Agronomic options to overcome soil water repellence improve crop performance regardless of sowing conditions in a gravelly duplex soil

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Abstract
Soil water repellence (SWR) is a significant constraint to crop establishment in South-West Western Australia (WA). A long term agronomic experiment commenced in 2015 to investigate a range of potential amelioration and mitigation options to manage SWR. All treatments improved crop establishment and yield by varying amounts over four seasons. The most effective treatments for improving yield were strategic deep tillage and banded wetting agents. Strategic deep tillage via mouldboard plough (MBP) or one-way plough (OWP) improved yield in all seasons regardless of rainfall patterns. The application of pre-emergent herbicides on strategic deep tillage treatments trended towards reduced crop growth and yield but rarely to a significant level. Near-row sowing increased plant establishment in two of the four seasons but yield improvements in these seasons were significantly lower than almost all other treatments. Improved crop performance from wetting agent techniques occurred only in years with dry soil conditions at sowing. Wetting agents were proven to be a good short term option for water repellent soils but strategic deep tillage provided the most consistent longer term yield improvement across all the growing seasons experienced.

Key Words
Soil water repellence, wetting agents, strategic tillage, herbicides

Introduction
SWR is a significant constraint to crop establishment in the cropping zone of the South-West WA, with 9.9M ha at risk (van Gool 2016). Growers are uncertain which potential amelioration options will provide the greatest and most reliable productivity improvements on these soils. A long term agronomic experiment commenced in 2015 to investigate potential options including sowing practices, wetting agent techniques and strategic tillage. The interaction of herbicide and strategic tillage was also examined. Near-row sowing has been shown in the field to improve crop establishment but has rarely been evaluated in comparison with soil wetting agents. Soil wetting agents have been shown to be effective in short term mitigation of SWR and improve crop performance on gravelly duplex soils in WA but are not considered effective across all soil types (Davies et al. 2019). Strategic tillage has been shown to be an effective and reliable practice for longer term amelioration of SWR but is significantly more expensive than wetting agents and can be less well suited to gravelly soils due to high rates of machinery wear and obstacles in the soil. Recent research from Edwards et al. (2018) and Bakker et al. (2015) has demonstrated that pre-emergent herbicide efficacy can be increased following strategic tillage which can result in crop damage and reduced establishment. This research aimed to compare these options for managing SWR in order to provide growers and industry with the confidence to select the best amelioration strategy for these gravelly duplex soils.

Methods
A long term field experiment was established in 2015 on water repellent soil (molarity of ethanol droplet test = 3.1) at Boscabel (-33.6865, 117.0323) in WA. The soil is a loamy gravel duplex (Ferric Kandosol) that is common (1.7M ha, van Gool 2018) across large areas of the South-West WA higher rainfall zones. Experimental plots were sown plot-on-plot each season and replicated in a randomised block design. The control treatment involved inter-row sowing that placed the seed between the previous years crop rows (off-row). The agronomic options for SWR mitigation were near-row (also known as on- or edge-row) sowing, where seed is placed as close as possible to the previous years crop rows, and three wetting agent application methods where the wetting agent was either banded behind the press wheels on the soil surface (on-furrow), banded with the seed when sowing (in-furrow) or as a blanket application to the soil surface over the whole plot. The soil wetting agents used were SACOA's LureH2O® and SE14® depending on treatment and season with both products applied at 2 L/ha (Table 1). Strategic deep tillage in the form of OWP and MBP was included as longer term amelioration options for SWR with and without annual pre-emergent herbicides (Table 1). The OWP and MBP strategic deep tillage was applied only once prior to the 2015 season and treated plots had buffer strips either side to ensure even treatment application on the plot area. Pre-emergent

herbicides, appropriate for each season's crop type, were applied before sowing and incorporated by sowing using knife points into dry soil whenever possible (Table 2). Crop rotation was selected to match the surrounding paddock in all years of the experiment. All treatments received pre-emergent herbicide except for the control and one of each of the two strategic deep tillage treatments (Table 1). A range of measurements were collected throughout the seasons including crop establishment, drone imagery, grain yield and grain quality. The measurements collected each season were dependent on crop type and symptoms of responses to SWR. Statistical analyses were conducted by using REML with Genstat® software (18th Edition; VSN International: Hemel Hempstead, UK).

Table 1. Treatment details for each season. Soil wetting agents applied at 2 L/ha for both products.

	Treatment	2015	2016	2017	2018
1	Control - off-row (inter-row) sowing + no pre-emergent				
2	Near-row sowing				
3	Off-row sowing + banded wetter on furrow	LureH2O	LureH2O	LureH2O	SE14
4	Near-row sowing + banded wetter on furrow	LureH2O	LureH2O	LureH2O	SE14
5	Near-row sowing + banded wetter with seed in furrow	LureH2O	SE14	SE14	SE14
6	Near-row sowing + blanket wetter (2015, 2017 only)	LureH2O		LureH2O	
7	One-way plough + no pre-emergent				
8	One-way plough				
9	Mouldboard plough + no pre-emergent				
10	Mouldboard plough				

Table 2. Crop rotation details.

