Ten years of managing water repellent soils research in Western Australia – a review of current progress and future opportunities

Stephen Davies, Giacomo Betti, Tom Edwards, Glenn McDonald, David Hall, Geoff Anderson, Craig Scanlan, Chad Reynolds, Jo Walker, Grey Poulish, Department of Primary industries and Regional Development; **Phil Ward, Priya Krishnamurthy, Shayne Micin, Ramona Kerr, Margaret Roper,** CSIRO; **Tim Boyes,** agVivo

Key messages

1) Choice of method for managing soil water repellence is influenced by soil type, climate and associated agronomic considerations.

2) Mitigation strategies (paired-row sowing, near-row sowing, and wetting agents) provide cheap management options, but must be implemented every year and need to be targeted at responsive soils and situations. Paired and near-row sowing typically increased early emergence by 50%, but had smaller and more variable effects on grain yield. Banded soil wetters are most beneficial for dry sown cereals on repellent forest gravels of the south-west with less reliable benefits for break-crops. Benefits of banded wetters are minimal or at best sporadic for dry sown crops on deep sands and there is no benefit with wet sowing for any crop or soil type. Benefits are larger in seasons with low and sporadic germinating rains in autumn.

3) Amelioration of repellent soils with strategic deep tillage (e.g. spading or inversion ploughing) provides long-term and reliable benefits across most repellent soils and locations. For pale deep sands the benefits are present for two-years before declining significantly at many sites. Clay spreading may help sustain benefits for longer on these less fertile soils, but the cost is high and yield potential of these soils is still limited.

4) Repellent soils are often prone to compaction and subsoil acidification and ameliorating these constraints is important for increasing and sustaining yield benefits. For example, deeper ripping following soil inversion can increase average grain yields by a further 10% (340 kg/ha), over inversion on its own.

Aims

1) Collate and present data from the past ten-years of field research into managing water repellent cropping soils.

2) Discuss findings in the context of management method, soil type, seasonal conditions and risk and identify ongoing gaps in knowledge and barriers to adoption.

Method

Data from applied research on how to manage water repellent cropping soils in Western Australia have been collated from the 2009-2018 cropping seasons. Most of the data have come from replicated field experiments, some of which have been presented previously (e.g. Davies et al. 2013, 2016, 2018; Betti et al. 2018; Blackwell et al. 2014; Hall et al. 2018; Kerr et al. 2017; McDonald and Davies 2018), with some data also collected from large-scale grower validation trials, sometimes replicated or including repeated control strips. Soil water repellence management methods assessed include paired row sowing, near-row sowing, banded wetters (including placement effects), soil inversion, deep soil mixing, clay spreading and clay delving. Some additional published data from other interstate research providers (see McBeath et al. 2016a, 2016b, 2018; Llewellyn et al. 2017) have been included in data sets where appropriate to help strengthen and validate the research findings for a given management practice. The aim of collating the data sets has been to broaden our understanding of how crop response to a soil water repellence management practice might be affected by soil type, location, crop type and any other major interacting factors. Averaging crop emergence and yield responses across sites does 'hide' much of the variability between sites, so data on what proportion of the comparisons have shown significantly positive benefits has been included to give an indication of the reliability of the response.

Results and Discussion

Mitigation Strategies

Mitigation strategies for managing water repellent soils consist of a range of approaches to improve the effectiveness of furrow sowing but they do not remove or reduce the repellent soil in the long-term. The advantage of mitigation strategies is that they are cheap to implement and can be applied over a large area of affected soils while seeding. The downside is that they generally need to be re-applied

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

every season and they do nothing to address other interacting soil constraints which, if present, will significantly limit yield.

Grain crops are typically sown with knife points followed by press-wheels for seed-soil contact and furrow formation. Research identified that dry repellent topsoil will typically flow around the knife point and into the seeding row with the seed, exacerbating the effect of the repellence (Blackwell et al. 2014). Use of winged, paired-row sowing boots allows seed to be placed on an undisturbed (firm) and often moist seedbed, which increases the amount of sown row over a given area, helps grade repellent soil out of the furrow and typically has good seed-fertiliser separation (McBeath et al. 2016a). All of these factors improve crop establishment from paired-row sowing by an average of 55% (32 plants/m^2) on repellent soils, with 83% of the comparisons showing a positive benefit (Table 1). This translates to a 20% (371 kg/ha) average yield improvement, three in every four comparisons showing significant benefit (Table 1).

Near-row sowing utilises the preferential water infiltration pathways of crop rows from the previous season to improve crop establishment on repellent soils (Kerr et al. 2017; Roper et al. 2015). Like the paired row sowing, near-row sowing shows quite large and consistent crop establishment benefits but this has only translated through to a yield benefit for 57% of the comparisons and an average yield benefit of 216 kg/ha (Table 1).

