Mounting evidence that soil amelioration can contribute to reduced frost severity on water repellent soils

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Key messages

1. Soil amelioration for water repellence in frost prone positions in the landscape reduces frost severity and duration.
2. Soil amelioration may have a role in reducing frost damage in crops, contributing to the yield improvements measured on water repellent soils in frost prone areas.
3. Soil amelioration benefits principally arise from overcoming soil constraints, including water repellence, and benefits from reducing frost damage will be of secondary importance.
4. The mechanism by which soil amelioration reduces the severity of frost is not known and there is no evidence currently to indicate that amelioration of other soils, which aren't repellent, would have any impact on frost severity and crop damage.

Background

In recent years, several anecdotal reports (Fulwood 2013; Williams 2016) and field assessments (Butcher et al. 2017) have suggested that soil amelioration for the management of water repellent soils can potentially reduce crop damage in frost prone areas. This is not a new hypothesis and evidence from previous research in South Australia (Rebbeck *et al.* 2007) have shown the positive effects of claying (by clay delving) in reducing frost damage in wheat. In more recent work by Butcher *et al.* (2017) the evidence gathered was insufficient to prove a direct connection between amelioration of water repellent soils and the reduction in frost severity and duration.

Aim

To collate and assess field research data collected from multiple sites and seasons, to test the hypothesis that amelioration of water repellent soils decreases severity of frost events and subsequent crop damage.

Method

Field trials and soil ameliorations

Three replicated field experiments near Moora, Esperance and Yealering and two large-scale demonstration sites located near Yealering and Wickepin were established between 2015 and 2018, on sandy-textured soils with topsoil water repellence ranging between 'moderate' to 'severe' (Table 1). All trials were conducted with the primary aim of assessing and validating various methods of soil amelioration, involving strategic deep tillage (mouldboard ploughs or rotary spaders) and clay subsoil addition (either by clay spreading or delving), for the management of soil water repellence. These sites are located in the frost prone parts of the landscape, including valley floors.

The experiment at Moora was established in 2016 on a deep yellow sand and the treatments included no-tillage and deep tillage (rotary spader), both in combination with and without the addition of clay-rich subsoil (30% clay content) spread at a rate of 250 t/ha. The Esperance experiment was also established in 2016 on a texture-contrast soil (sand over sodic clay), with deep tillage treatments (rotary spader) tested in combination with and without subsoil delving to bring some of the clay rich subsoil to the surface. The replicated field experiment at Yealering was established in 2018 on a gravelly sandy-loam and included lime spreading and deep tillage (rotary spader) treatments for remediation of subsoil acidity and water repellence.

The demonstration site at Yealering was established in 2014 by the grower with a paddock-length mouldboard plough strip and a neighbouring control strip on a predominantly pale deep sand soil. Ten permanent paired monitoring transects were established. The Wickepin demonstration site, was established by the grower in 2015 and comprised of 3 strips: 1) an untreated control; 2) deep tillage with a rotary spader; 3) deep tillage with a rotary spader after the spreading of a clay-rich subsoil. Four permanent transects were established for monitoring purposes.

Table 1. Description of the sites, soil types and amelioration treatments implemented.

#	Location	Year estab.	Soil type	Design	Amelioration types	Tillage and clay treatment
1	Yealering (Demo)	2014	Pale deep sand to sandy texture-contrast	2 demo strips 10 transects	Deep Tillage	Mouldboard plough
					Deep Tillage + Subsoil Clay	n.a.
2	Wickepin (Demo)	2015	Pale deep sand	3 demo strips 4 Transects	Deep Tillage	Spading
					Deep Tillage + Subsoil Clay	Clay Spreading + Spading
3	Moora	2016	Deep yellow sand	3 reps randomised complete block design	Deep Tillage	Spading
					Deep Tillage + Subsoil Clay	Clay Spreading 250 t/ha + Spading
4	Esperance	2016	Sandy texture-contrast	3 reps randomised complete block design	Deep Tillage	Spader
					Deep Tillage + Subsoil Clay	Clay delving + Spading
5	Yealering (Trial)	2018	Gravelly sandy loam	3 reps randomised complete block design	Deep Tillage	Spading
					Deep Tillage + Subsoil Clay	n.a.

