants grown under different quantities and levels of decomposition of stubble at Ginninnderra Experiment Station 2 (GES 2)

β is the rate of emergence

	Burn	Decomp3t	Decomp6t	Undecomp6t	s.e.d.
		Emergence			
Plant establishment/m^2	93	88	63	58	7
Variate β	3.19	2.93	2.25	1.96	0.24
		Flowering			
No. of plants/m^2	96	97	61	44	8
Shoot biomass (g/m^2)	1096	551	201	140	58
Hypocotyl length (mm)	0	14	20	22	3
		Seed harvest			
No. of plants/m^2	92	63	45	24	8
Yield (t/ha)	3.61	2.72	2.25	1.46	0.29

the least toxic of the cultivars and Gabo, Snipe-1998 and Snipe were among the most toxic.

Laboratory and field experiment correlations

Data from germination at 48 and 120 h, and radicle elongation from laboratory assays were regressed against plant growth measurements from stem extension and flowering from the field. All data presented are a percentage change from the bare or control treatments. At Moombooldool, there was a significant linear relationship between the effect of stubble on shoot biomass in the field and the number of seeds germinated at 48 h in the leachate experiment with the regression accounting for 72% (P = 0.03) of the variation (Fig. 6). At that site, higher toxicity of the leachates was associated with an increase in the impact of the retained stubble on canola biomass in the field. There were no other significant correlations between laboratory phytotoxicty and field response to stubble at the other sites.

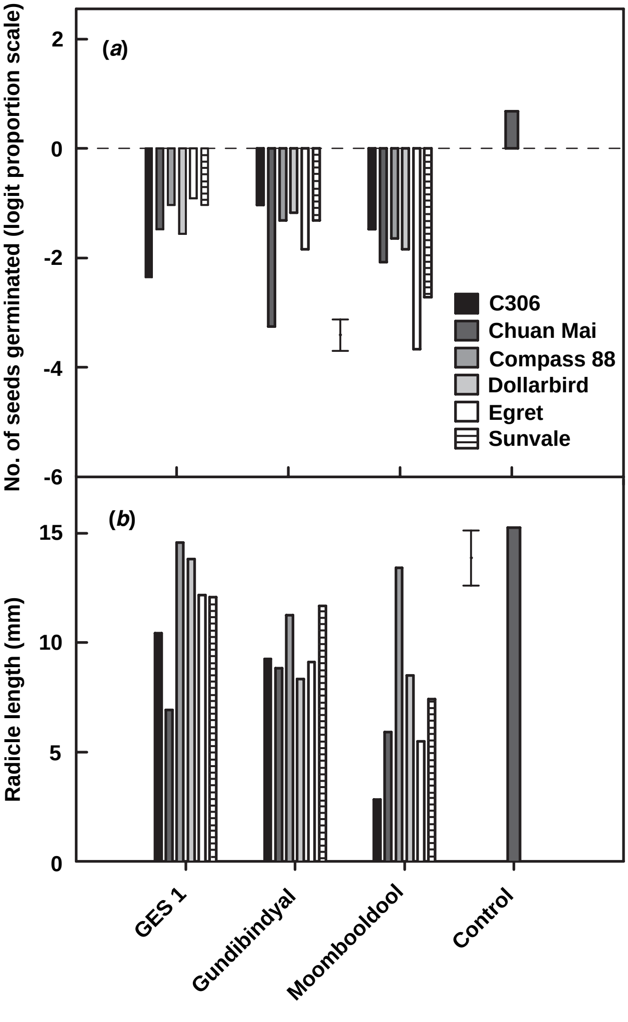

Figure 4. The effect of (*a*) cultivar and site on seed germination at 48 h; and (*b*) cultivar and site on radicle elongation of canola (cv. Oscar) grown in petri dishes and treated with leachates from stubble collected from the GES 1, Gundibindyal and Moombooldool sites. The vertical bars indicate the s.e.d. Note that the s.e.d. presented for (*a*) is used for determining the difference between the treatments and excludes the control. Due to the small number of replicates of the control, the s.e.d. between the control and the treatments is determined for (*a*) as $\text{s.e.d.}_{\text{control}}$ = 0.635.