Table 1. Impact of paired-row or near-row sowing on crop establishment (plants/m^2 and %) and grain yield (kg/ha and %) for repellent soils from 2011-2018. The number of comparisons (No. Comp.) and proportion (% Positive Comparisons) of these which had a statistically significant (P<0.1 or better) positive response are shown.

Mitigation Sowing Method	Average Crop Establishment Increase				Average Crop Yield Increase			
	No. Comp.	Plants/m^2 Change	% Change	% Positive Comparisons	No. Comp.	kg/ha Change	% Change	% Positive Comparisons
Paired row	6	32	55	83	9	371	20	75
Near-row	8	22	50	63	7	216	14	57

Banding of soil wetting agents is not a new technology and previous research has demonstrated some success with their use on repellent soils in WA (Blackwell et al. 1994; Crabtree and Henderson 1999). Testing of 'current' commercial soil wetter formulations over the past ten-years reveals that their value in cropping systems is dependent on the soil type and whether the crop has been wet or dry sown (Table 2). On average, cereal grain yield responses to banded soil wetters in sand have been minimal, less than 100 kg/ha benefits with only one in four comparisons showing a significant benefit (Table 2). Where cereal crops were dry sown responsiveness improved but remained low. Break-crops on sand, all of which were sown dry, showed a better response with an average 141 kg/ha yield increase but still only in two of the five comparisons (Table 2). Dry sown sandy gravels appear to be more responsive to banded wetters but more comparisons are needed to determine the reliability of wetters on these soils. The data demonstrates that while occasionally there can be very good responses to banded wetters on sands and sandy gravels, generally the response has been inconsistent.

Table 2. Average crop grain yield responses (kg/ha and %) to soil wetter banded on top of the furrow or blanket applied by soil type and moisture at sowing for cereals (wheat and barley) or break-crops (Lupin on Deep Sand and Sandy Gravel; Canola on Loamy Gravel) from 2011-2018. The number of comparisons (No. Comp.) and proportion (% Positive Comparisons) of these with a statistically significant (P<0.1 or better) positive response are shown.

Soil Type	Sowing moisture	Cereal Crop Yield Change				Break-Crop Yield Change			
		No. Comp.	kg/ha	%	% Positive Comparisons	No. Comp.	kg/ha	%	% Positive Comparisons
Deep Sand	All	12	34	3	25	-	-	-	-
	Dry	6	83	12	33	5	141	7	40
	Wet	6	-15	-5	17	-	-	-	-
Sandy Gravel	All	5	138	8	20	-	-	-	-
	Dry	2	250	15	50	1	100	5	-
	Wet	3	63	3	0	-	-	-	-
Loamy (Forest) Gravel	All	12	421	15	64	3	230	9	33
	Dry	8	594	21	88	2	295	11	50
	Wet	4	76	3	25	1	100	4	0
	All Blanket*	6	254	21	43	3	57	9	33

Location (data not shown) appears to have had no impact on response to banded wetting agent in deep sands. Experiments have been conducted throughout the northern, central and south-west regions, the three most responsive of which were at South Stirling, Badgingarra and Binnu, with other experiments in these areas showing little or no benefit. At South Stirling and Badgingarra the 2012 season was characterised by low rainfall in April and May, which increases the expression of soil water repellence and the potential benefit of banded soil wetting agents. At Binnu in 2014 good rainfall early in May (52mm on 5 May) was followed up very poor rainfall through June-August and very low yields of only 0.5 t/ha or less, again increasing the likelihood of achieving a benefit with soil wetters.

In contrast to sandy soils, banded soil wetters have shown much larger and more consistent responses on the repellent forest gravels of the south-west (Table 2). With dry seeding, average cereal yield responses were nearly 600 kg/ha with 88% of comparisons being significantly positive, though there was no benefit from their use when wet sowing. There have been insufficient comparisons of break-crops on the forest gravels, but in general they appear less responsive than cereals but more responsive than break-crops on the deep sands and sandy gravels (Table 2).

Placement of banded soil wetters has been the subject of more recent research with commercial release of soil wetter formulations that can be used in-furrow, banded near (within 20mm) of the seed, often through existing liquid fertiliser kits in combination with other in-furrow liquids (Sherriff 2016). Relatively few replicated research experiments have been conducted but in general in-furrow banding of wetter has resulted in either similar or better improvement in crop establishment compared to the traditional approach of banding wetter on the furrow behind the press-wheels (Table 3). Crop yield responses reflect what has already been discussed with no yield benefit on the deep sands, irrespective of placement, but good yield increases on the forest gravels, with an indication that for cereals in-furrow placement may provide larger yield benefits (520 kg/ha, 17% increase) than on-furrow placement (380 kg/ha, 12% increase; Table 3).

Table 3. Impact of banded wetter placement either on top of the furrow or in the furrow near the seed on crop establishment and grain yield for cereals and break-crops (canola and lupin) on repellent deep sand or loamy (forest) gravel. Note: 'No. Comp.' is the number of experimental comparisons providing the average values.

