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Delving of sandy surfaced soils reduces frost damage in wheat crops

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Abstract. Delving is a farming practice involving the mixing of a deep clayey subsoil layer with a sandy topsoil. One of the many effects of this practice is to reduce soil albedo and increase water-holding capacity of the topsoil, thus increasing the potential for storage and release of heat and potential attenuation of the effects of radiative frost. At Keith, a frost-prone location of South Australia, we investigated the effect of management practices with putative capacity to reduce frost damage, with emphasis on delving. Three field experiments were established on Brown Sodosols with a water-repellent sand topsoil.

In relation to crops in untreated control soil, delving increased wheat yield from 1.9 to 3.1 t/ha in 2003, and from 0.5 to 1.5 t/ha in 2004. This large delving effect contrasted with the minor effects of other treatments including soil rolling, sowing rate, row spacing, and cultivar mixture. Lack of significant interactions between treatments indicated a robust response to delving across a range of management practices.

Topsoil and canopy-height minimum temperatures were consistently higher in the delved treatment. The average difference in canopy-height minimum temperature between delved and control treatments was 0.3–0.4°C, with a maximum of 1.6°C in 2003 and 1.2°C in 2004. A single, robust relationship between yield and frost damage fitted the data pooled across treatments and seasons. This, together with the temperature differential between treatments, and significant relationships between minimum canopy-height temperature around flowering and frost damage supported the conclusion that a substantial part of the yield gain attributable to delving was related to reduced frost damage.

Additional keywords: yield, protein, grain number, grain size, temperature, canopy.

Introduction

Frost around flowering reduces wheat yield by reducing grain set and harvest index, whereas frost during grain filling may reduce grain size (van Herwaarden and Passioura 2001; Snyder and Melo-Abreu 2005). Manipulation of timing of flowering, through selection of cultivars and sowing date, is the single most important element of frost risk management in cereals and other annual crops. In many cases, however, there is a trade-off between yield losses associated with late sowing (e.g. Batten and Khan 1987) and reduced frost risk at critical reproductive stages. Using climate records (1957–2000) for south-eastern Australia, modelled flowering date, and a Type I extreme value probability density function (Snyder and Melo-Abreu 2005), it was estimated that the probability of below-zero screen temperature around flowering ranges from 5 to 13% for wheat sown in mid May (V. O. Sadras, unpublished).

Several practices have been identified with potential application to mitigate yield losses caused by frost in extensive cropping systems. Spreading risk by manipulation of crop phenology can be achieved by combination of cultivars and sowing date at the farm or paddock scale, e.g. sowing a mixture of cultivars. In addition to phenology, other traits that may be related to frost tolerance include the presence of awns, glaucosity, and glume pubescence (Maes *et al*. 2001; Whaley *et al*. 2004). In cultivated soil, rolling to break up clods and compact topsoil could improve heat storage and transfer by decreasing soil porosity and increasing its thermal conductivity and heat capacity (Snyder and Melo-Abreu 2005). Spreading dark substances on topsoil to reduce albedo and increase heat storage has been used with some degree of success in orchards (Sharratt and Glenn 1986, 1988*a*, 1988*b*). Under radiative frost (net radiation = –60 $\mathrm{W\,m^{-2}}$), coal dust spread on an orchard soil in West Virginia (USA) enhanced radiative loss by 5 $\mathrm{W\,m^{-2}}$, increased air temperature by 1°C and peach bud temperature by 0.5°C (Sharratt and Glenn 1986). Very small changes in minimum temperature at the ear level may have dramatic effects on wheat grain set (Marcellos and Single 1984; Maes *et al*. 2001). It is generally assumed that lower plant population density may reduce frost damage for reasons related to phenological development, tillering, canopy cover, and canopy architecture, but experimental evidence is inconclusive (Whaley *et al*. 2004).

Soils with sandy surface horizons and clayey subsoils are widespread in the Australian wheatbelt (Hamblin *et al*. 1988; Harper and Gilkes 2004). In some of these sandy soils, hydrophobic particulate organic matter induces water repellency (Franco *et al*. 1995), low infiltration rates, and preferential flow paths (Harper and Gilkes 1994; Ritsema and Dekker 1996). To increase the clay content of these sandy topsoils, the practice of delving involves the use of specialised cultivation equipment

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to bring more clay materials to the soil surface (Harper and Gilkes 2004). Some potential, largely undocumented, effects of this practice are reduced albedo, increased water-holding capacity and, in non-wetting sands, increased hydraulic conductivity. Collectively, this may increase the potential for storage and release of heat and potential attenuation of the effects of radiative frost.