Field Measurements

Plant establishment was determined by plant counts or by green ground cover percentage estimated from aerial imagery (Moora experiment) in order to asses any influence of soil amelioration treatments on plant density. Harvest indexes were determined from biomass cuts while grain yields were measured either by harvest cuts (Yealering and Wickepin) or plot harvesters (Moora and Esperance).

The severity and duration of frost events were monitored at each site during the 2017 and 2018 growing seasons using Tinytag® temperature loggers (TGP-4017). The loggers were set up to measure the air temperature at canopy height every 15 minutes and were placed at the centre of each plot in areas of uniform crop growth. A frost event was defined as having taken place when at least one temperature logger in the trial recorded a zero or sub-zero temperature. Frost duration was analysed by summing total hours below critical temperature thresholds (0, -2, and -4°C), according to the SAGI West protocols used in the GRDC National Frost Initiative (Butcher et al 2017).

Varied approaches were used to assess crop performance and potential frost damage depending on the site, crop and seasons and presented in Tables 4 and 5. In November 2016, barley frost damage at Moora was assessed by measuring floret sterility (FS) from several harvest cuts taken soon after a severe frost event occurred during the flowering window when crop damage became apparent. With non-cereal crops at Moora and Esperance (2017), yield components were used to indirectly indicate potential crop damage due to frost. In 2018, due to technical difficulties, FS on wheat could not be measured at Moora and frost damage was determined by visual assessments of frost affected grains collected at harvest (percentage on 500 grains samples). Frost damage on barley crop at the Yealering demonstration site was also assessed by measuring FS from harvest cuts collected at Z89 (hard dough) in 2016. At the Wickepin demonstration site and Yealering Trial (2018), several yield components were also determined from harvest biomass cuts taken at Z89.

Results

Seasonal conditions and crop establishment

At Moora, there were contrasting seasonal conditions for the growing seasons between 2016 and 2018. The 2016 season was characterised by above-average rainfall, while 2017 experienced below-average rainfall and was particularly dry during seeding and crop emergence (March-June). The 2018 season started similarly to 2017 but eventually ended up with average rainfall. Expression of soil water repellence at Moora was reduced in the wet 2016 season and the amelioration treatments did not significantly improve crop establishment in comparison to the control. In contrast, the dry start in 2017 increased the expression of soil water repellence and the soil amelioration treatments significantly improved lupin establishment (Betti *et al*. 2017 and 2018; Edwards *et al.* 2018). In 2018, deep tillage increased the wheat emergence compared to the control but negative effects were found when the deep tillage was combined with 250 t/ha of clay-rich subsoil. (Table 2)

At Esperance, both 2017 and 2018 seasons experienced dry conditions, particularly during seeding. However, deep tillage (with or without clay delving) did not significantly improve plant establishment. Given the dry conditions at

Wickepin in 2017, plant establishment was significantly higher only in the treatments with added clay-rich subsoil in comparison to the control and deep tillage alone (Davies and Turner 2017). No significant differences in plant establishment were found at Yealering sites in 2018 (Turner 2018).

Frost severity and duration

A summary of the results from the temperature loggers at all the sites is presented in Table 2. At all sites and in all seasons, crop canopies in the ameliorated soils consistently experienced fewer hours below the critical temperatures compared to the untreated control treatments (Table 2).

In 2016 at Moora, data loggers were not installed as the farmer was not aware of the occurrence of frost in that location. Nonetheless, several severe frost events were recorded by field observations during the 2016 season. Consequently, temperature data loggers were installed at Moora and frost events were recorded in August-November 2017 and 2018 respectively (Table 3). In both seasons, the lowest temperatures were found in the control treatment, which experienced significantly more hours below 0, -2, and -4°C when compared to the soil amelioration treatments. Combining subsoil clay with the deep tillage did not significantly impact on the canopy temperatures compared to deep tillage alone. Moreover, in both seasons at Moora, the canopy air temperatures in the ameliorated soil treatments never dropped below -4°C, unlike the control treatment which spent nearly 3 hours below -4 in each season.

The 2017 season at Esperance was particularly severe, recording 27 frost events with minimum canopy air temperatures as low as -8.9 °C in the control treatment (Table 3). The control treatment experienced several hours more below 0, -2, and -4°C when compared to the soil amelioration treatments but the difference was only significant when the deep tillage was combined with clay delving (Table 3). In contrast, no significant difference in the duration of frost was found at Esperance in 2018. However, on average, the control treatment experienced several hours more below the 3 temperature thresholds and its mean lowest temperature (- 6.6°C) was significantly lower than those recorded in the ameliorated soils. On this occasion, lack of significant difference was partially attributed to the high variability in the data.