Soil Type	Crop Type	No. Comp.	Average Crop Establishment Increase				Average Grain Yield Increase			
			Plants/m^2		%		kg/ha		%	
			On-furrow	In-furrow	On-furrow	In-furrow	On-furrow	In-furrow	On-furrow	In-furrow
Deep sand	Cereal	3	5.0	14.0	5	13	-100	-120	-8	-9
	Lupin	2	9.0	5.5	22	13	-50	0	-3	0
Forest gravel	Cereal	6	13.5	18.3	12	17	380	520	12	17
	Canola	3	3.0	5.7	6	12	220	240	6	12

Biannual blanket application of soil wetters is an alternative for repellent forest gravel soils, however, higher application rates on a per hectare basis can increase the cost (typically $25-50/ha) compared to targeted banded wetter approaches depending on product and rate (typically $12-28/ha). Yield responses to blanket wetters are highly variable. Dry sown cereals are more responsive but responses also appear site specific, despite soil types being ostensibly similar. On average cereal yields were increased by 254 kg/ha, 21%, but only 2 in 5 comparisons were significantly responsive, while break-crop (canola) yield benefits were even less reliable (Table 2).

More recent research is investigating coating seed with soil wetters, requiring even lower rates of product application (Anderson et al. 2018). Preliminary research indicates crop establishment and growth benefits can be similar to banded soil wetters in responsive situations (Anderson et al. 2018) but also show little benefit in seasons with good germinating rainfall (Anderson and Valentine 2017; Anderson et al. 2019). The technology is yet to be commercialised and may have more value on small-seeded, high-value crop and pasture seed than on larger-seed cereal grains.

Amelioration Strategies

Amelioration strategies aim to remove or substantially reduce topsoil water repellence for many years (Table 4). In WA's cropping systems, strategies for amelioration fall into two broad groupings, one involving strategic deep tillage, to bury and/or dilute the repellent topsoil, the other involving the addition of clay-rich subsoil either through spreading or delving on duplex soils. Both approaches can significantly reduce the severity of topsoil water repellence (see examples Table 4). In most instances complete soil inversion almost completely eliminated topsoil water repellence as wettable subsoil was brought to the surface, and only in cases of incomplete or poor inversion did soil retains some repellence (Table 4). The reduction in water repellence with inversion can be sustained for up to eight or more years and the repellence of the buried topsoil typically declines over the first few seasons to a low level (Davies et al. 2018). Rotary spading consistently reduced topsoil water repellence but due to the mixing action of the spader some repellence remained (Table 4). Sites with very severe repellence and low clay and silt content throughout the spading depth were the most likely to retain some repellence, with repellence reductions as low as 39% (Table 4). The practice of deep ripping prior to spading, allowing a deeper working depth, and spading when there was adequate subsoil moisture improved the outcome.

Table 4. Molarity of ethanol droplet (MED) test for topsoil (0-10cm) water repellence for a number of experimental sites in response to soil amelioration treatments involving strategic deep tillage or clay spreading with incorporation. Repellence MED ratings are: Low = 0-1.0; Moderate = 1.1-2.0; Severe = 2.1-3.0; Very severe = >3.0.

Soil Amelioration Treatment	Site (Year) and Soil Type						
	Badgingarra (2017)	Moora (2016)	Meckering (2016)	Goomalling (2017)	York (2018)	Kojonup (2015)	Gibson (2014)
	Deep sand	Deep sand	Duplex sandy gravel	Deep sand	Deep sandy duplex	Loamy gravel	Deep sandy duplex
Control (untreated)	1.8	2.4	2.1	1.5	1.6	3.1	3.6
Deep ripped	-	-	2.4	1.7	0.5	-	-
Offset discs (shallow)	1.8	1.8	-	-	-	-	-
Rotary spaded	1.1	0	0	0.3	0.3	-	1.9
One-way plough	-	-	0.3	0.3	0	1.7	-
Mouldboard plough	-	-	0	0.2	0	0	1.2
Clay spreading	0.8	0	-	-	-	-	0.8
LSD (P<0.05)	*0.2*	*0.3*	*0.8*	*0.5*	*0.5*	*0.9*	*0.2*

Cereal grain yield responses to strategic deep tillage using rotary spaders or inversion ploughs were of a similar magnitude in the first two years after treatment, with size of the average yield gain reflecting higher yield potential of soils and environments (Table 5). For example, average gains in cereal yields from soil inversion were 541 kg/ha (61%) on a pale deep sand, 744 kg/ha (42%) on a higher yielding deep sand over clay or gravel duplex soil. On a higher rainfall, high yield potential environment on forest gravels, the average yield gain was 882 kg/ha (29%; Table 5). For the most part, reliability of positive yield response in the first few years after strategic deep tillage was high, 70% or more, except for inversion ploughing of the deep sands (56%; Table 5). In all cases the non-responsive comparisons of inversion on these soils was as a result of either drier, difficult seasons or poor crop establishment as a consequence of herbicide damage, wind damage or surface crusting coupled with dry conditions. There were no significant negative responses at these sites but expected yield outcomes were not achieved. For the deep sands the rotary spader had more consistent positive yield responses in the first two years, with 84% of comparisons giving significant increases.