In this study, we experimentally assessed a number of management practices with potential to mitigate frost damage in wheat grown on sandy surfaced soils in South Australia. Particular emphasis was placed on delving because there are growers interested in this practice and its actual effects on frost damage are largely unknown.

Methods

Three experiments were established between 2003 and 2005 on a Brown Sodosol (Isbell 1996) in a farm close to Keith (36°S, 140°E; 98 m a.s.l.), a frost-prone location in South Australia. Delving treatments were established in the year prior to the experiment. In 2003 and 2004, the delving machine comprised three 1.3-m spaced blades (150 mm wide, 480–720 mm deep). The effects of delving on soil profiles were similar in 2003 (not shown) and 2004 (Table 1), including a substantial mixing of the topsoil, doubling the proportion of clay in the top 0.2 m. In 2005, a deep-ripper was used with smaller blades (80 mm wide, 600 mm deep); this treatment brought up less clay than the delver but allowed clay to be ripped and some sand to drop into the cracks (not shown). A range of secondary treatments was combined with delving in each season. Weeds were controlled with glyphosate (1 L/ha) and trifluralin (1 L/ha).

2003 experiment

Wheat crops were sown on 17 June and fertilised with 80 kg DAP per ha at sowing. A factorial experiment combined 3 cultivar variants (Krichauff, Yitpi, and a mixture of both), 2 sowing rates (50 and 100 kg/ha), and 2 soil treatments (delved and control). Krichauff and Yitpi are commonly used in the region, and are usually sown at 90 kg/ha. Treatments were arranged in a split-plot design with 3 replicates. Soil treatment was assigned to main plots, and sowing rates and cultivar variants to subplots. Each individual plot was 9 by 12 m.

2004 and 2005 experiments

Wheat (cv. Wyalkatchem) was sown on 17 June 2004 and 24 June 2005. Fertiliser, 80 kg DAP per ha, was applied at sowing. A factorial experiment combined 2 row spacings (0.2 and 0.4 m), 2 rolling treatments (rolled and unrolled), and 2 soil treatments (delved and control). Rollers consisted of sets of car tyres in tandem behind the seeder. Treatments were arranged in a split-plot design with 3 replicates. Soil treatment was assigned to main plots, and row spacing and rolling treatments to subplots. Each individual plot was 9 by 12 m.

Measurements and analyses

Temperature was measured and logged at 15-min intervals during the growing season using a system of individually calibrated thermistors (650 7A) and dataloggers (Unidata 6004–11) by Measurement Engineering Australia (Magill, South Australia). Measurements were taken at canopy height and on the soil surface in each plot. To measure canopy-height temperature, sensors were mounted on wooden frames and moved up during the season to account for canopy growth. At maturity, plots were harvested with a 1.65-m-wide header to determine grain yield. Protein content (near infrared spectrophotometer Perten DA7000) and individual grain weight were measured in subsamples.

Prior to harvest, 30 randomly selected heads per plot were examined and frost damage was calculated as the ratio between number of aborted grains and number of florets. As symptoms of frost could be confounded with those of heat stress, we evaluated

Table 1. Profiles of delved (D) and control (C) soils at Keith in 2004

Depth (m)	ECe (mS/cm) D	ECe (mS/cm) C	pH 1 : 5 CaCl$_2$ D	pH 1 : 5 CaCl$_2$ C	Coarse sand[A] (%) D	Coarse sand[A] (%) C	Fine sand[B] (%) D	Fine sand[B] (%) C	Silt[C] (%) D	Silt[C] (%) C
0.0–0.05	0.93	0.70	6.0	5.4	32.2	38.9	55.9	54.0	0.0	1.0
0.05–0.10	1.82	0.66	6.1	–	22.9	36.6	36.0	45.5	2.0	1.0
0.10–0.20	1.43	0.46	6.5	6.1	18.8	30.6	27.9	39.6	3.0	3.0
0.20–0.40	1.15	0.52	6.7	6.4	22.3	22.5	32.5	38.5	1.0	1.0
0.40–0.60	0.98	1.27	7.4	7.1	28.5	21.4	35.0	43.0	1.0	1.0

Depth (m)	Clay[D] (%) D	Clay[D] (%) C	PAW[E] (mm) D	PAW[E] (mm) C	UL[E] (mm) D	UL[E] (mm) C	Water repellence[F] D	Water repellence[F] C
0.0–0.05	12.0	6.0	3.7	3.6	8.5	6.7	N	S
0.05–0.10	39.1	16.8	4.3	3.8	15.0	9.8	N	R
0.10–0.20	50.4	26.8	9.6	8.2	36.4	23.9	N	N
0.20–0.40	44.1	38.1	17.6	15.3	64.8	75.2	N	N
0.40–0.60	35.5	34.6	16.4	16.4	55.4	55.4	N	N

[A] 200–2000 mm. [B] 20–200 mm. [C] 2–20 mm. [D] <2 mm.