Year	Crop/Variety	Pre-emergent herbicide as per treatments	Sowing date	Seed rate (kg/ha)	Sowing soil moisture	Apr-Oct rainfall
2015	Hindmarsh Barley	Trifluralin (2 L/ha)	4 May	100	Marginal	275
2016	Hyola®600RR Canola	Propyzamide (1 L/ha)	3 May	2	Moist	388
2017	Scepter Wheat	Pyroxasulfone(1180 g/ha), Trifluralin (1.5 L/ha)	9 May	70	Dry	322
2018	LaTrobe Barley	Trifluralin (2 L/ha)	23 May	80	Dry	345

Results & Discussion

Crop establishment

For the three seasons a cereal was sown, almost all treatments resulted in a significant increase in crop establishment compared to the control ranging from 72-108% in 2015, 16-27% in 2017 and 14-28% in 2018 (Table 3). Canola in the 2016 season was sown into a moist seed bed and the effects of SWR on crop establishment was reduced. In 2016 most treatments reduced plant density by 12-39% when compared to the control. This reduction in canola establishment was greatest for the strategic tillage treatments ($p=<0.05$) and is likely caused by deeper seed placement. Poor establishment of canola following any form of strategic tillage is often a problem in commercial plantings and represented in these results. Apart from the 2016 canola, there is no clear advantage in crop establishment between using either soil wetting agents or strategic tillage.

Table 3. Crop establishment (plants/m^2). Different to control at $p<0.01$ = ***, $p<0.05$ = **, $p<0.10$ = *

Treatment	2015	2016	2017	2018
Control - off-row (inter-row) sowing + no pre-emergent	72.0	73.2	117.5	92.3
Near-row sowing	46.7	64.7	142.5***	108.2*
Off-row sowing + banded wetter on furrow	131.2**	59.4**	137.5**	105.4*
Near-row sowing + banded wetter on furrow	150.1***	62.1*	145.6***	118.3***
Near-row sowing + banded wetter with seed in furrow	149.8***	62.4	148.8***	97.0
Near-row sowing + Blanket wetter (2015, 2017 only)	131.8**	60.1*	131.0	109.9**
One-way plough + no pre-emergent	142.6***	55.9**	142.5***	112.1**
One-way plough	124.1**	49.9***	136.8**	112.8**
Mouldboard plough + no pre-emergent	129.1**	50.0***	139.7**	109.4**
Mouldboard plough	123.8**	44.4***	140.5**	102.5
LSD 0.05	46.4	13.4	17.9	16.3

In 2015, the near-row treatment had not been established and this treatment is identical to the control except for the application of the pre-emergent herbicide. It is possible the combination of SWR expression and pre-

emergent herbicides delayed or restricted crop establishment. Near-row sowing has been demonstrated to increase crop emergence on repellent soils (Kerr et al. 2017; McDonald et al. 2018) and once the near-row sowing technique was established, the negative effect observed in 2015 for the near-row sowing treatment was not evident in the following seasons. When pre-emergent herbicides were applied on the strategic deep tillage treatments small reductions in crop establishment (p=ns) were observed in all years.

Grain yield

For all seasons except 2016 where soil conditions at sowing were moist, the yields for almost all soil wetting agent treatments were significantly higher ($p<0.05$) than both the control and near-row sowing treatments (Table 4). Rainfall prior to sowing in 2016 created conditions where SWR was not strongly expressed and this accounts for the reduced grain yield response in the non-tillage mitigation treatments that year. The yield advantage of the wetting agent treatments over the near-row sowing treatment was greatest in 2015 ($p=<0.01$) and 2017 ($p=<0.05$). For the non-tillage treatments in 2018, only the two surface banded wetting agent treatments yielded significantly higher than the near-row sowing treatment ($p=<0.05$). Near-row sowing significantly increased yield compared to the control in 2017 by 22% ($p=<0.05$) and by 15% in 2018 ($p=<0.10$), while in 2015 the near-row sowing treatment was not yet established, hence there was no yield difference. Across all seasons the tillage treatments had significantly higher yields than the control with 29-64% increases in 2015, 2017 and 2018, and 13-19% increases in the 2016 canola when SWR was less severe. The tillage treatments also had the highest yields in all seasons when compared to any other treatments except for where pre-emergent herbicides were applied in 2017 and 2018. Deep tillage loosens the soil profile enabling more rapid root growth. This effect when combined with reduced SWR and possibly enhanced nitrogen uptake from mineralisation of buried organic matter, explains the improved yields from the tillage treatments regardless of seasonal conditions. Improved grain protein content of these treatments, while not significant, provides additional evidence of this nitrogen mineralisation later in the season (data not shown). In addition, NDVI imagery from this experiment in 2017 showed that the strategic deep tillage remained green later into the season which indicated improved root access to soil water and conversion into yield (McDonald et al. 2018). The pre-emergent herbicide applications only caused significant yield reductions for the MBP in 2018 where yield was reduced by 14% ($p=<0.05$). There was a trend for pre-emergent herbicides to reduce yields in this experiment, but while this effect was largely not significant, it supports results in recent research when trifluralin at 2 L/ha was applied as pre-emergent on dry soil (Edwards et al. 2018, Bakker et al. 2015).