The higher yield potential, and typically more fertile soils, maintained the cereal yield benefits for a longer time than the pale sands, with larger yield benefit three or more years after the amelioration event (Table 5). Note that for the pale deep sand, the average increase in yield benefit for soil inversion after three or more years, was 714 kg/ha yield gain, but this was driven by one highly responsive long-term grower site. This site was extremely repellent and establishment in the untreated control strips was always poor, irrespective of season. While this was a legitimate response and benefits of inversion at this site were very high, the ongoing benefits at the few other longer-term sites have been much more modest, similar to those from spading, (220 kg/ha) with only half the comparisons showing a significant benefit (Table 5). Accounting for this, the benefits on the pale deep sands, whilst high in the first few years, declined significantly thereafter, except for severely repellent sites. For the other soil types average yield benefits in excess of 500 kg/ha were maintained for three or more years after amelioration (Table 5), with 75% or more of the comparisons showing significant positive yield benefits, except the forest gravels, where only 60% showed positive responses. Further research on strategic deep tillage on forest gravel soils is required as some of the experimental sites have sustained consistently high benefits, while others have remained consistently unresponsive. Better understanding and diagnostics needs to be developed to determine which scenarios and soils will be most responsive.

Table 5. Average cereal grain yield responses (kg/ha) to amelioration of a range of water repellent soil types through strategic deep tillage using either a rotary spader or inversion ploughs over 2009-2018. The number of comparisons (No. Comp.) and proportion (%) of these which had positive response (% Positive Comp.), defined as either statistically significant (P<0.1 or better) for replicated experimental data or a yield increase of at least 300 kg/ha or more for large-scale grower validation trial data are shown.

Amelioration Type	Soil Type	Cereal Crop Yield Response to Amelioration							
		Years 1-2				Years 3+			
		No. Comp.	Yield Change (kg/ha)	Yield Change (%)	% Positive Comp.	No. Comp.	Yield Change (kg/ha)	Yield Change (%)	% Positive Comp.
Rotary Spader (Deep soil mixing)	Pale sand	14	460	51	71	4	220	11	50
	Deep sand & Duplex	25	728	50	84	9	550	33	78
Soil inversion (Mouldboard and One-way Plough)	Pale sand	8	541	61	75	8	714*	49*	75
	Deep sand	9	559	35	56	8	513	27	100
	Sandy duplex	7	744	42	86	4	680	22	75
	Forest Gravel	5	882	29	80	5	558	21	60

* This result is driven by a very responsive, extremely repellent site that has been measured for 7-seasons. It has consistently large yield responses due to untreated controls having very poor establishment and yield. See text for further discussion.

For break-crops, insufficient data are available to assess grain yield responses according to soil type or years after amelioration (Table 6). Overall, average yield responses of canola and lupin to soil inversion are higher than for rotary spading. The yield response of canola to soil inversion is quite reliable with 73% of comparisons showing a significantly positive benefit (Table 6). This was surprising as risks surrounding wind damage and poor establishment of break-crops, and poor nodulation for lupins, were expected to be higher for inversion than for spading. For canola there was only one significantly negative yield response to spading, in addition to a number of non-responsive sites. While the causes for this poor response remain unclear, if it was excluded the average canola yield benefit to spading increased to 340 kg/ha, still lower than the average benefit to inversion of 412 kg/ha (Table 6). For inversion the canola yield benefit at responsive sites was quite consistent ranging from 270-570 kg/ha. The capacity for canola to compensate for poorer crop establishment was an advantage on inverted soils. For lupins, establishment on severely repellent soils was typically greatly improved by inversion, and the lower proportion of positive comparisons was largely a result of several consistently non-responsive sites, one of which was monitored for ten years and contributes four of the thirteen comparisons. Negative or nil yield responses of lupins to spading were either a result of sandblasting of the lupin crop resulting in seedling mortality or dry seasons with periods of high drought stress, especially during early growth.

Table 6. Average break crop grain yield responses (kg/ha and %) to amelioration of water repellent soils through strategic deep tillage using either a rotary spader or inversion ploughs over 2009-2018. The number of comparisons (No. Comp.) and proportion of these which had positive response (% Positive Comp.), defined as either statistically significant (P<0.1 or better) for replicated experimental data or a yield increase of at least 300 kg/ha or more for large-scale grower validation trial data are shown.