[E] Maximum plant-available water (PAW) and drained upper limit (UL) estimated as a function of texture using CropSyst (version 3.4.8) functions (http://c100.bsyse.wsu.edu/cropsyst/).

[F] N, Non-water-repellent (water is absorbed into soil in 10 s or less); R, water repellent (water takes more than 10 s and 2-M ethanol takes 10 s or less to be absorbed); S, strongly water repellent (2-M ethanol takes longer than 10 s to be absorbed) (McDonald *et al.* 1990).

the soundness of this measure of frost damage considering: (*a*) occurrence of hot days, i.e. maximum temperature above 31°C (Wheeler *et al*. 1996) in the 4-week period centred on anthesis, and (*b*) the relationships between frost damage score and minimum temperature around flowering. The wheat module in APSIM (Keating *et al*. 2003) was used to estimate flowering time using locally calibrated parameters for the cultivars in each experiment and temperature data from Keith (Australian Bureau of Meteorology Station 025507).

Statistical effects of treatments on response variables were assessed with ANOVA, and regression analysis was used to explore links between variables. Frost damage was logit transformed prior to statistical analysis (Dyke 1997), but percentages are reported for better interpretation.

Results

Overview

Grain yield averaged 2.5 t/ha in 2003, 1.0 t/ha in 2004, and 3.4 t/ha in 2005. Rainfall and evaporative demand in the critical months of September and October partially accounted for the 3-fold range in seasonal yield (Table 2). In 2003 and 2004, there were severe frosts around flowering, which substantially reduced grain yield. Crops in delved soil consistently out-yielded their counterparts in untreated soil (Table 3, Fig. 1). All other treatments had negligible effects on yield, frost damage (Table 3), and soil and canopy temperature (not shown). A marginal benefit of soil rolling in 2004 (Table 3) warrants further, better focussed research on this practice. In 2005, none of the treatments affected grain yield (Table 3); the lack of yield response to delving was partially attributable to our failure to properly establish the treatment. Hereafter, we concentrate on the effects of delving in 2003 and 2004.

Grain yield and its components

In 2003, crops in delved soil yielded 3.1 ± 0.11 t/ha compared with crops in untreated soil, which produced 1.9 ± 0.14 t/ha. In 2004, crops in delved soil yielded 1.5 ± 0.05 t/ha compared with crops in untreated soil, which produced 0.5 ± 0.05 t/ha. A number of factors may mediate the effect of delving on yield, including change in soil surface colour and temperature, increased availability of nutrients and water, and reduction of soil mechanical impedance. The relationships between grain yield

Table 2. Meteorological conditions during the experiments

Variable	Season	June	July	Aug.	Sept.	Oct.	Total June–Oct.
Average solar radiation (MJ/m^2.day)	2003	7.9	9.7	11.4	15.4	19.2	
	2004	8.1	8.3	11.7	14.6	20.6	
	2005	8.6	9.1	11.4	15.5	19.0	
Average max. temp. (°C)	2003	15.9	15.5	15.2	17.4	18.7	
	2004	16.0	14.3	16.7	17.8	23.2	
	2005	17.0	15.6	16.7	18.4	21.1	
Average min. temp. (°C)	2003	7.9	5.6	5.9	6.7	6.9	
	2004	8.1	6.0	6.9	7.1	8.1	
	2005	6.8	6.2	7.0	7.4	9.0	
Rain (mm)	2003	96	54	73	42	39	304
	2004	71	62	64	34	15	246
	2005	76	31	72	36	88	303
Reference evaporation (mm)	2003	49	53	68	95	119	384
	2004	54	50	75	77	160	416
	2005	52	46	85	90	130	403

Table 3. *P*-values from ANOVA for the field trials at Keith

Second- and third-order interactions were not significant: $P > 0.12$ in 2003, $P > 0.20$ in 2004, $P > 0.75$ in 2005