At the Yealering trial, 30 frost events occurred in 2018 and the soil amelioration significantly reduced frost severity (as minimum air temperatures at canopy height) on ten occasions (Table 3). In general, the control treatments experienced more hours below 0, -2, and -4°C and recorded the lowest temperature. At this site, significant differences in the duration of frost were found only for the number of hours below -4°C (Table 3).

At the Yealering demonstration site (2018), several temperature loggers malfunctioned so that only 2 pairs of loggers out of the five pairs installed could be used for comparisons of the occurrence and duration of frost events between September 17th and November 1st. During this period, 7 frost events occurred and one of the loggers in the control recorded the minimum temperature of -3.9°C. Crops in the ameliorated treatments experienced fewer hours below 0 and -2°C in comparison to the control ones (Table 3). The differences however where not significant and this was attributed to the limited replication reducing the power of the statistical analysis.

The Wickepin demonstration site had the mildest frost conditions in 2018, with 8 frost events occurring between August and November, although -5.8°C was the lowest temperature recorded in the control strip (Table 3). When deep tillage was combined with clay spreading, the crop canopies experienced fewer hours below 0, -2, and -4°C compared to the control, with the largest difference for the number of hours below -4°C.

Grain yield, harvest index and frost damage

Within the sites and seasons there was high variability in terms of yields, harvest indexes and assessments of crop damage but the results were generally consistent with the air canopy temperature data. As a result, stronger evidence of the treatments reducing frost damage were obtained at the sites where severe frost events occurred, as summarised in Table 2 and shown by the data in Tables 4 and 5 and Figures 1b and 1c.

Table 2. Overview of the trial results.

Summary of trial result	Trial year, location and crop	Season rainfall conditions	Crop establishment
Trials with sufficient frost damage. Soil amelioration significantly reduces frost severity, duration, damage and increases grain yield.	- 2016 Moora (Barley) - 2016 Yealering Demo (Barley) - 2017 Esperance (Canola) - 2018 Yealering (Wheat)	- Above average - Above average - Below avg., dry start - Below avg., dry start	- No significant difference - No significant difference - No significant difference - No significant difference
Trials with significant temperature effects between treatments but not sufficient frost damage to discriminate treatment effects. Amelioration increases grain yield.	- 2017 Wickepin Demo (Barley) - 2017 Moora (Lupin) - 2018 Moora (Wheat) - 2018 Esperance (Wheat)	- Below avg., dry start - Below avg., dry start - Average, dry start - Below avg., dry start	- Better only in tilled + clay - Better in tilled - Only reduced with high clay - No significant difference

Table 2. Total hours experienced by the crops at canopy air temperatures below 0, -2, and -4°C between the control and amelioration treatments at the different sites and seasons. Significant differences are indicated by different letters ($P < 0.05$).

Location	**Year**	**Crop**	**Sowing date (dd/mm)**	**Temperature recording period (dd/mm)**	**Number of frost events (lowest temp. recorded, °C)**	**Hours below 0°C**				**Hours below -2°C**				**Hours below -4°C**			
						Control	**Deep Tillage**	**Deep tillage + clay**	**LSD 5%**	**Control**	**Deep Tillage**	**Deep tillage + clay**	**LSD 5%**	**Control**	**Deep Tillage**	**Deep tillage + clay**	**LSD 5%**
Wickepin (Demo)	2017	Barley	20/04	24/08 - 31/10	8 (-5.8)	25.1	25.3	22.5	n.a.	7.3	7.3	5.1	n.a.	3.3	1.9	1.4	n.a.
Moora	2017	Lupin	15/5	01/09 - 14/11	20 (-4.5)	115.4^{a}	93.0^{b}	93.1^{b}	**18.1**	48.6^{a}	30.4^{b}	30.6^{b}	**13.5**	2.8^{a}	0^{b}	0^{b}	**2.3**
Esperance	2017	Canola	12/5	17/08 - 18/10	27 (-8.9)	155.1^{a}	129.8^{ab}	119.0^{b}	**35.9**	95.6^{a}	73.3^{ab}	62.0^{b}	**27.5**	40.2^{a}	22.5^{ab}	14.8^{b}	**20.2**
Moora	2018	Wheat	30/05	31/08 - 30/10	17 (-4.8)	77.6^{a}	62.6^{b}	60.3^{b}	**11.6**	29.0^{a}	19.8^{b}	18.3^{b}	**7.9**	2.8^{a}	0^{b}	0^{b}	**1.7**
Esperance	2018	Wheat	03/06	07/08 - 12/12	25 (-6.6)	111.4	93.0	89.1	24.9	50.5	42.8	41.2	12.2	20.8	15.9	14.6	8.2
Yealering (Trial)	2018	Wheat	21/05	28/7 – 22/10	30(-7.3)	75.8	69.3	n.a.	14.8	33.4	29.8	n.a.	5.2	15.4^{a}	12.9^{b}	n.a.	2.2
Yealering (Demo)	2018	Barley	20/05	17/9– 1/11	7(-3.9)	17.1	15.2	n.a.	n.a.	3.8	2.9	n.a.	n.a.	0	0	n.a.	n.a