Discussion

The impact of wheat stubble on canola growth and yield

This work has quantified the impact of surface-retained wheat stubble on seedling emergence, growth and yield of canola in southern NSW. Increasing stubble loads reduced emergence, growth and in some instances yield. At stubble loads less than 3–4 t/ha, impacts were sometimes not different to the bare or burn treatments, but this varied with site and season. These results are consistent with reports of fewer negative impacts of wheat stubble observed in lower rainfall areas of Victoria and South Australia, where yields of wheat are generally between 1 and 3 t/ha resulting in stubble loads less than 4 t/ha (Bruce 2003).

In general, the rate of seedling emergence and plant establishment was lower in the presence of stubble and was reduced with increasing stubble quantity, which is consistent with other studies on canola (Azooz and Arshad 1998) and other species (Arshad *et al*. 1995; Jessop and Stewart 1983; Kimber 1973). In contrast, the level of decomposition and stubble cultivar had no impact on emergence. On average, the rate of emergence was reduced by 25% and plant establishment was reduced by 33% by 5 t/ha stubble. In the Harden experiment in 1999 and at GES 2 in 2000, emergence decreased as the amount of stubble increased. However, at stubble loads ≤4 t/ha there was either no effect or a positive effect on plant establishment. Thus, it seems likely that stubble loads ≤4 t/ha should not pose problems for emerging seedlings, although it is likely that the mechanism of impact of stubble may be dependent on environmental conditions.

The impact of wheat stubble on canola growth was generally consistent with the impact on emergence, although even low stubble loads (<4 t/ha) caused some growth reduction. Development was delayed due to slower emergence, and leaf area and biomass were reduced and hypocotyls were longer in the presence of stubble. At Harden in 1999, these differences had diminished by flowering, presumably due to the relatively high plant populations (>50 plants/m^2) and favourable seasonal conditions providing an opportunity for compensatory growth. At Gundibindyal and Moombooldool, wheat stubble cultivar influenced canola plant density, shoot biomass and leaf area index (LAI) at stem extension. Most cultivars did not affect plant density, although 3 cultivars reduced plant density at both the sites. A similar trend occurred for shoot biomass and LAI, although the ranking of the cultivars in order of their suppressive effect on growth varied between the 2 sites. Evidence was provided to demonstrate that variation in impacts of different stubble cultivars might arise from both differences in SLD and allelopathic potential of the cultivars.

Overall, the presence of 5–6 t/ha stubble led to a mean decrease in seed yield of 23% at the 5 sites, while stubble cultivar had no impact on seed yield at any of the sites. The lower seed yields of canola associated with retained wheat stubble are likely to be a consequence of the reduced plant density, delayed development, reduced leaf number and area during stem elongation and reduced vegetative biomass, similar to the impacts of sowing late (Hocking and Stapper 2001). At Gundibindyal and Moombooldool in 2000, the early suppression of growth caused by stubble had disappeared at final harvest. Lower than average rainfall during flowering may have been responsible for the lower than expected yields in the bare treatments. It is likely that less water was used before flowering in the stubble-retained treatments than in the bare treatments due to the reduced early vegetative growth, reducing the water stress during flowering. In addition, the surface-retained stubble may have reduced water loss through less evaporation. As plant populations were high (>50 plants/m^2) and moisture availability during pod-filling was probably high, plants under stubble were able to avoid the water stress at flowering and compensate for the reduced early growth to out-yield the bare treatments at Gundibindyal (Potter *et al*. 2001). At Moombooldool, the lack of effect of stubble on yield is likely to have resulted from the warmer conditions in this environment, reducing seedling loss during winter and increasing seedling vigour, and thereby reducing the impact of slower early growth. It is clear that seasonal conditions can interact with stubble management to influence the impact of wheat stubble on canola seed yield.

Possible mechanisms for growth reduction

Several potential mechanisms for growth reduction caused by retained stubble were observed in these experiments including changes in temperature, the quality