Amelioration Type	Average Break-Crop Yield Response to Amelioration (kg/ha)							
	Canola				Lupin			
	No. Comp.	Yield Change (kg/ha)	Yield Change (%)	% Positive Comp.	No. Comp.	Yield Change (kg/ha)	Yield Change (%)	% Positive Comp.
Rotary Spader	9	270	24	44	10	320	20	40
Soil Inversion (Mouldboard & One-way Plough)	11	412	24	73	13	462	51	54

At some of the experimental sites multiple soil amelioration implements and combinations were assessed, enabling direct comparison of responses between implements or the additive benefit of deep ripping after soil inversion. For soil inversion with a mouldboard plough compared to rotary spading there were 23 yield comparisons across eight research sites (data not shown). Yield differences between the implements varied markedly, with up to 500-600 kg/ha yield differences favouring one implement or the other in some instances. As a result overall there was, on average, no difference in grain yield benefit between the implements, although this was not always the case at particular sites and seasons (data not shown). No consistent soil type, crop type, seasonal or location effect was evident. In general the mouldboard plough performed more poorly than the spader in situations where achieving good crop establishment was difficult, due mostly to an uneven seedbed, greater damage from pre-emergent herbicides (Edwards et al. 2018), variable seeding depth, furrow infill and surface crusting. Some of these issues were an artefact of having small ploughed areas embedded within a larger trial area or growers paddock. However, these risks should be reduced in well managed grower scenarios.

Use of a modified one-way disc plough to allow greater working depth and soil turnover is an alternative to the mouldboard plough as an implement for soil inversion. Cereal grain yields in response to amelioration by these implements were directly compared nine times across four sites and soil types (Fig. 1A). In seven of the nine comparisons, the yields achieved from the mouldboard plough exceeded those of the one-way plough (Fig. 1A). Exceptions to this were: 1) in the first season on a deep sand over gravel, where establishment on the mouldboard plough treatment with more complete inversion was reduced more than the one-way plough treatment resulting in lower yield. In subsequent seasons the mouldboard has yielded more and; 2) on a sand over clay duplex soil where the mouldboard brought up more heavy clay (including clods) to the soil surface than the one way plough. Use of a mouldboard plough on shallow sand over clay (duplex) soils is generally not recommended, but depth to clay typically varies on these soils and some areas where the clay is deeper can respond very well to inversion. Indeed at the sand over clay site the mouldboard plough treatments still yielded 880 kg/ha more than the untreated control, while the one-way plough yielded 1350 kg/ha more than the control (data not shown). On average the mouldboard plough across these comparisons yielded on average 196 kg/ha more than the one-way plough. If the negative results due to incorrect soil type and management issues were excluded, the average yield benefit increased to 389 kg/ha. Both implements resulted in considerable benefit over the untreated control with average yields across these sites being 2.5 t/ha for the control, 3.3 t/ha for the one-way plough and 3.5 t/ha for the mouldboard. The reason for the greater yield response to the mouldboard in unclear. Ploughing depths were similar, though may have favoured the mouldboard by 2-5cm at some sites. Topsoil burial pattern varied with the mouldboard, concentrating the topsoil in thicker lenses at the base of the furrow, while the one-way plough generally laid the topsoil into a narrower crescent, but whether this affected crop performance is not clear. Despite this apparent performance difference on some soil types, the much lower cost to purchase and modify a one-way plough compared to a mouldboard plough and its capacity to be used across a broader range of soil types means that use of either tool can be readily justified depending on grower needs, finances and soil types. Other agronomic benefits and risks can also influence the decision. For example, more complete inversion with a mouldboard plough is preferred for control of herbicide resistant weeds (Scanlan and Davies 2019).