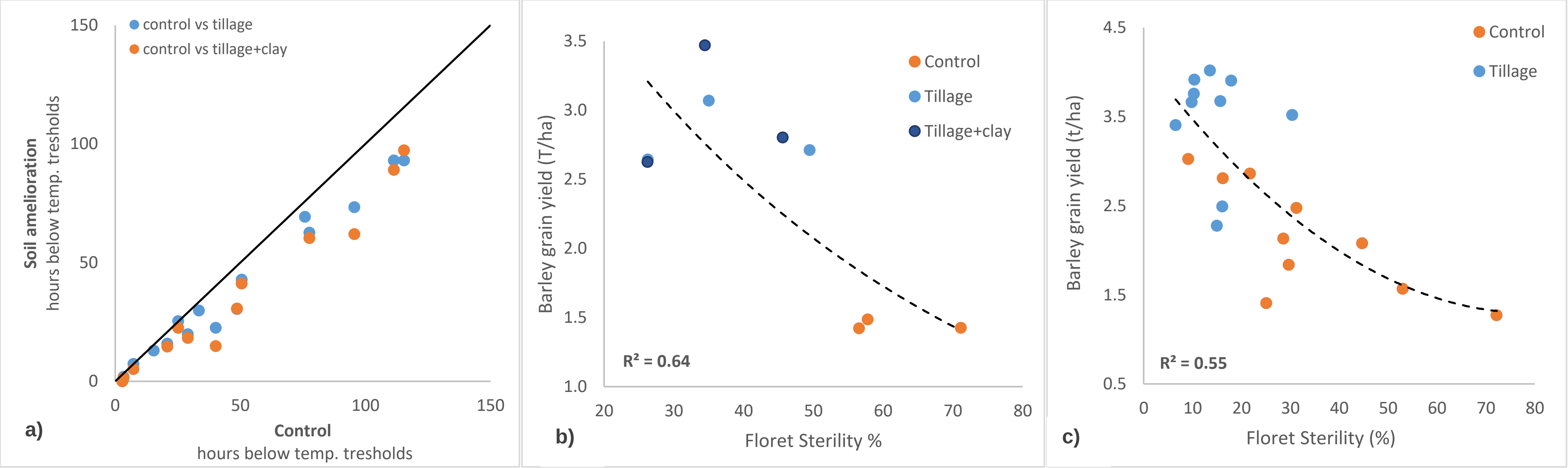

Fig.1 **a)** Comparison of the total number of hours below the critical temperatures (0, -2 and -4) experienced by crops in the control and ameliorated treatments. The black solid line represents equal (1:1) hours. **b)** Correlation between Floret Sterility (%) and grain yields of barley crops at the Moora site in 2016 and **c)** at the Yealering Demonstration site in 2016.