Season	Source of variation	Grain yield	Grain number	Individual grain weight	Grain protein concentration	Frost score[A]
2003	Soil treatment (delved *v*. control)	<0.0001	<0.0001	0.03	<0.0001	<0.0001
	Sowing rate (50 *v*. 100 kg/ha)	0.56	0.29	0.08	0.50	0.63
	Cultivar variant (Krichauff, Yitpi, mixture)	0.15	0.75	<0.0001	0.01	0.04
2004	Soil treatment (delved *v*. control)	<0.0001	<0.0001	0.02	<0.0001	<0.0001
	Row spacing (0.2 *v*. 0.4 m)	0.56	0.35	0.45	0.80	0.48
	Rolling (rolled *v*. control)	0.06	0.08	0.23	0.09	0.09
2005	Soil treatment (delved *v*. control)	0.21				0.44
	Row spacing (0.2 *v*. 0.4 m)	0.44				0.15
	Rolling (rolled *v*. control)	0.76				0.51

[A] Frost scores (fractions) were logit transformed for analysis.

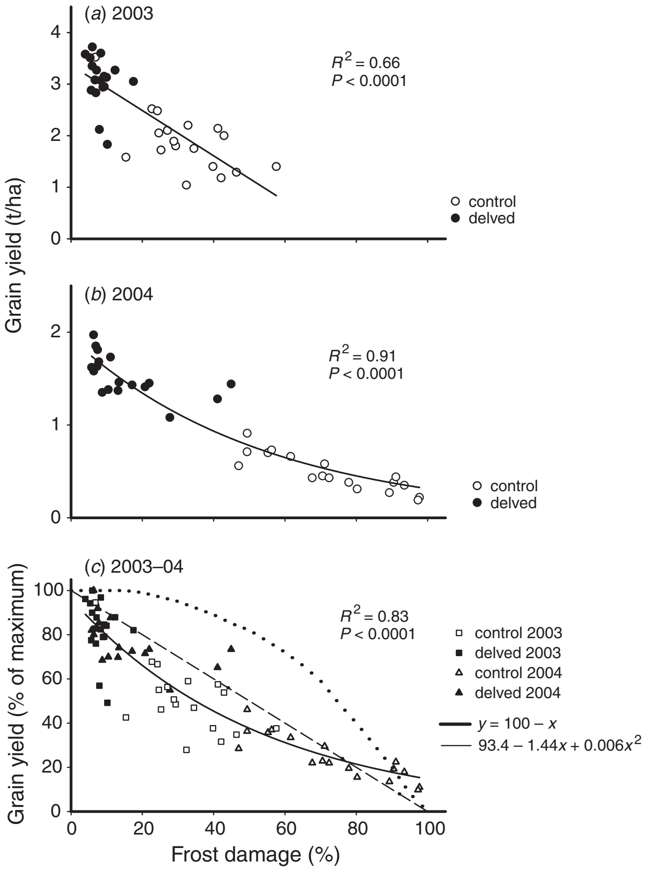

Fig. 1. Relationships between grain yield and frost damage at Keith in (*a*) 2003, (*b*) 2004, and (*c*) 2003–04 combined using a normalised yield scale. Solid lines are fitted regressions. In (*c*) the dashed line represents perfect proportionality between damage and yield loss, i.e. 1% damage causes 1% yield loss, and the dotted curve shows hypothetical compensation as proposed by Sadras *et al.* (1999).

and its components, and frost damage indicated that a substantial part of the effect of delving in our experiments was related to reduced frost damage (Figs 1 and 2). In 2003, frost damage in crops grown in delved soil was typically below 20%, whereas in their counterparts in untreated soil it ranged from 20 to 60% (Fig. 1*a*). In 2004, frost damage for crops in delved soil ranged from 6 to 45% compared with their counterparts in untreated soil with damage between 47 and 98% (Fig. 1*b*). Pooling the data of both seasons, frost damage accounted for 83% of the variation in grain yield (Fig. 1*c*). Grain number accounted for most of the variation in grain yield (Table 3, Fig. 2). Grain size contributed to further reduction in yield of crops where frost damage was over 50%.

Grain protein concentration

Grain protein concentration increased with frost damage (Fig. 3). The effect of frost on protein concentration was accounted for by the inverse relationship between yield and frost damage (Fig. 1) and the inverse relationship between yield and protein concentration (2003: $r = -0.71$, $P < 0.0001$; 2004: $r = -0.94$, $P < 0.0001$).