Table 4. Grain yield (t/ha). Different to control at p<0.01 = ***, p<0.05 = **, p<0.10 = *

Treatment	2015	2016	2017	2018
Control - off-row (inter-row) sowing + no pre-emergent	2.75	2.36	2.61	2.67
Near-row sowing	2.44	2.34	3.18^{**}	3.06^{*}
Off-row sowing + banded wetter on furrow	3.47^{**}	2.51	3.90^{***}	3.48^{***}
Near-row sowing + banded wetter on furrow	3.51^{**}	2.47	3.89^{***}	3.57^{***}
Near-row sowing + banded wetter with seed in furrow	3.80^{***}	2.37	3.69^{***}	3.14^{**}
Near-row sowing + Blanket wetter (2015, 2017 only)	3.79^{***}	2.52^{*}	3.67^{***}	3.33^{***}
One-way plough + no pre-emergent	4.24^{***}	2.63^{**}	4.08^{***}	3.69^{***}
One-way plough	3.98^{***}	2.63^{**}	3.84^{***}	3.45^{***}
Mouldboard plough + no pre-emergent	4.44^{***}	2.78^{***}	4.24^{***}	4.05^{***}
Mouldboard plough	4.48^{***}	2.75^{***}	4.27^{***}	3.50^{***}
LSD 0.05	0.71	0.20	0.49	0.41

The use of soil wetting agents resulted in $141-179/ha extra return per year on average compared to the control but the greatest economic benefit came from strategic deep tillage treatments at $221-350/ha average net value over the four years (Table 5). One of the advantages of strategic deep tillage techniques is reduced weed competition and substantial savings of $63-77/ha/yr averaged across the four years were realised after strategic deep tillage through reducing herbicide expenditure. Since the strategic deep tillage was only applied prior to the 2015 growing season, based on previous research the average net value will continue to increase as the long term effect of the strategic tillage can continue for some time (Davies et al. 2019).

Table 5. Average financial values for SWR amelioration treatments compared to the control. All values are averaged over the four experimental years. Grain prices = 5 year average from Australian Crops Annual Review (2017), wetting agent costs = $7/L, MBP = $120/ha, OWP = $50/ha, trifluralin, propyzamide, Sakura® = $7.5/L, $24.2/L, $340/kg respectively.

Treatment	Change in grain production ($/ha)	Treatment cost ($/ha)	Net value ($/ha)
Near-row sowing	58.31	26.56	31.74
Off-row sowing + banded wetter on furrow	215.95	40.56	175.39
Near-row sowing + banded wetter on furrow	218.59	40.56	178.03
Near-row sowing + banded wetter with seed in furrow	181.33	40.56	140.76
Near-row sowing + Blanket wetter (2015, 2017 only)	212.17	33.56	178.60
One-way plough + no pre-emergent	310.95	12.50	298.45
One-way plough	260.05	39.06	220.99
Mouldboard plough + no pre-emergent	380.31	30.00	350.31
Mouldboard plough	344.14	56.56	287.57

Conclusion

This experiment has shown that there is little difference between SWR management techniques on improving crop establishment provided good seed placement is achieved at sowing. It is during the season where the treatment responses begin to diverge, with greater improvements in crop growth, development and subsequently yield for the strategic deep tillage treatments compared to other treatments. This improved crop performance for the strategic tillage treatments is also evident in the increased average net return per hectare. The application of soil wetting agents consistently demonstrated an improved crop performance and economic benefit. Therefore, the use of wetting agents on these soils is a viable option especially for situations where strategic tillage is unsuitable or cost prohibitive. While near-row sowing was effective at improving crop establishment, there was little in-season advantage after this crop stage compared to other treatments (McDonald et al. 2018). Therefore, the near-row sowing was the least effective at increasing yield. Even when the 2015 season is removed from the economic comparison, the resulting average net value of $59.54/ha for the near-row sowing was less than half of the next best treatment (banded wetter with seed) and almost one sixth that of the highest treatment (mouldboard plough, no pre-emergent). Some negative effects of pre-emergent herbicides on the tillage treatments were encountered which reduced yield.

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