Moora

Floret sterility (FS) in barley indicated significant flowering and grain frost damage at Moora in 2016 (Table 4). Floret sterility was 40-43% lower in the ameliorated treatments than the control and was well correlated to grain yield (R^2=0.64; Fig 1b). Grain yield, harvest index, grain number and grains per spike were significantly lower in the control compared to ameliorated treatments (Table 4). There was, however, no significant difference between the deep tillage alone or deep tillage combined with subsoil clay treatments. Soil amelioration at Moora significantly improved the harvest index (+12-18%) and yield (+38-40%) of Lupin in 2017 over the control (Table 5). However, the harvest indices were all in 40% to 50% range, which suggested that other factors (such as early plant establishment; Betti et al. 2018) were more likely to be the main cause of variation in grain yield. In 2018, the wheat crop at Moora did not achieve their potential yield as indicated by the low harvest indices in all treatments (Table 5). Low harvest index could be attributed to poor soil moisture availability during grain fill, which experienced below average rain. However, a low proportion of grains collected at harvest were assessed to be affected by frost (Table 5), with significant differences between the control and amelioration treatments. These results were consistent with observed frost damage and sterility in the field, suggesting that wheat in the control treatments were more affected by frost events during flowering and early grain filling. However, given the low September rainfall it's likely the sterility may be a combination of sterility from frost, heat and water stress. The ameliorated treatments with more plant available water, may have been able to cope better with the combined effects of these stresses.

Esperance

The 2017 season at Esperance was characterised by a combination of poor early rainfall, several severe frost events and a dry finish. All these factors potentially contributed to the very low harvest indexes and poor canola yields (< 500 kg/ha, Table 4). Yield differences were mainly driven by differences in harvest index, as no significant differences were found between biomass at maturity. This result, in conjunction with the canopy air temperatures in Table 2, suggest that differences in frost severity had a role in the greater reduction for the control treatment for the amount of viable canola grain (data not shown). This was also confirmed by a simple regression analysis that showed a correlation (R^2=0.65) between the number of hours experienced by the crops at temperature below 0 and the harvest index. In 2018, the wheat harvest index and yield were significantly higher in the ameliorated treatments than the control at Esperance (Table 5). Nonetheless, all harvest indices fell above 40% indicating that grain fill was reasonably effective in all the treatments. The average number of grains per spike was higher in the ameliorated treatments but with high variability the difference is not significant (Table 5).

Yealering

At the Yealering trial, the average number of grains per spike, harvest indices, viable spikes, total grain number and grain yield of wheat were significantly higher in the deep tillage amelioration (spaded) treatment (Table 4). The number of non-viable spikes and screenings % were significantly lower in the ameliorated treatment. This data was consistent with the air canopy temperature data that showed reduced frost severity (Table 2) and with the clear visual observation of reduced frost damage at the site.

Significant differences in the harvest index and barley grain yield were also found between the control and ameliorated (mouldboard ploughed) treatment at the Yealering demonstration site in 2016 (Table 4). The harvest index of the control treatment (19.2) was lower than the ameliorated treatment (35.9) and the control had 49% fewer grains per spike. Floret sterility was high (>30%) and more than double in the control compared to the amelioration treatment, indicating that amelioration reduced floret sterility and contributed to higher grain yield (Fig. 1 c), which, on average, was 61% higher than the control yield (Table 4).

Wickepin

Mild frost conditions at the Wickepin demonstration site in 2017 did not produce a severe reduction in grain number. However, on average, more grains per spike were found in the ameliorated treatments in comparison to the control, consistent with the frost duration data. The difference was greatest when deep tillage was combined with subsoil clay application (Table 5).

Table 4. **Trials with sufficient discriminating frost damage**; Crop measures, yield components, grain yield and quality from control and ameliorated treatments. Values are the mean of 3 reps at Moora, Esperance and Yealering trial and 10 transect samples at Yealering demo. Significance is indicated by different letters ($P < 0.05$).