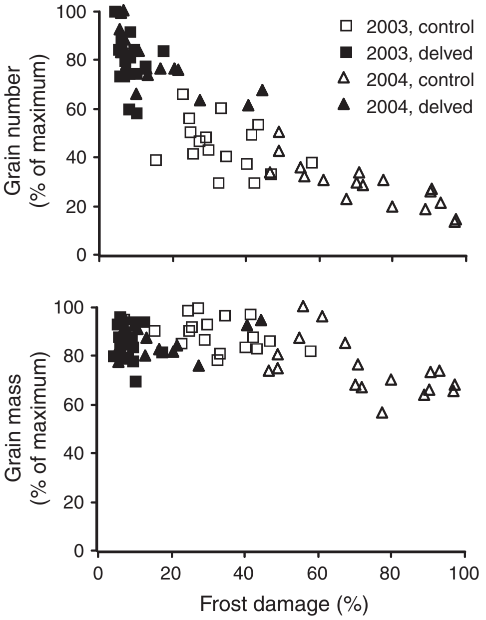

Fig. 2. Grain number and individual grain mass as a function of frost damage for wheat crops at Keith in 2 seasons. A normalised scale is used to account for differences between seasons. Maximum grain number was 10312/m^2 in 2003 and 4842/m^2 in 2004; maximum grain mass was 43.4 mg/grain in 2003 and 44.7 mg/grain in 2004.

Soil and canopy-height temperature

Figures 4*a*, *b* and 5*a*, *b* show the seasonal dynamics of minimum temperature at canopy height and soil surface. In control crops, there were 26 days when canopy-height minimum temperature was below 0°C in 2003 (Fig. 4*a*) and 21 days in 2004 (Fig. 5*a*).

Soil and canopy-height temperature were consistently higher in the delved soil treatment (Figs 4*c*, *d* and 5*c*, *d*). The average difference in canopy-height minimum temperature between delved and control treatments was 0.3–0.4°C, with a maximum of 1.6°C in 2003 and 1.2°C in 2004.

In the 4 weeks bracketing flowering, canopy-height temperature was below 0°C on 12 days in 2003 and on 5 days in 2004. These low-temperature events were consistently less severe in the delved treatment (Figs 4*e*, 5*e*). In the week prior to flowering, there were no records of maximum screen temperature above 31°C in 2003, and maximum temperature above this threshold for pollen sterility (Wheeler *et al.* 1996) was recorded on 2 days in 2004 (Figs 4*f*, 5*f*). Hence, low and high temperature around kernel set could be confounded in our scoring of 'frost' damage, particularly in 2004. There was, however, a significant correlation between percentage frost damage and the lowest temperature at canopy height in the critical period of 4 weeks around flowering (Fig. 6). This supports the interpretation that frost damage scores were primarily reflecting this phenomenon in our experiments.

Discussion

Effect of delving on temperature, frost damage, and yield

We found a consistent increase in grain yield of wheat crops grown in delved soil, with minor effects of other treatments