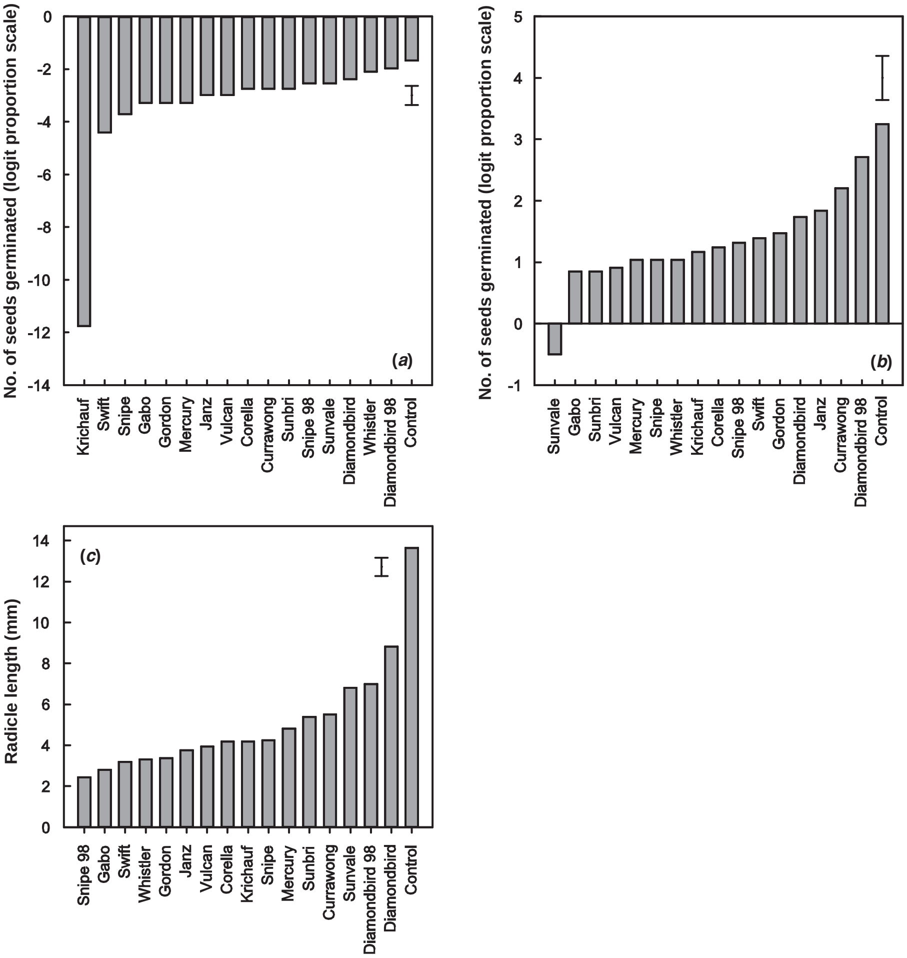

Figure 5. The effect of wheat cultivar leachates from stubble collected from GES 2 on canola cv. Oscar seed germination at (*a*) 48 h and (*b*) 120 h; and (*c*) radicle elongation after 72 h. The vertical bars indicate s.e.d.

and quantity of light penetrating the stubble and allelopathic effects of stubble leachates.

Extremes in temperature were recorded at the surface of the stubble at GES 1 and in some instances temperatures below zero were recorded. Low temperatures may result in seedling death and may explain the low seedling densities recorded in stubble at GES 1 (Itzhaki *et al*. 1991). In one instance at GES 1, temperatures at dawn were as low as –6.8°C on the surface of the stubble, 3.8°C cooler than the surface of the adjacent bare ground. Low temperatures have also been found to reduce photosynthesis and relative growth rates in spring-type rape (Hurry *et al*. 1995) and other species (Ball *et al*. 1991, 1997), which may partly explain the slower rates of emergence in the stubble treatments. Unlike wheat, the growing meristem of canola at this stage of growth is positioned aboveground and is not insulated by the stubble, and is exposed to greater temperature variation. However, temperature alone cannot explain all of the early growth reductions observed. For example, at Moombooldool and Gundibindyal in 2000, minimum temperatures on the surface of the stubble were similar to those for bare ground, but both sites had poor early growth of canola through stubble, indicating that other factors played a more important role in early growth suppression at these sites. Sowing times in southern NSW typically extend from early to mid-June; therefore, it is likely that if sown early while temperatures are warmer, these problems may be reduced.