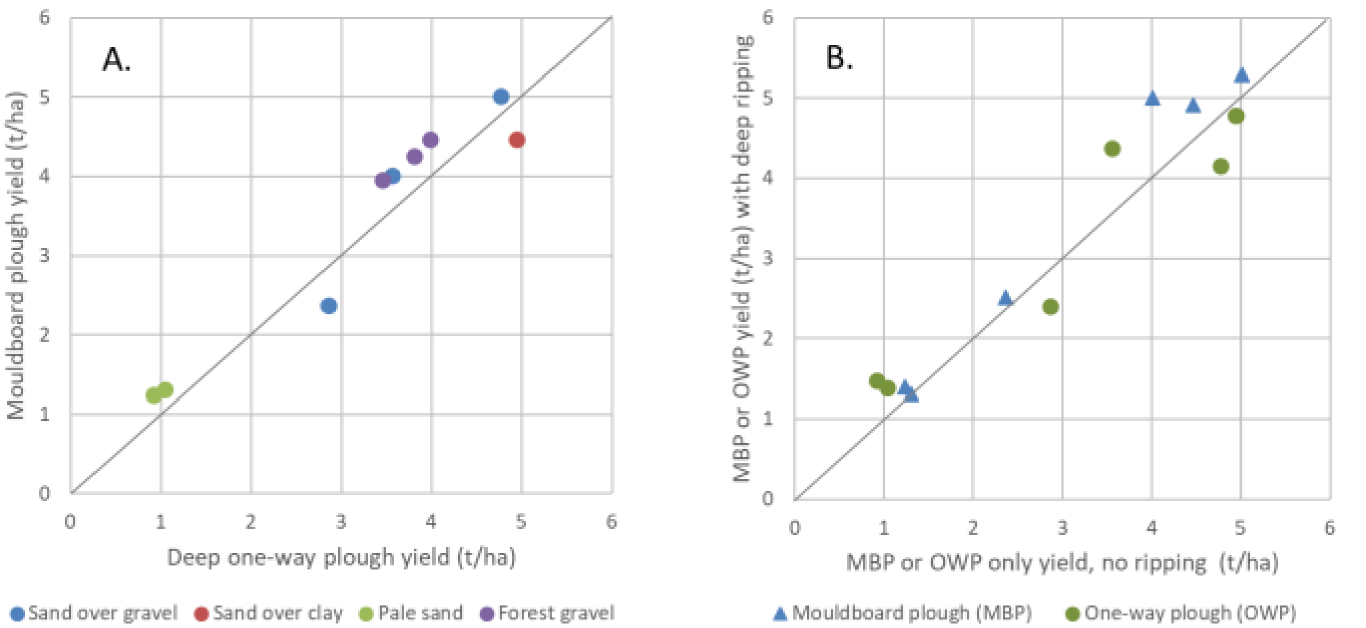

Figure 1. Plot A. Comparison of cereal grain yields (t/ha) for soil inversion with either a mouldboard plough or one-way plough across four soil types (sites) from 2015-18. Plot B. Comparison of cereal grain yield (t/ha) responses from soil inversion with a mouldboard or one-way plough on their own or with the additional deep ripping across three sites from 2016-18.

Additional deeper ripping, typically to 50cm or more, following soil inversion (typically after 1-4 years) further improved and sustained productivity benefits compared with inversion alone. There were twelve comparisons over three sites where deeper ripping was added to soil inversion with either a one-way or mouldboard plough (Fig. 1B). For the mouldboard plough, deeper ripping gave a yield benefit for five of the six comparisons, with an average yield improvement of 340 kg/ha (10%) over mouldboard ploughing without ripping. For the one-way plough responses from additional ripping were more variable, though the reasons for this are unclear.

Addition of clay-rich subsoil to water repellent sandy topsoils, through either delving or spreading, can almost permanently eliminate soil water repellence (Roper et al. 2015; Hall et al. 2010). Rotary spaders have now become a common implement for incorporating clay following spreading or delving, as poor clay incorporation was often found to be a problem on clayed soils (Hall et al. 2010) but spaders also reduce repellence in their own right (Table 4). The benefits of adding clay in addition to spading appear to accrue over the longer term, with minimal benefit in the first three to four years evident from the research sites (see Betti et al. 2018; Hall et al. 2018) but more benefit in subsequent years (Hall et al. 2018). Some growers are using a strategy of ameliorating their constrained sandplain soils with strategic deep tillage first, then only adding additional clay to poorer areas which do not respond well or have a relatively short-lived response. Clay addition comes at a high cost but, as well as reducing water repellence, claying can improve crop and pasture establishment (Cann 2000; Hall et al. 2010), wetting of the soil profile (Betti et al. 2015), crop nutrition (Bell et al. 2017), soil carbon (Hall et al. 2010; Schapel et al. 2018), reduce wind erosion and has been implicated in reducing frost damage (Rebbeck et al. 2007).

Conclusion

The past ten-years of research into managing water repellent soils in WA cropping systems has resulted in a greater understanding of what factors can influence the expression of water repellence, has aided the development of a range of profitable new approaches and helped to refine and asses existing strategies (Table 7).

Table 7. Summary of options for managing water repellent cropping soils in WA showing estimated costs and factors (soil type, seeding and seasonal) and benefits associated with responsive situations.