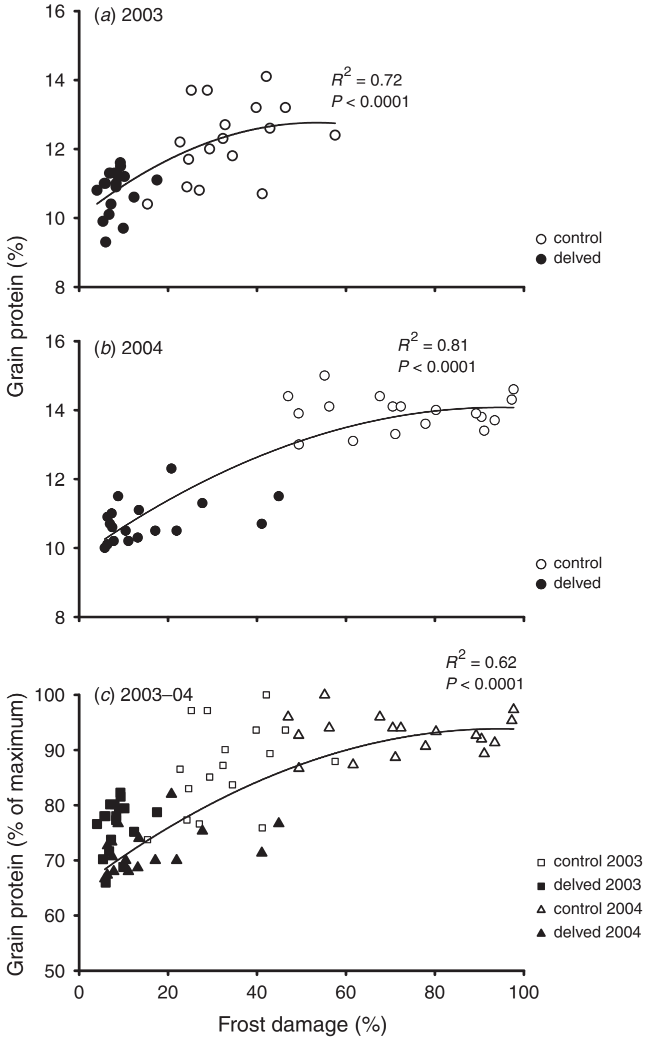

Fig. 3. Relationships between grain protein and frost damage at Keith in (*a*) 2003, (*b*) 2004, and (*c*) 2003–04 combined using a normalised scale. All fitted functions are quadratic.

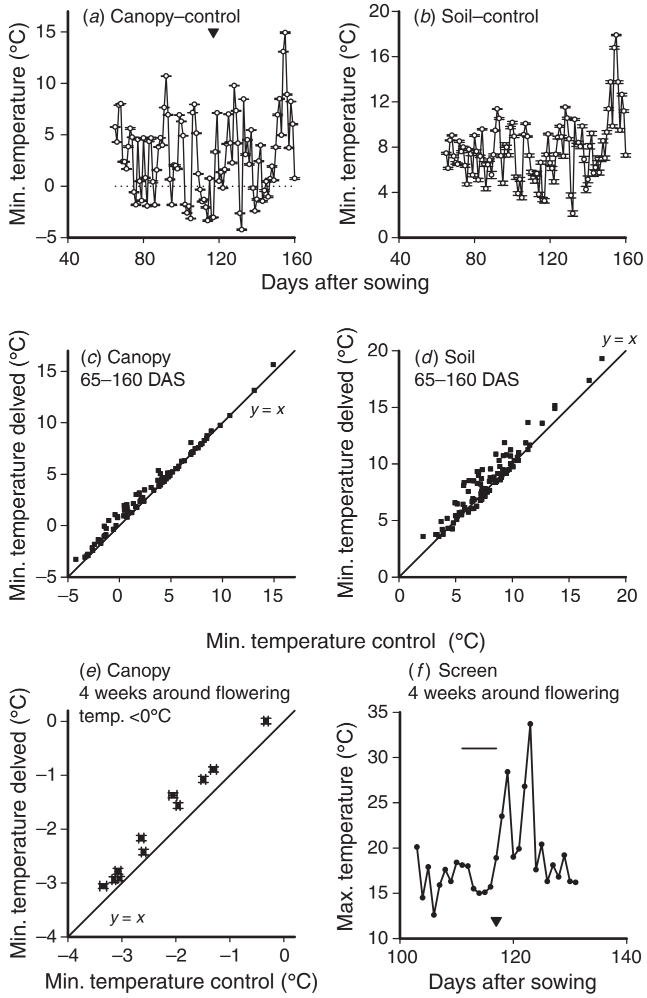

Fig. 4. Soil and canopy temperature in 2003. Seasonal dynamics of (*a*) canopy height and (*b*) soil surface temperature in control plots. Comparison of minimum temperature at (*c*) canopy height and (*d*) soil surface measured in delved soil and controls during the period 65–160 days after sowing. (*e*) Comparison of below-zero minimum temperature at canopy height between delved soil and controls during 4 weeks centred on anthesis. (*f*) Maximum temperature around flowering measured in a meteorological station at Keith. In *a*–*e*, each point is the average of 12 measurements resulting from pooling all treatments except delved and control. In (*a*), (*b*), and (*e*), error bars are 2 standard errors of the mean. In (*a*) and (*f*), arrowheads indicate flowering. In (*d*) the horizontal line highlights critical temperature for pollen sterility in the week prior to flowering (Wheeler *et al.* 1996). Flowering time was estimated with the APSIM model.

including rolling, sowing rate, and cultivar mixture. Importantly, lack of significant interactions between treatments indicated a robust response to delving across a range of management practices. Three putative factors may account for the yield benefits of delving: (*i*) increased water and nutrient availability in topsoil, (*ii*) reduced mechanical impedance due to soil ripping, and (*iii*) reduced frost damage. Lack of background measurements (e.g. harvest index, soil water, and nutrients) precludes a definite allocation of effects to each of these factors. Based on the following arguments, however, we propose that reduced frost damage accounted for a substantial part of the delving effect in our experiments.