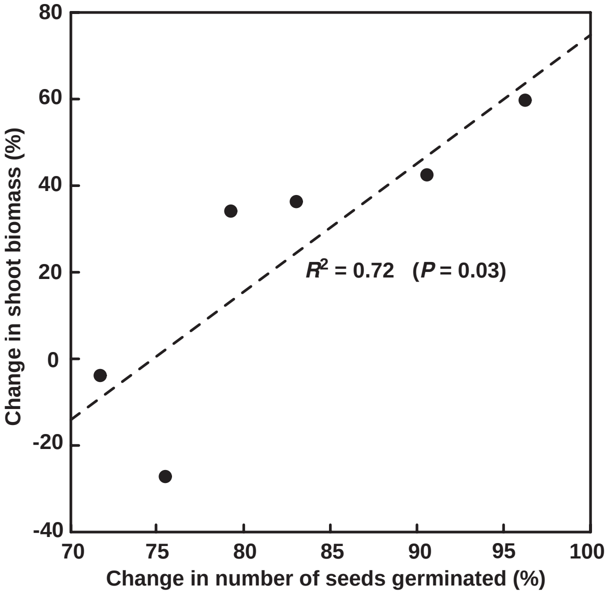

Figure 6. The relationship between the percentage change in the number of seeds germinated at 48 h in stubble leachates and the percentage change in shoot biomass (g/m^2) for Moombooldool at stem extension in stubble treatments. The R^2 and P values for the linear regression are presented. All data are the percentage change from the bare and control treatments.

The relationship between the SLD of wheat stubble cultivars and plant density at Moombooldool and Gundibindyal suggests that changes in the quantity or quality of light penetrating the stubble may have an influence on emergence of the canola seedlings. As similar amounts of stubble by weight were retained for each cultivar, the plots with lower SLD stubble would have had more pieces of straw per unit area, potentially decreasing the availability and spectral quality of light, possibly resulting in reduced plant density at Gundibindyal and Moombooldool. In addition, stubble-retained plots generally produced plants with longer hypocotyls. Elongation of hypocotyls is known to be induced by a reduction in the red:far-red ratio (R:FR) of incident light (Ballare *et al*. 1991), which is a potential impact of surface-retained stubble. The diversion of resources to the elongation of the hypocotyl required to penetrate the stubble layer may have contributed to the delay in dry matter accumulation and may partly explain the poor growth and yield of canola in the stubble-retained treatments, and the greater impacts observed as the stubble load increased.

Phytotoxins in leachates from some wheat stubble cultivars delayed germination and reduced radicle elongation of canola (cv. Oscar) in the laboratory, although those from Moombooldool appeared to be the most suppressive. Endogenous phytotoxins may be influenced by the environmental conditions during the growth of the plant (Einhellig 1996; Rice 1984) and increased water stress at the drier Moombooldool site may have increased the toxicity of the leachates from wheat cultivars grown there. Variation in canola shoot biomass at Moombooldool was correlated with the variation in germination at 48 h caused by the phytotoxins in the wheat stubble leachates from the site, suggesting allelochemicals may be partly responsible for the growth reductions observed at that site. There was further evidence that allelochemicals may play a role in plant response at GES 2, where 6 t/ha of undecomposed stubble reduced growth and yield more than 6 t/ha of decomposed biomass despite similar numbers of plants established and no significant difference in hypocotyl length (Table 5). It is possible that the leachates from the undecomposed residues had an allelopathic impact on seedling growth that had diminished in the decomposed stubble. The lack of cultivar correlations for this site or from Gundibindyal suggests that other factors may have been playing a more significant role in the growth suppression at those sites. The lack of significant correlation between the impact of laboratory leachates on radicle elongation and the impact of stubble in the field, may arise for a number of reasons: (i) the leachates reduced radicle length in the field but this reduced radicle length did not contribute to the poor growth in the field; or (ii) the leachates were modified by soil microorganisms or adsorbed onto soil colloids in the field environment and did not affect radicle growth; or (iii) the concentrations leached under field conditions were too low to cause a growth reduction.

Conclusions

The work reported has confirmed that wheat stubble loads common in many areas (above 3–4 t/ha) can reduce emergence, growth and in some cases yield of canola. The work has also demonstrated that increasing stubble load or decreasing SLD (i.e. thinner straw) of the stubble results in reduced canola establishment and biomass accumulation, and is associated with elongated hypocotyls, presumably due to impacts on light penetration to the seedlings. The impact of wheat stubble varies between environments and may be worse in colder environments due to slow growth rates and increased likelihood of frosts above the stubble layer, especially if crops are sown late. The release of allelochemicals may play a role in growth suppression, although this seems to be influenced by environmental conditions. Further studies using more appropriate methods to separate allelopathic interference from other effects of stubble on seed-bed microclimate and from other potential growth inhibiting factors, such as nitrogen tie-up, are necessary to assess the importance of allelopathy in the observed plant responses.

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