Location	Yield Components	Control	Deep Tillage	Deep tillage + clay	LSD 5%
Moora **2016** **Barley**	**Floret sterility (%)**	61.8^{a}	36.9^{b}	35.5^{b}	**22.5**
	Viable spikes (m^{2})[1]	549a	627b	605ab	**56.7**
	Kernel weight (mg)	29.8	33.9	35.5	9.4
	Grains per m^{2}	5648^{a}	8651^{b}	8766^{b}	**1.8**
	Grains per spike	10.4^{a}	13.7^{b}	14.5^{b}	**1.8**
	Harvest Index %	24.5^{a}	39.1^{b}	38.8^{b}	**7.9**
	Maturity biomass (t/ha)	6.8	7.5	8.1	2.1
	Grain Yield (t/ha)[3]	1.74^{a}	3.24^{b}	3.52^{b}	**0.36**
Yealering (Demo) **2016** **Barley**	**Floret sterility (%)**	33.2	14.6	n.a.	n.a.
	Viable spikes (m^{2})[1]	1446	1506	n.a.	n.a.
	Non-viable spikes (m^{2})[2]	0	40	n.a.	n.a.
	Kernel weight (mg)	38.2	38.3	n.a.	n.a.
	Grains per m^{2}	5638	9018	n.a.	n.a.
	Grains per spike	4.1	6.1	n.a.	n.a.
	Screenings (%) <2mm	0.66	0.53	n.a.	n.a.
	Harvest Index %	19.2	35.9	n.a.	n.a.
	Maturity biomass (t/ha)	11.7	9.8	n.a.	n.a.
	Grain Yield (t/ha)[3]	2.15	3.46	n.a.	n.a.
Esperance **2017** **Canola**	**Harvest Index %**	1.6^{a}	14.9^{b}	17.3^{b}	**7.5**
	Maturity biomass (t/ha)	4.8	5.2	4.6	2.7
	Grain Yield (t/ha)[3]	0.05^{a}	0.37^{b}	0.29^{b}	**0.20**
Yealering (Trial) **2018** **Wheat**	**Viable spikes (m^{2})[1]**	235^{a}	289^{b}	n.a.	**44**
	Non-viable spikes (m^{2})[2]	65^{a}	8^{b}	n.a.	**20**
	Kernel weight (mg)	44.7	47.9	n.a.	3.4
	Grains per m^{2}	5690^{a}	8812^{b}	n.a.	**1101**
	Grains per spike	25.2^{a}	31.5^{b}	n.a.	**4.4**
	Screenings (%) <2mm	1.74^{a}	0.23^{b}	n.a.	**0.53**
	Harvest Index %	26.7^{a}	37.5^{b}	n.a.	**3.4**
	Maturity biomass (t/ha)	9.5^{a}	11.0^{b}	n.a.	**0.71**
	Grain Yield (t/ha)[3]	2.51^{a}	3.95^{b}	n.a.	**0.66**

[1] Spikes which developed and contained at least a single grain. [2] Sum of stems with heads that do not contain any grain and stems where the head has not emerged from the leaf sheath and contains no grain. [3] Yields where obtained from plot harvester

Table 5. **Trials with insufficient frost damage**; Crop measures, yield components, grain yield and quality from control and ameliorated treatments. Values are the mean of 3 reps at Moora, Esperance and Yealering trial and 4 transect samples at the Wickepin demo. Significance is indicated by different letters ($P < 0.05$).

Location	Yield Components	Control	Deep Tillage	Deep tillage + clay	LSD 5%
Wickepin (demo) 2017 Barley	**Viable spikes (m^2)[1]**	439	514	418	n.a.
	Non-viable spikes (m^2)[2]	10	7	14	n.a.
	Kernel weight (mg)	33.2	31.9	35.4	n.a.
	Grains per m^2	5763	6507	6378	n.a.
	Grains per spike	13.3	12.8	15.2	n.a.
	Screenings (%) <2mm	7.49	8.93	1.51	n.a.
	Harvest Index %	48.7	45.7	52.4	n.a.
	Maturity biomass (t/ha)	4.0	4.6	4.4	n.a.
	Grain Yield (t/ha)[3]	1.95	2.11	2.27	n.a.
Moora 2017 Lupin	**Seed weight (mg)**	129.2^{a}	164.6^{b}	178.7^{b}	**14.2**
	Grains per m^2	1623^{a}	2145^{b}	2005^{b}	**245**
	Harvest Index %	45.7^{a}	51.2^{b}	54.0^{b}	**3.2**
	Maturity biomass (t/ha)	4.9^{a}	6.9^{b}	6.7^{b}	**1.8**
	Grain Yield (t/ha)[3]	1.36^{a}	1.91^{b}	1.88^{b}	**0.44**
Moora 2018 Wheat	**% of frost affected grains**	12.8^{a}	10.8^{b}	9.1^{b}	**1.9**
	Viable spikes (m^2)[1]	282	291	323	43.0
	Kernel weight (mg)	42.7	44.0	43.5	5.8
	Grains per m^2	4147	4285	5241	1324
	Grains per spike	14.9	14.8	16.3	5.4
	Screenings (%) <2mm	1.57^{a}	1.60^{a}	2.25^{b}	**0.90**
	Harvest Index %	32.0	32.2	32.9	9.4
	Maturity biomass (t/ha)	5.6^{a}	5.8^{a}	6.8^{b}	**0.9**
	Grain Yield (t/ha)[3]	1.51^{a}	1.62^{ab}	1.87^{b}	**0.19**
Esperance 2018 Wheat	**Viable spikes (m^2)[1]**	209	217	241	107
	Kernel weight (mg)	48.7	47.5	48.5	5.7
	Grains per m^2	6991	7658	6954	3784
	Grains per spike	29.6	35.3	33.1	10.2
	Screenings (%) <2mm	0.66	0.82	0.65	0.25
	Harvest Index %	47.8^{a}	52.4^{b}	52.4^{b}	**4.2**
	Maturity biomass (t/ha)	7.2	7.0	6.4	4.1
	Grain Yield (t/ha)[3]	2.08^{a}	2.63^{b}	2.59^{b}	**0.26**