First, the magnitude of yield response, up to 3-fold, is incommensurate with the relatively minor effect in water and nutrient availability expected from re-distribution of clay in the topsoil (Table 1). Estimates of maximum soil plant-available water for the experiment in 2004 (Table 1), and a yield-water ratio of 20 kg grain/ha.mm, indicate negligible differences between treatments, in the order of 80 kg/ha. In a toposequence in Western Australia, increasing the depth of the sandy horizon from 0.6 to 1.3 m reduced biomass in 3 out of 7 cases, and had no significant effect on grain yield in any of 7 cases resulting from the combination of crop species and seasons (Hamblin *et al.* 1988). This suggests that the nutrient and plant water availability component of delving in our study, if any, was minor. Increased infiltration rate expected from claying (Harper and Gilkes 1994) and greater water-holding capacity in the top 0.20 m of soil (Table 1) may have contributed to water and hence heat storage.

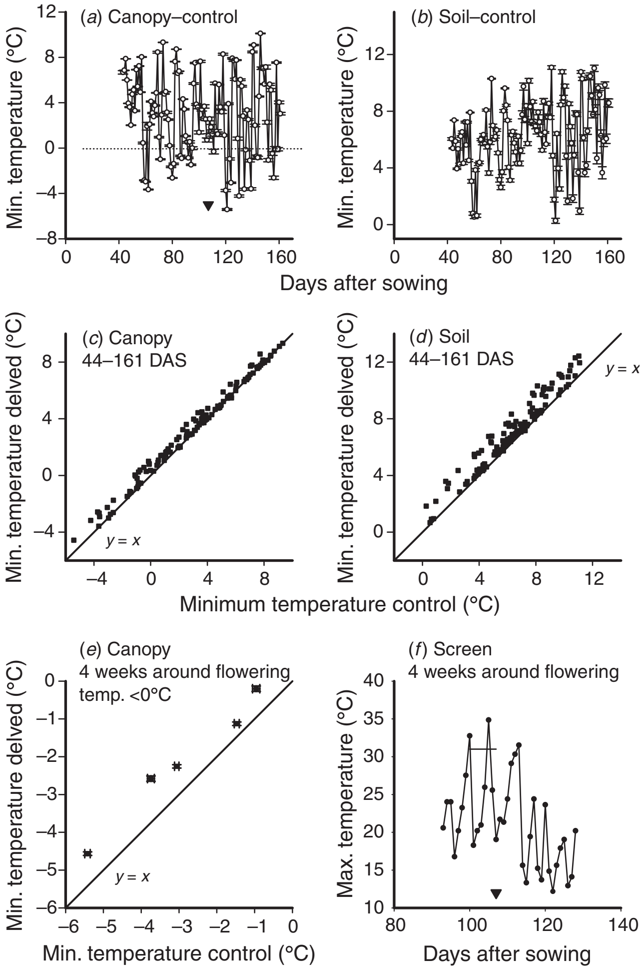

Fig. 5. Soil and canopy temperature in 2004. Seasonal dynamics of (*a*) canopy height and (*b*) soil surface temperature in control plots. Comparison of minimum temperature at (*c*) canopy height and (*d*) soil surface measured in delved soil and controls during the period 44–161 days after sowing. (*e*) Comparison of below-zero minimum temperature at canopy height between delved soil and controls during 4 weeks centred on anthesis. (*f*) Maximum temperature around flowering measured in a meteorological station at the field site. In *a*–*e*, each point is the average of 12 measurements resulting from pooling all treatments except delved and control. In (*a*), (*b*), and (*e*), error bars are 2 standard errors of the mean. In (*a*) and (*f*), arrowheads indicate flowering. In (*d*) the horizontal line highlights critical temperature for pollen sterility in the week prior to flowering (Wheeler *et al.* 1996). Flowering time was estimated with the APSIM model.