Soil Water Repellence Management Method	Approx. Cost ($/ha)	Responsive Situations				
		Soil Types	Seeding or Seasonal Factors	Avg. Cereal Yield Benefit (kg/ha)	Years of Benefit	Years to Break-even
Paired-row sowing	1-5 p.a.	All repellent soils	-	370	1	1
Near-row sowing	1-5 p.a.	All repellent soils	Dry seeding Dry autumn	220	1	1
Banded soil wetters	10-30 p.a.	Forest gravels	Dry seeding Dry autumn	320-520	1	1
Blanket soil wetters	25-50 p.a.	Forest gravels	Dry seeding	~250	2	2
Deep soil mixing (e.g. Rotary Spader)	120-150	Deep sands Deep sandy duplex	Avg. to good autumn rain	220-730	4-10+	1-2
Deep soil inversion (e.g. Mouldboard or One-way)	100-150	Deep sands Deep sandy duplex Sandy gravels Forest gravels	Avg. to good autumn rain	510-880	10+	1-2
Clay delving and incorporation	300-450	Deep sandy duplex	Avg. to good autumn rain	830 (limited data)	20+	3-4
Clay spreading & incorporation	600-750	All repellent soils	Med-high rainfall	660	20+	~5+

Improved seeding strategies such as paired-row and near-row seeding can benefit establishment on repellent soils but this does not always translate to yield. Banded wetters are currently best suited to dry seeding of cereals on the repellent forest gravels of the south-west. Further, development of this technology is needed to achieve more consistent benefits on a broader range of repellent soil types. Current research is continuing to examine the molecular interactions between the hydrophobic organic matter and mineral surfaces and which factors increase the expression of soil water repellence. Improvements in understanding of the chemistry and expression of repellence on various soils could enable development of more effective and better targeted soil wetters. For all of these mitigation approaches it will be necessary to address underlying subsoil constraints to achieve long-term substantive yield benefits on these soils.

Amelioration approaches using strategic deep tillage can be highly successful and result in large yield benefits, partly because they address multiple soil and agronomic constraints. For soil inversion, key factors for success are; 1) avoid soils where there is a risk of bringing too much clay or toxic soil to the surface; 2) minimise establishment risks through effective seedbed preparation, careful seeding (slowing down can help!), and cautious use of pre-emergent herbicides. Most sandplain soils are responsive to strategic deep tillage though benefits can decline after 2-3 years on the pale deep sands. Further research is needed to determine how the productivity benefits can be better maintained on these soils. Future benefits will come from greater precision and technology associated with seeding operations, improved diagnostics and management packages for more effective amelioration of spatially variable soils with multiple interacting soil and agronomic constraints.

Key words

Soil water repellence; Banded wetting agents; Near-row sowing; Paired row; Rotary spading; Soil inversion; Claying

References

Anderson G, Erickson T, Davies S, McDonald G (2018) Seeds coated with wetters improved cereal germination on water repellent soils. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Anderson G, Erickson T, Davies S, McDonald G, Edwards T (2019) Seed coatings with various surfactants and glues to improve on crop establishment on water repellent soils. 2019 GRDC Grains Research Updates, 25-26 February, Perth, Western Australia.

Anderson G, Valentine C (2017) Seed and fertiliser coating technologies for crop production in Western Australia. 2017 GRDC Grains Research Updates, 27-28 February, Perth, Western Australia. www.giwa.org.au/2017researchupdates

Bell RW, Hall D, Sochacki S (2017) Crop nutrition and the response to claying of sands. 2017 GRDC Grains Research Updates, 27-28 February, Perth, Western Australia. www.giwa.org.au/2017researchupdates

Betti G, Grant C, Churchman G, Murray R (2015) Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* **53**, 125-136.

Betti G, Davies S, Reynolds C (2018) How can we ameliorate water repellent soils cost-effectively? Indications from three trials in WA. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Blackwell P, Hagan J, Davies S, Bakker D, Hall D, Roper M, Ward P, Mathews A (2014) Smart no-till furrow sowing to optimise whole-farm profit on non-wetting soil. 2014 Agribusiness Crop Updates, 24-25 February, Perth, Western Australia. www.giwa.org.au/2014-crop-updates

Blackwell P, Morrow G, Nicholson D, Webster T (1994) Effects of furrow sowing design for crop production on water repellent sands: furrow spacing and seeding rate, firming, surfactants and water absorbing gels. *In* 'Proceedings of the 2nd National Water Repellency Workshop', 1-5 August 1994, Perth, Western Australia.

Cann MA (2000) Clay spreading on water repellent sands in the south east of South Australia – promoting sustainable agriculture. *Journal of Hydrology* **231-232**, 333-341.

Crabtree WL, Henderson CWL (1999) Furrows, press wheels and wetting agents improve crop emergence and yield on water repellent soils. *Plant and Soil* **214**, 1-8.

Davies S, Boyes T, Reynolds C, Petersen L, Walker J, Fulwood T, Dempster R, Andrew J (2018) Understanding the impact of a comprehensive range of deep tillage practices on crop performance and soil properties for two water repellent soil types. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Davies SL, Newman P, Best B (2010) Impact of soil inversion, soil dilution and claying on non-wetting sandplain soils. 2010 Agribusiness Crop Updates. 25-26 February, Perth Western Australia. (Department of Agriculture and Food, Western Australia and Grains Research and Development Corporation).