[1] Spikes which developed and contained at least a single grain. [2] Sum of stems with heads that do not contain any grain and stems where the head has not emerged from the leaf sheath and contains no grain. [3] Yields where obtained from plot harvester

Conclusions

Amelioration of constrained sandplain soils using strategic deep tillage and soil amendments, such as subsoil clay and lime can significantly increase crop grain yields (Davies et al. 2019; Betti et al 2018). Much of this benefit comes from overcoming or reducing soil constraints, typically compaction, acidity and water repellence, but other agronomic benefits arising from amelioration can also contribute to grain yield improvements. Frost has occurred every year, with varying severity, at the three experimental and two demonstration sites presented. In all the seasons where air temperatures at canopy height have been measured there has been a consistent trend of the ameliorated treatments having fewer hours below critical thresholds (0, -2 and -4°C) than the untreated control treatments. This has occurred across a wide geographic range and a variety of repellent soil types, crop types and seasons and is consistent with previous work (Rebbeck et al 2007; Butcher et al 2017).

As expected, grain yield and harvest index have been consistently higher for ameliorated than the control treatments but from this data set we are unable to attribute how much of this might be due to a reduction in frost damage. Reductions in floret sterility and higher grain number per spike and harvest index for ameliorated treatments suggest that reduced frost damage may be a factor, but we cannot rule out other factors which could impact on these measures. Nor are we able to elucidate the mechanism(s) by which soil amelioration reduces frost severity, as this was not an objective of the study. We can rule out stubble burial as a factor as of all the data shown Moora in 2016 was in its first year after amelioration (spading and claying) and stubble loads would have been equivalent or higher on the ameliorated soils in subsequent seasons. There is also no evidence from these sites that an albedo (heat reflection/absorption) effect from bringing darker soil to the surface is a factor as had been suggested previously (Rebbeck et al 2007). At many of these sites the sandy subsoil brought to the surface is paler in colour than the topsoil, so greater heat reflection and less absorption would be expected in these cases. The evidence, however, does suggest that the topsoil does need to be modified in order to see a substantial reduction in frost severity. Where some of the sites have had a deep ripping treatment which has reduced compaction but not significantly altered the topsoil condition the reductions in frost severity are minimal if they are there at all (data not shown). On trend addition of clay to the strategic deep soil mixing or inversion, which further changes the topsoil properties, tended to further reduce frost severity, though this was generally not significant.

In conclusion, we found strong evidence of the effect of soil amelioration using strategic deep tillage on frost severity and indications that this can reduce crop damage. However, this was seen only when seasonal conditions produced severe, and therefore discriminating frost events. Moreover, the findings highlight the benefits of soil amelioration in reducing frost severity on repellent soils but leaves many questions unanswered and the need for more specific research on the subject. Some of the key research questions arising include:

1) What are the mechanisms by which soil amelioration reduces frost severity?

2) Can soil amelioration reduce frost severity on soils that aren't water repellent?

3) To what extent does the reduction in frost severity contribute to grain yield?

Key words

Frost, Water repellence, Mouldboard ploughing, Rotary Spading, Clay delving, Soil amelioration

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