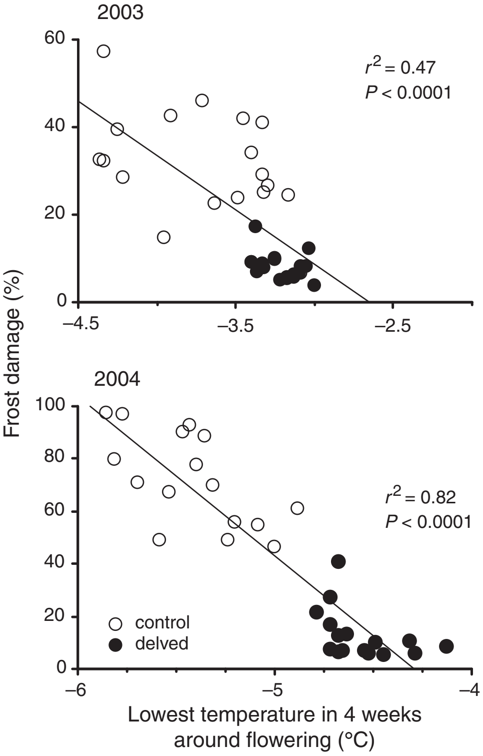

Fig. 6. Relationship between frost damage and the lowest canopy-height temperature in the 4 weeks around flowering for crops at Keith in 2003 and 2004. The fitted lines are: $y = -66.1 - 24.9x$ (2003) and $y = -260.1 - 60.7x$ (2004).

Second, the delving treatment, in addition to lifting clay from the subsoil to the soil surface, might have alleviated subsoil compaction. In sandy-loam Mallee soils, deep ripping could increase wheat grain yield by up to 40% (Sadras *et al.* 2005). Thus, part of the effect of delving in our study may be attributable to its effect on soil impedance. Reduction of soil compaction favours yield primarily through improved canopy cover and capture of radiation (Sadras *et al.* 2005), but the influence of canopy cover on frost remains elusive (Whaley *et al.* 2004).

Third, detailed measurements of soil and canopy temperature, frost scores, and grain yield provided direct evidence of an important alleviation of frost in crops grown in delved soil. Importantly, the magnitude of the increase in canopy-height temperature attributable to delving, on average 0.4°C with a maximum of 1.2–1.6°C, was sufficient to substantially improve kernel set and yield (Marcellos and Single 1984; Maes *et al.* 2001). The increase in temperature associated with delving in our study was comparable with the increase in temperature associated with coal dust spread on orchard soil reported by Sharratt and Glenn (1986). The relationship between minimum temperature around flowering and frost score, together with the few episodes of heat stress around flowering, supports the validity of our measure of frost damage. Frost damage, in turn, accounted for most of the variation in grain yield, with a clear discrimination between delved and undelved controls in the relationship between frost damage and yield. The weakest point in this otherwise strong set of relationships is the lack of actual observations of flowering date. To account for both the critical period of grain yield determination (Fischer 1985) and the error in flowering date estimated with a phenology model, we used a 4-week window around the time of simulated flowering date. The root mean square error of phenological stage simulated with APSIM is around 4 days for normal sowing dates (Asseng *et al.* 1998, 2000) but is larger for unusually early or late sowing (Stapper and Lilley 2001). Although critical experiments are required for a conclusive isolation of the components of delving affecting grain yield (e.g. response to delving in the absence of frost), indirect and direct evidence in this study supported the notion that delving can contribute substantially to yield stability in frost-prone areas.

General relationships between temperature, frost damage, and grain yield

Across seasons and treatments, there was a unique, robust relationship between grain yield and frost damage (Fig. 1*c*). The non-linear function fitted to the data could have practical application, such as providing the basis to estimate yield losses attributable to frost for insurance purposes. At the ear level, Marcellos and Single (1984) identified a compensatory mechanism whereby the reduction in kernel set in dominant ear positions enhanced setting of kernels in secondary positions. For mild frost around flowering, it may also be possible that increased grain size could partially compensate for reduced kernel set. In our field study, these mechanisms did not seem relevant, as the yield–frost relationship was well below a hypothetical curve of compensatory response, and even below the reference line of perfect proportionality ($y = 100 - x$, Fig. 1*c*). The robustness of the relationship between yield and frost damage contrasts with the strong seasonal effect on the relationship between minimum temperature and frost damage (Fig. 6). Whereas frost damage increased linearly with decreasing minimum temperature in both seasons, the parameters of the fitted lines were quite different, e.g. the threshold temperature for damage was −2.6°C in 2003 and −4.2°C in 2004. In the experimental conditions of Marcellos and Single (1984), the threshold for grain set reduction was around −3°C. Growing conditions prior to and during frost events underlie this seasonal effect (Vágújfalvi *et al.* 1999; Rapacz 1999; Jacobsen *et al.* 2005). An important corollary of these findings is that frost damage scores could be used with predictive purposes, but strong seasonal effects preclude, at this stage, more mechanistic models involving relational sequences of minimum temperature–frost damage and frost damage–yield.

Acknowledgments

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