Davies S, McDonald G, Betti G, Harte L, Poulish G, Bakker D, Devlin R, Jenkinson R (2016) Assessing options for managing water repellent gravels. 2016 Grains Research Updates, 29 February – 1 March, Perth, Western Australia. www.giwa.org.au/2016researchupdates

Davies SL, Blackwell PS, Bakker DM, Scanlan CA, Gazey C, Hall DJ, Riethmuller GP, Abrecht DG, Newman PD, Harding A, Hayes DW, Smart SD (2013) Deep soil cultivation to create improved soil profiles for dryland crop production. In 'Proceedings 2013 Society for Engineering in Agriculture (SEAg) Conference: Innovative Agricultural Technologies for a Sustainable Future.' 22-25 September 2013, Mandurah, Western Australia.

Desbiolles J (2015) Seeder tracking and guidance considerations for guided row sowing. Mallee Sustainable Farming, Karoonda Field Day Booklet 2015. www.msfp.org.au/resources/field-day-booklets

Edwards T, Davies S, McDonald G, Hall D, Moore J (2018) Understanding interactions between pre-emergent herbicides and inversion tillage. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Hall D, Edwards T, Davies S, Bell R, Farre I, Petersen L, Dodge D (2018) Longer term effects of spading, mouldboard ploughing and claying on the south coast of WA. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Hall DJM, Jones HR, Crabtree WL, Daniels TL (2010) Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia. *Australian Journal of Soil Research* **48**, 178-187.

Kerr R, Ward P, Roper M, Micin S, Davies S (2017) Managing water repellency with minimal soil disturbance. 2017 GRDC Grains Research Updates, 27-28 February, Perth, Western Australia. www.giwa.org.au/2017researchupdates

Llewellyn R, Kleeman S, Preston C, McBeath T, Aggarwal N, Davoren B, Gupta V, Gill G, Shoobridge W, Kroker S, Hicks M (2017) Testing crop row placement and pre-emergence herbicide options for brome grass on Mallee sand. Mallee Sustainable Farming Systems Research Report, 2016. www.msfp.org.au/publications/research-articles

McBeath T, Desbiolles J, Vadakattu G, McKay A, Llewellyn R, Davoren B, Moodie M, Correll R (2016a) Sowing strategies to improve the productivity of crops in low rainfall sandy soils. 2016 GRDC Grains Research Updates, 9-10 February, Adelaide, South Australia.

McBeath T, Vadakattu G, Davoren B, Kroker S, Llewellyn R, Shoobridge W (2016b) Sowing strategies to improve productivity on sandy Mallee soils. Mallee Sustainable Farming Systems Research Report, 2015. www.msfp.org.au/publications/research-articles

McBeath T, Vadakattu G, Davoren B, Kroker S, Llewellyn R, Shoobridge W (2018) On-row sowing for Brome competition on non-wetting sands. Mallee Sustainable Farming Systems Research Report, 2017. www.msfp.org.au/publications/research-articles

McDonald G, Davies S (2018) Soil wetting agents can carry over to following seasons on repellent loamy gravels. 2018 GRDC Grains Research Updates, 26-27 February, Perth, Western Australia. www.giwa.org.au/2018researchupdates

Rebbeck M, Lynch C, Hayman PT, Sadras VO (2007) Delving of sandy surfaced soils reduces frost damage in wheat crops. *Australian Journal of Agricultural Research* **58**, 105-112.

Roper MM, Davies SL, Blackwell PS, Hall DJM, Bakker DM, Jongepier R, Ward PR (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806.

Scanlan CA, Davies SL (2019) Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil and Tillage Research* **185**, 139-145.

Schapel A, Marschner P, Churchman J (2018) Clay amount and distribution influence organic carbon content in sand with subsoil clay addition. *Soil and Tillage Research* **184**, 253-260.

Sherriff M (2016) Improving crop establishment with in-furrow liquids. 2016 Grains Research Updates, 29 February – 1 March, Perth, Western Australia. (Grains Research and Development Corporation). www.giwa.org.au/2016researchupdates

Ucgul M, Saunders C, Desbiolles JMA, Davies SL, Parker W (2019) Improving the effectiveness of overcoming constraints by optimising soil amelioration practices. 2019 GRDC Grains Research Updates. 25-26 February 2019, Perth, Western Australia. (Grains Research and Development Corporation). www.giwa.org.au/2019researchupdates

Acknowledgments

Research presented was funded by GRDC, DPIRD, CSIRO and ‘The Farm Shop’, Northam. Authors acknowledge substantial contributions of former DPIRD researchers Paul Blackwell, Derk Bakker and Peter Newman. The authors are grateful for the input and collaboration of host-growers, consultants, regional catchment councils and partnering grower groups including: WMG, MIG, NAG, YFIG, Liebe, CFIG, WANTFA, Facey, Southern Dirt, Stirlings-to-Coast, Gillami Centre, RAIN and SEPWA,

GRDC Project Numbers: DAW00244, DAW00242, DAW00204 and CSP00139